Gamut Clipping and Mapping Based on the Coloroid System

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Abstract

The paper presents novel techniques based on the Coloroid color system which hitherto has not been applied to gamut mapping. The introduced methods described are hue preserving and use three gravity centers in a hue-dependent way. Two of the gravity centers are shifted toward the direction of 'negative saturation', and can be used for regions of bright and dark colors, while a third gravity center is used for saturated colors.

After a short survey of gamut mapping an introduction to the Coloroid describes concisely its features and formulas. Then a simple color clipping rule is presented applicable to any rendering applications. A gamut mapping method will be defined mapping from a generic input image to an RGB display. Other variations of the method describe RGB-CYMK transformation and also cross-media mapping for known input and output gamut boundaries.

The introduced methods apply hue and chroma dependent lightness compression. They can be applied in realistic computer graphics and digital photography as well as in printing technologies. They are straightforward to implement and have low computational costs.

Introduction

An image generated by computer graphics or by digital photography represents a 3D set of colors which is called the image gamut. In general this gamut contains points which are outside the device gamut, and therefore cannot be reproduced correctly. In this case the exterior colors must be transformed into the destination gamut in order to display them.

A transformation is called "gamut clipping" or "color clipping" when only image colors outside the destination gamut are changed. Numerous simple rendering software apply the non hue-preserving 'pro channel' clipping commonly used in classical color photography.

More general gamut mapping techniques change not only the external colors but also part of the destination gamut. Gamut mapping techniques typically modify the original image colors little near an unchanged kernel of the destination gamut, and shoving off more strongly, ensuring a soft transition between an exact reproduction and heavily modified image colors.

Due to their industrial importance many different transformations are applied. A comprehensive survey of a large number of publications can be found at the web site of the CIE Technical Committee 8-03 on Gamut Mapping or in [Moro01a]. The gamut mapping methods can be classified by their different aims: gray axis preservation, maximum contrast or increasing saturation, minimizing the hue shifts, etc. They can be classified by generations, at which the current generation is the third. The first generation LCLIP, LLIN, LNLIN methods [Moro01b] use linear clipping or compression or non-linear compression of chroma after some global linear lightness compression. SLIN and CUSP uses single gravity centers differently and apply lightness and chroma compression simultaneously. The second generation GCUSP is a combination of an initial chroma dependent lightness compression with CUSP. CARISMA [Gree00] is also an important method used by the second generation. Third generation models (UniGMA, LCUSPH) and the trends of the gamut mapping are described in [Moro99]. Good visual examples can be seen for a couple of the methods in [Moro02]. Furthermore it is important to mention that an efficient relative lightness changing model is introduced in [Herz00] and the topographic gamut compression in [MacD01].

The question of evaluation has an even deeper problem, namely the missing criteria and the possibility at different requirements for a "good" mapping. Therefore, there is not a best gamut mapping. There are always problems to be addressed partly by empirical or psychophysical assessment of skilled observers, and partly by a feeling of "style". [Ston88] introduced an alternative basic concept of 'MetaWYSIWYG' in order to save the total impression of the image rather than its individual colors.

Fortunately, there are some common, although unexceptional, convergence points in the different models. The most important common requirement of the existing approaches is hue preservation. But, a question appears here concerning the definition of the hue dependent on the applied color system or color appearance model. Another common experience is that the values of lightness and the chroma (or saturation) must change simultaneously, depending on hue. Furthermore, it is more important to preserve the lightness in bright color regions, rather than the chroma, while in the dark region preservation of the chroma is preferred. The ultimate goal is a visually pleasant

appearance without visible artifacts and low computational costs.
A new gamut mapping method will be introduced in this paper, it will be based on the Coloroid color space which has hitherto not been applied in this area. The Coloroid has simple formulas and some interesting and practical features concerning its requirements for the conditions of the observation. Some techniques will be presented for images captured digitally or computed by rendering software. They are allowed to contain colors outside the CRT-gamut containing areas with high brightness, but we will not deal with real HDR mapping here. Then the evergreen RGB-CMYK problem will be discussed briefly as well as the question of cross-media mapping.

1. The Coloroid Color System

1.1. The history of the Coloroid

The Coloroid Color System was developed by Antal Nemcsics in Hungary at the Technical University of Budapest [Nemc80], [Nemc87]. He used the results from experiments that involved over 70,000 people. ‘The aim is to provide a system in which the colors are spaced evenly in terms of their aesthetic effects, rather than of color differences as in the Munsell system, or perceptual content as in the NCS.’ [Hunt92].
The aesthetically uniform Coloroid is an easily understandable color order system and at the same time it is a continuous color space with simple conversion rules into and from the CIE XYZ color measurement system. We will use their unique features for the new clipping and mapping methods, in which features are matched fairly to the viewing conditions of the real life in the practical photopic range.

1.2. Conditions of observation

The Coloroid color order system is one of the most important six systems in the world [Hunt92], [Bill87]. The Coloroid formulas are based on a huge number of observations in different kinds of experiments simulating the ‘real world’ instead of laboratory viewing conditions. A set of color samples were used in a wide visual field for every observation performed with semi-adapted eyes. This means that the adaptation to the reference white and an ambient light was ensured by a longer precondition time, but the observations of the individual test pictures have been performed quickly. The situation is similar to the case of a pedestrian in the street, quickly tracking different objects and having no time to adapt to the details. For example no difference can be perceived between some dark colors, which could be distinguished in a test room within a small viewing angle and after a longer adaptation time. Consequently, e.g. the Munsell color order system in dark region is ‘overrepresented’ [Nemc95].
Due to the viewing conditions and the number of the observations the Coloroid is unique. It is a so called ‘aesthetically uniform color-space**’** based on the *dH* ‘harmony threshold’ instead of the just noticeable *ds* line element after full adaptation, which *dH* is between one four times greater than *ds*. Terminology for the harmony threshold refers to the greatest acuity of the system with which it is possible to formulate aesthetical rules of color harmonies [Nemc93] easily. The *dH* harmony threshold is applied successfully since the end of the sixties but its relation to the *ds* line element is still a matter of ongoing research. This field is related to the perceptibility thresholds of large images [Uroz02].

1.3. The three ‘axioms’ of the Coloroid

Te variables in the Coloroid system are hue (*A*), saturation (*T*) and lightness (*V*). Colors with the same hue are linear combinations of white, black and a highly saturated so-called ‘limit-color’. This arrangement had inspired our idea to using three gravity centers for the gamut mapping (see Section 3).
In contrary to most of the other color spaces a constant hue value defines a *plane* instead of a generic curved surface, resulting very simple mapping formulas. This is a consequence of observations by a semi-adapted eye viewing a set of colors simultaneously. Each vertical hue plane contains a common neutral axis with black and white endpoints. The formula of psychometric lightness is very simple given by excellent correlation in the form $V = 10\, sqrt(Y)$.
The third perceptual attribute, the psychometric saturation, is constant along each vertical line in the 3D Coloroid space arranged inside a straight-sided cylinder. We observe that the ‘psychometric saturation’ is a better terminological fit for the ‘chroma’ in most of other color systems, such as that in CIE Lab.
The aforementioned additive black-white-color mixing has been realized in the Coloroid experiments by rotating Maxwell disks containing these 3 components in 3 sectors with different angles. If the size of the third sector containing the limit-color (i.e. the highly saturated solid color) had been fixed and only the black-white ratio had changed then the psychometric saturation was perceived the same. This means that, for a given hue, the colors having equal saturation also have an equal *ratio of limit-color*. Thus, a spectral color with decreasing luminance must have decreasing saturation, since it corresponds to mixing a decreasing color sector only with black, and the saturation is defined by the ratio of the color sector.
The three most important features of the Coloroid can be described as three ‘axioms’, expressing the strong correlation of *over 20 million* elementary observations:

axiom 1: constant hue (*A*) form a plane
(containing the neutral axis and a limit-color)
axiom 2: lightness (*V*) $= 10\, sqrt(Y)$
axiom 3: saturation (*T*) = a hue dependent const ***** ratio of the limit-color

1.4. Perceptually Euclidean metrics

There is no exact perceptually uniform 3D color space only some approximations thereof, such as the CIE Lab or CIECAM02. These systems attempt to approximate the Euclidean metrics, but typical errors occur always in different regions of the color space.

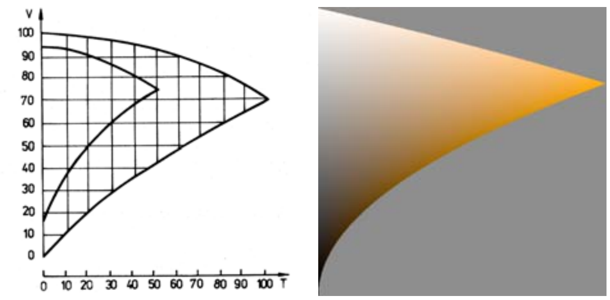

Figure 1. Constant hue plane with orthogonal saturation (T), and lightness (V) coordinates; a yellowish hue plane in Coloroid with typical curved borderlines

Nevertheless, the constant hue planes of the Coloroid system are *perceptually perfectly uniform.* That is they form Euclidean *2D subspaces* with *V* lightness and *T* saturation coordinates (see Fig.1). This will be sufficient for our investigations, because any operation in our method will be performed within the hue plane, and thereby the Coloroid based gamut mapping can be considered as working on perfectly Euclidean metrics.

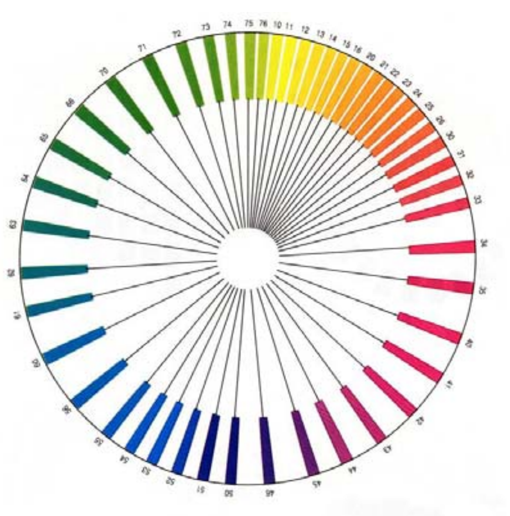

Figure 2. Circle of the Coloroid basic colors

Although, the whole 3D Coloroid space is not uniform (similar to other color spaces and color order systems), a special set therein gives a perceptually uniform series, namely the *color circle,* see Fig.2. This intersects every individual hue planes, and consists of the 48 limit colors obtained from numerous experiments and representing the 7 basic groups of hues. It is sufficient to define the perceptual distance in terms of separate constant hue planes for our method, as mentioned above. However, some local metrics could be defined relying on perceptual distance between two color samples on neighboring hue pages of the Coloroid color atlas having the same *(T,V)* values, since this distance depends only on the *(T,V)* and their roughly common hue value. This local metrics could be extended to a global perceptual distance measure but this research will be reported in future papers.

1.5. Coordinates and transformations

It is not necessary to have an intimate knowledge of the Coloroid to use it in our new gamut mapping method. Instead of defining a wavelength and the value A of the hue, as written in the original formulas [Nemc87], [Hunt92], it is sufficient to compute the cylindrical hue-angle φ

$$\varphi = 180 / \pi \ \text{atan}\,[(y - y_w)/(x - x_w)], \quad [\text{degree}] \ \text{in} \ (-180, +180) \qquad (1)$$

where *(x,y)* are the CIE chromacity values of the color sample and (x_w, y_w) corresponds to the *reference white*. It can be mentioned here that the Coloroid originally has been defined at the standard light source CIE-C, and it was later standardized for D65 as well. According to our current research, the white point of the Coloroid can be changed in a practical chromacity area in photopic luminance range [Nemc03], similar to CIE Lab or Luv models. Thus, the Coloroid is also a very simplified color appearance model, which makes it possible to *change the white point* conforming to the different gamut. The white point must be connected to the *48*, spectral or purple, *limit-colors* of the color circle, see [Table 1], which limit-colors represent the *T=100* saturation value independently on the selection of the white point, but of course the chromacity of white must remain in a reasonable field.

The lightness formula is given by

$$V = 10\ \text{sqrt}\,(Y) \qquad (2)$$

where *Y* is the relative luminance coordinate of the color sample.

Saturation will be derived here different way from the original formulas of the Coloroid [Hunt92]. For mapping a color sample it is sufficient to restrict the gamut to the colors having the same hue value, that is to remain on one "saturation-lightness page". For an easier understanding let us introduce the following vector notations on the given plane, using the 2D coordinate system of the non-orthonormal $\mathbf{t}$ and $\mathbf{v}$ base vectors.

Let the ideal 'blacK' be $\mathbf{K} = (0,0,0)$ in the original 3D XYZ space, $\mathbf{W}$ the 'White' point with coordinates (X_w, Y_w, Z_w) and $\mathbf{C} = (X, Y, Z)$ the color sample. Let now $\mathbf{v} = 0.01 \cdot \mathbf{W} = (X_w/100, 1, Z_w/100) = (v_X, 1, v_Z)$, assuming that $Y_w = 100$.

Let $\boldsymbol{N}$ neutral (gray) color on the blacK–White axis be equiluminant to the $\boldsymbol{C}$ color sample, noticing that the gray axis is not orthogonal to a plane being defined by a constant Y value. It can be seen that $\boldsymbol{N} = Y\boldsymbol{v}$, by the Y luminance of the given color. Furthermore, let the $\boldsymbol{H}$ vector pointed from the $\boldsymbol{N}$ neutral color to the $\boldsymbol{C}$ color sample be is given by

$$\boldsymbol{H} = \boldsymbol{C} - Y\boldsymbol{v} \tag{3}$$

while, saturation T is proportional to the length of vector $\boldsymbol{H}$

$$T = s(\varphi)\ \|\boldsymbol{H}\| \tag{4}$$

where factors $s(\varphi)$ with φ are defined in [Table 1] for the CIE-C, D65 and D50 white points respectively for all the above mentioned *48* Coloroid *limit-colors*. Between these colors linear interpolation can be applied by φ [Nemc87]. T is always equal to *100* for the (spectral and purple) *limit-colors* of the Coloroid, although φ and the *distance* between the *limit-color* and the appropriate reference white change in the CIE xy chromacity diagram.
Let finally $\boldsymbol{t} = \boldsymbol{H} / \|\boldsymbol{H}\| = (t_X,\ 0,\ t_Z)$ unit vector be defined in the intersection of the given hue plane and the constant Y-plane in order to ease the computation of the inverse transformation. The second coordinate of $\boldsymbol{t}$ is zero because the auxiliary $\boldsymbol{H}$ vector has zero Y component in (3). Working on a given 2D hue plane defined by φ, after the clipping or mapping (X,Y,Z) comes back from (φ,T,V). According to (2)

$$Y = (V/10)^2 \tag{5}$$

and the X and Z coordinates on the hue plane are expressed by the 3D vectors $\boldsymbol{t}$ and $\boldsymbol{v}$:

$$X = T\,t_X + Y\,v_X \ \ and \ \ Z = T\,t_Z + Y\,v_Z \tag{6}$$

Their angle is equal to the angle of the constant Y planes and the neutral axis which is not orthogonal unless the white point identical to *(100,100,100)*. We shift or warp these directions to rightangle making the slightly angular system orthogonal, thereby they will be used as an orthogonal system, and the iso-luminant and iso-saturated samples build an orthogonal regular grid in the Coloroid color atlas (see Fig 1a). Note that following the original formulas of the Coloroid this virtual ‘problem’ does not occur.
Later we will use the ‘orthogonal’ *(T,Y)* and *(T,V)* systems simultaneously. The *black–white–limit-color* triangle [Nemc93] and the additive mixture are easier to understand in the *(T,Y)* coordinates, but the real clipping or mapping is performed in the perceptually uniform *(T,V)* planes having triangles with characteristically curved Coloroid borderlines according to Fig 1a, Fig 1b, and Fig 3b.

2. Bifocal Clipping Method

2.1. General description

The new clipping method uses a *bifocal projection with two centers of gravity*. The ‘White’ point of display $\boldsymbol{W_D}$ and the ‘blacK’ is $\boldsymbol{K_D}$ following the CYMK notations. The device has some other characteristic points too describing the shape of the gamut. In the case of an RGB display for example these consist of the three most saturated *R, G* and *B* colors, in a simple CYMK model they are the *Cyan–Green-Yellow-Red-Magenta–Blue* colors.

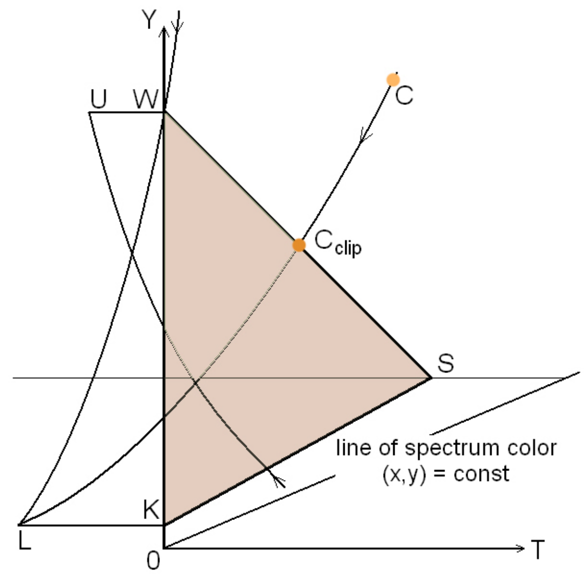

Figure 3a. Bifocal clipping. The shortest ways in T-Y system are quadratic curves. L and U are the gravity centers.

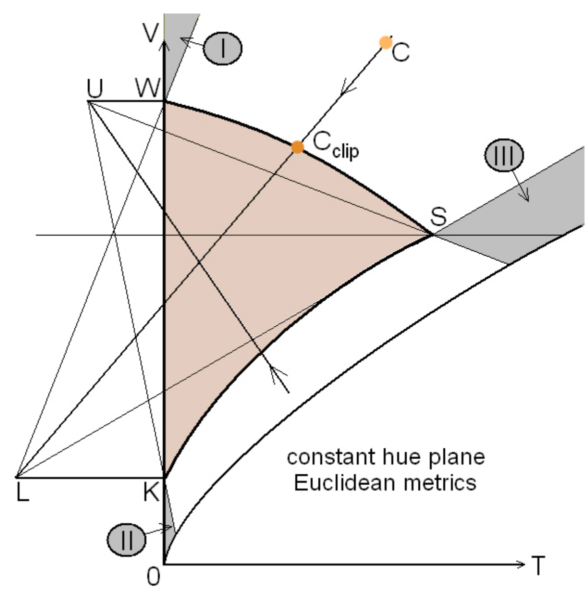

Figure 3b. Bifocal clipping. In T-V system the metric is Euclidean. The I, II, III areas will be mapped to W, K and S respectively.

Now let all of the coordinates *(X,Y,Z)* of $\boldsymbol{W}$, $\boldsymbol{K}$, as well as those of the other characteristic colors be multiplied by the normalization’s multiplicative factor $m = 100 / Y(\boldsymbol{W_D})$. Thus the gamut is normalized according to changes from the original Y of white to *100*. The notations, without the index

D, refer to the already normalized device colors. After the whole mapping process the colors must be returned to the non normalized destination device, using a division by *m* is to be used for *X, Y* and *Z*.

First, the cylindrical hue-angle φ is computed using formula (1) and then the most saturated limit-color is defined in the hue-plane belonging to φ, which can be realized on the given display device. Its computation needs plane-line intersections, and knowing the gamut boundary other classical operations are very simple e.g. for the gamma corrected linear RGB gamut. The device limit-colors can be pre-tabulated as well as other characteristic borderline points according to the given values for φ.

Knowing the hue plane and the device limit-color on it, gravity centers can be selected using either the bright gravity center if the actual color is darker than the *limit-color* or the dark gravity center if the actual color is brighter. The gravity centers can represent imaginary colors too according to Fig 3a and Fig 3b. We recommend that let the dark gravity center have a relative big 'color' shifting by negative saturation direction, while let the bright center have small or even zero shifting.

Then a color sample (being outside the gamut) will be connected to the appropriate gravity center depending on its lightness and the intersection with the gamut boundary will be defined. A color outside the gamut will be displayed by this intersection point. The border lines are curved lines according to the square-root formula of Coloroid-lightness. In Fig 3b it is simply a curved triangle.

The method provides a compromise between lightness-preserving and saturation-preserving clipping. There is a region of very saturated colors outside the device gamut determined by lines from the two gravity centers to the limit-color, which whole region will be represented by the limit-color itself.

2.2. Formulas

Only (T,V) coordinates can be used by defining the hue plane. Let $\boldsymbol{L}$ be the lower (darker) and $\boldsymbol{U}$ the upper (brighter) gravity center. Now

$$\boldsymbol{L} = (-T_L, V_K) \text{ and } \boldsymbol{W} = (-T_U, 100) \qquad (7)$$

where T_L and T_U have non-negative values. Let the device *limit-color* in the given hue be $\boldsymbol{S} = (T_S, V_S)$, and let the *actual color* to display be either unchanged or clipped, be $\boldsymbol{C} = (T_C, V_C)$. There is a sector outside the gamut, which results the $\boldsymbol{S}$ *limit-color* (sector III in Fig 3b) by being clipped. This sector can be defined by the slope of appropriate lines. If

$$(V_C - V_K) \;/\; (T_C + T_L) < (V_S - V_K) \;/\; (T_S + T_L) \quad \text{and}$$
$$(V_C - 100) \;/\; (T_C + T_W) < (V_S - 100) \;/\; (T_S + T_W) \qquad (8a)$$

then the clipped color is the saturated limit-color:

$$\boldsymbol{C}_{CLIP} = \boldsymbol{S} \qquad (8b)$$

If the $\boldsymbol{C}$ color is not highly saturated according to (8a), then first the gravity center $\boldsymbol{G}$ for clipping has to be selected so that

$$\text{if } V_C > V_S, \text{ then } \boldsymbol{G} = \boldsymbol{L}, \text{ otherwise } \boldsymbol{G} = \boldsymbol{U} \qquad (9)$$

For bright colors a white area will be returned (sector I, Fig 3b).

$$\text{If } (V_C - V_K)/(T_C + T_L) > (100 - V_K)/T_L \text{ than } \boldsymbol{C}_{CLIP} = \boldsymbol{W} \qquad (10)$$

For dark and unsaturated colors a black area will be returned (sector II, Fig3b).

$$\text{If } (V_C - 100)/(T_C + T_U) < (V_K - 100)/T_U \text{ than } \boldsymbol{C}_{CLIP} = \boldsymbol{K} \qquad (11)$$

If the color is not in such special sectors, intersection has to be defined between the gamut borderline and a line across the appropriate focus $\boldsymbol{G}$ and color $\boldsymbol{C}$. In a simple case, such as that of an RGB display, the actual gamut slice forms a triangle in the (T,Y) coordinate system. Let the color brighter than color $\boldsymbol{S}$ so the gravity center $\boldsymbol{G}$ is $\boldsymbol{L}$. The borderline is curved in the (T,V) coordinate system between $\boldsymbol{W}$ and $\boldsymbol{S}$, which would be an interval of a straight line in the '*Y*-space'. Now in the '*V*-space' again, let the equation $V = a + b\,T$ define a line across (T_L, V_L) and (T_C, V_C) and in the '*Y*-space' the equation $Y = c + d\,T$ define a line across the white $\boldsymbol{W} = (0, 100)$ and $\boldsymbol{S} = (T_S, Y_S)$.

Thus, according to $Y = V^2/100$ in (2), we can obtain the desired T_I value for the intersection in the 'Y-system' from the equation $(a + b\,T)^2 = 100\,(c + d\,T)$. This results in a second order equation in the form of $AT^2 + BT + C$, where

$$A = b^2,\; B = 2ab - 100d,\; C = a^2 - 100c \qquad (12)$$

The first positive solution of (12) is the desired T_I. If $T_I > T_C$ then $\boldsymbol{C}$ is inside the gamut so the color remains *unchanged*, otherwise it shall be replaced by the *intersection point*. The result of the intersection is $V_I = a + b\,T_I$. The (X, Y, Z) coordinates of the *clipped color* can be computed from known (T_I, V_I) using (5), (6a) and (6b).

We suggest this robust clipping rule for simple rendering software. It avoids the hue shifting associated with the widely used 'pro channel' clipping.

This section can be considered for an introduction to gamut mapping techniques resulting in a more pleasant appearance.

3. Trifocal Mapping Method

3.1. Basics

For gamut mapping a reduced gamut, in the example a reduced white-black-limit-color triangle, and the original gamut are used simultaneously (see Fig 4). The white point and the colors of the smaller triangle remain untouched. Between the small and original triangles, with the typical curved Coloroid boundaries, will be the gamut mapping realized. The idea of using black and white gravity centers and a third one around the *limit-color* has already been

[Ito95] published in Japanese and shortly referred by [Moro01a]. They used the CIELab space and their centers were the device black and device white points. The third gravity center is the most saturated color of the fixed smaller area had the same lightness than the *limit-color* belonging to the original one.

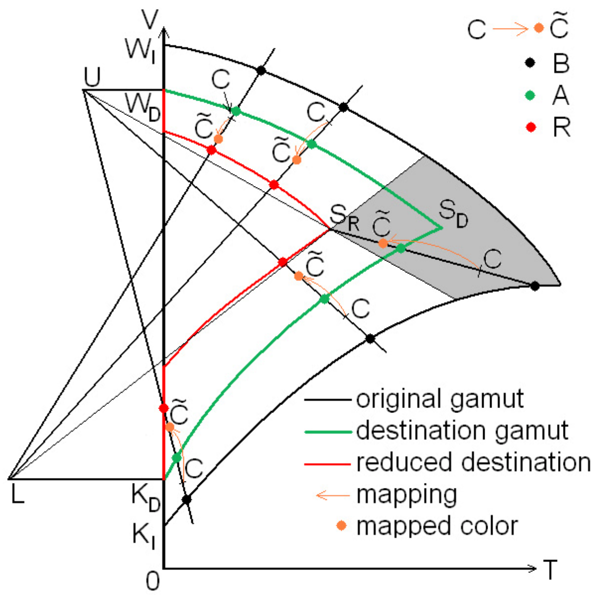

Figure 4. Trifocal mapping with L, U, and S_R centers.

Studying the figure in [Ito95] it can be observed that our methods result in greater differences compared to method described above. The '*Coloroid observer*' significantly differs from CIELab and other color spaces recording its hue, lightness and saturation definition. Secondly we can use two different, *negative shifted* gravity centers ensuring the appropriate lightness/saturation ratio. *Our shifting depends on hue*. Also the *new* inner *limit-color* at the cusp can has a different lightness to that of the device gamut.

First, 3 gravity centers are selected and a new inner black point for the smaller triangle. The white gravity center is shifted as well as in Section 2 but less on the negative direction than the lower one, or in some cases not at all. For dark color we prefer to preserve the color content or the psychometric saturation rather than the 'darkness'. But the new lower center will be significantly shifted. The style of the mapping strongly depends on selection of an 'inner' limit-color and generally on the *shape of the invariant gamut* field. The inner limit-color can be received by an iso-luminant shift, such as in [Ito95].

We suggest two further possibilities. First we shift the *limit-color* by a given distance to $(T, V) = (50, 0)$ or to a somewhat different point $((V_L+V_U)/2, 0)$. We try to use the relative highly saturated colors of destination device therefore the 'inner' cusp can not be too far from the old one.

3.2. Mapping to RGB display

In this case the destination gamut is very simple. The triangle of RGB primaries of the CRT is known in the CIE XYZ color space, they will be connected to the white and black points. We assume a calibrated monitor with known linear RGB components. The display has a given contrast value where the measured black point has positive lightness (notified by V_K in Section 2.2) because of unwanted ambient reflections or self illumination.

The gamut of the image is practically unlimited. The image can be obtained from *image synthesis* software or from a *digital camera*. Also possible chromacity values of the input image can be in the widest space, for example the Adobe RGB or the CIE Luv space, while the destination gamut corresponds to the sRGB. We will not present a HDR method in this paper, only a simple hue preserving mapping, which ensures acceptable sense of areas around light sources and allows perception of (original) colors in the dark areas. In HDR cases the local contrast effects will be lost in highlights, therefore this global and fast approach is not a HDR method [Pic 1a,b], but it gives often nice results.

3.3. Exponential Mapping

An early and practical tone mapping technique used in computer graphics [Fers94] compresses the rgb values using an exponential function. The change is small for a normal lightness value and the mapped color tends to the display maximum as the original luminance approaches infinity. However, the lightness of the reference white of the raw image, being an appropriate solid color, is unknown and coming from rendering computations often contains rgb radiance values in fictive unit. This leads to the question as how a middle gray can be selected for $V=50$? [Neum98] presents a method for different rendering techniques using a generalization of the incident light metering commonly used in professional photography. Having the appropriate *median irradiance* value coming from this method (X,Y,Z) coordinates of the middle gray and the white point can be easily selected.

We now present a generalized form of the exponential mapping, see red and green lines of Fig 4. Firstly the intersection ***A*** of the appropriate ***GC*** (gravity center – color sample) line with the borderlines of the display gamut will be computed. There is another line, which is not computed explicitly, namely the inner borderline of the band of color points closer to the intersection than a given value of D. It is also intersected by the ***GC*** line in the point ***R***. Finally, let ***N*** be the intersection of ***GC*** with the neutral axis. The ***G***, ***N***, and ***R*** points can be ordered on the ***GC*** line in a different way. Since ***G***, in our constructions cannot be on the 'positive' side of the neutral axis, it will always be the utmost point in addition to ***R*** on the other side. Normally ***N*** is closer to ***G*** than ***R*** but it can change depending on the ***GC*** line and also on D. Thus let ***R'*** be the point closer to ***G*** out of ***R*** and ***N***. Let d equal the distance between ***R'*** and ***A***, thus $d \leq D$ and generally $d=D$. This set of points is completed by the utmost color ***B*** in the ***GC*** line out of the input gamut, which can be a finite or an infinite point as well. The order

of these points on the line is (***G***, ***N***, ***R'***, ***A***, ***B***), see Fig 4. The method maps now the ***NB*** interval to the ***NA*** interval so that the ***NR'*** remains as it is and ***R'B*** is mapped to ***R'A***, that is the non-identical part of this mapping is performed on ***R'B***.
The ***R'B*** interval is identified with the *[0,b]* interval preserving distances, such that ***R'*** corresponds to *0*, ***A*** corresponds to *d* and ***B*** corresponds to *b*=|***R'B***| which can be finite or infinite. The problem is simplified to finding a smooth mapping function $M:[0,b]\rightarrow[0,d]$. The original mapping function shall extends to the identity mapping on ***NR'*** smoothly, therefore in addition to its smoothness $M'(0)=1$ is also expected. An appropriate function for $b=\infty$ is

$$M(x) = d\,[\,1 - pow\,(2\,,\,-x\,/\,d)\,] \tag{13}$$

The mapping, corresponding to this function, ensures a soft transition and better preservation of the nearest colors to the invariant kernel. It is easy to describe the details using the formulas in Section 2. The mapping is dependent on *d*, so finally *D* regulates the softness of mapping. We suggest selecting the appropriate *D depending* on the *hue* by using the saturation of the *limit-color*. We have found mapping by *D* in interval *[T(S)/8, T(S)/4]* visually pleasing.
The area close to the device *limit-color* has to be treated similarly. The original gamut has to be shrunk by a constant *D*, except the zone near to ***W*** and ***K***, where *d* differs from *D*. It is insufficient to compute the shifted new limit-color S_D explicitly, but it is sufficient to store the *(T,V)* coordinates of S_D in a table after the computation for different φ values, such as the s(φ) values. If ***C*** is in the limit-color sector corresponding to (8a), a similar mapping can be performed. Note that ***R'***=***R***, but the *d* length of the ***R'A*** interval still differs from *D.*
This method is illustrated by digital photos in the [Pic 1a] and [Pic 1b].

3.4. Hue dependent gravity centers

The formulas from this section can be applied to the method described above as well as for other Coloroid based mappings. An appropriate hue dependent selection of lower and upper gravity centers ensures a *hue and chroma dependent* lightness compression.
Without detailing any formulas, we explain the basic idea of this approach. First, we try to maintain the average ratio of changes in the lightness and the chroma. However, for yellowish colors the lightness of the upper side of the Coloroid-triangle decreases slowly, and the saturation of yellow is high, in contrast to bluish colors this upper line decreases quickly. The chroma of the blue *limit-color* is less than that of yellow and the luminance of the blue limit-color is significantly less then that of yellow. We use an adaptive approach following these different triangles to preserve the desired lightness/chroma and darkness/chroma ratios for the different hues.
Let us introduce the factor *w:*

$$w = (100 - V_L)\,/\,T_S \tag{14}$$

T_L and T_U are:

$$T_L = w\,C_L\,(100 - V_S) \tag{15}$$

$$T_U = w\,C_U\,V_S \tag{16}$$

where $C_L = 3\ldots6$ and $C_U = 0\ \ldots\ 0.5$ defining the values T_L and T_U , belonging to the lower and upper gravity centers respectively.

3.5. Mapping in general cases

The RGB-CYMK mapping and the cross-media mapping is of utmost importance for industrial use. In particular for ink jet printers and other printing technologies. The general approach is similar to the method described in Section 3.2. An important difference is that the original media, in general case, also has a finite gamut with a physical extent that sketches beyond the space of visible colors.
The gamut is approximated typically by piecewise planar surfaces, but only a hue plane intersection of gamut is used by working with straight intervals in the *T-Y* space, which appear as curved intervals in the *T-V* plane. The method described in Section 3.2 use different *d* distances for determining the inner gamut borderlines in order to maximize the part of the gamut preserved. This distance changes adaptively dependent on the original and destination gamut according to Fig.4.
If the destination gamut is bigger than the input gamut in some regions than these better colors will not be used, for example a printer has a more saturated yellow than the sRGB space. By such hue values the most saturated ***S*** color within the common part of the input and output gamut shall be selected for the role of the *limit-color*. Another S_I 'inner *limit-color'* is obtained by shifting ***S*** by e.g. *T(**S**)/8* towards the middle gray. Also an 'inner black' and an 'inner white' point shall be selected using a distance *dV=3...12*, see the red line in Fig 4.
Thus, the destination gamut is subdivided to bright, dark and saturated regions, as described in Section 3.2. Comparing the lightness of S_I to a color sample ***C***, first the upper or lower gravity center is to be selected or the saturated gravity center at the cusp. Now ***R***, ***A*** and ***B*** colors can be defined as well as in Section 3.3. The *[**R**,**B**]* to *[**R**,**A**]* transformation realizes the mapping, by linear or other transition functions [Moro01b].
The method has been tested by data from old commercial printer with a poor gamut and new professional printer with a large gamut according to [Table 2].

Conclusion and future work

Important and previously not published features of the Coloroid have been presented in the paper, after consultation with its creator [Nemc03]. In particular the possibility of changing the reference white point, which could be a postulate of all gamut mapping techniques.
The Coloroid system has been developed using a huge number of observers, using natural view-conditions resulting in a unique and straightforward system of rules and notations. These properties made the Coloroid system especially suitable for application to mapping techniques.

This paper realizes the first implementation of mapping techniques using the Coloroid system. The paper has changed some of the notations and the formulas from the original Coloroid notations making it more illustrative for gamut mapping. A hue preserving robust gamut clipping was introduced and also associated gamut mapping techniques.

The experimental pictures demonstrate the methods for CRT using digital photography in a raw format and for a printer starting from a known test image. Results in both cases are very promising. The exponential mapping method, known in computer graphics, has been generalized to obtain a transition function for CRT mapping. This has been compared with the simplest 'pro channel' clipping currently widely used in commercial rendering software. [Pic 2a] presents the original image, [Pic 2b] does the clipped, and [Pic 2c] does the mapped version of it simulating an old commercial printer, while [Pic 2d] demonstrates a hp5500ps inkjet printer with Photo Imaging Gloss paper, [Pic 1a] and [Pic 1b] the exponential mapping.

Comparisons with CIELab, CIECAM02 based methods have not been treated, as well as further testing with other images. These are important future work. The Coloroid is based on the perceptual attributes: hue (A), lightness (V) and psychometric saturation (T) = 'chroma'. It is an interesting challenge to replace the perceptual attributes of Coloroid model in other mapping techniques based originally e.g. on CIELab or CIECAM02. This could have different advantages in addition to a reduction in computational costs until a more pleasing appearance in different regions of gamut.

The suggested parameters of the presented methods are experimentally optimized for test pictures. However, optimizing free parameters regulating the invariant kernel of the gamut is an open question. Also the optimal shifting length of the black and the white gravity centers.

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[Table 1, 2], [Pic 1a, 1b] and [Pic 2a, 2b, 2c 2d] are at http://www.cg.tuwien.ac.at/~aneumann/CGIV04/