On Device Independent Color Characterization Modeling and Management

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Abstract

The problem of device independent color in color management systems is abstracted as that of involving a set of transformations from device space to a reference space (normalization), reference space to a reference space (gamut compression), and from reference space to a device space (rendering). Issues of color management such as color calibrations, corrections, matching, and soft proofing can then be addressed in terms of this frame work.

Pentahedral type multidimensional interpolations are applied in this paper for both LUT estimation from calibration data and for color space transformations/ conversions. Efficient discrimination schemes are developed for locating a point of interest with in a Pentahedral volume. The structure of a decision scheme depend on its corresponding space partition. Decision schemes that can be implemented with tree structures are very fast. Complexity of storage and computations are discussed for interpolating at a given point. Efficient storage schemes for lookup table contents that permit high speed color space transformations implementations are presented. Switching between different types of volume partitions minimizes the artifacts and maintains the continuity of the estimated variables.

Methods are also developed in the paper for the estimation of LUTs for transformations between different devices and color spaces. Pentahedral type multidimensional interpolations and grid search based optimizations are applied for constructing LUTs from colorometric calibration data. Pentahedral type formulations provide unique estimates for inverse problems involving m -> m variable transformations/conversions. For inverse problems with n -> m variables transformations, constrained optimization schemes are developed for estimating LUTs. Gamut mapping is also addressed in the estimation of LUTs.

The algorithms are applied for a number of electronic imaging applications and the evaluation results are presented.

1. Introduction

Current digital imaging systems[1] comprise many cases of color management and reproduction between different media. Several manipulations/transformations between different devices and color spaces are required to achieve acceptable color reproduction. These involve transformations from a device space to a reference space, reference space to a reference space[1] (gamut compression) and from a reference space to a device space (rendering).

The transformations from an input color space to an output color space can be efficiently implemented using multidimensional interpolations through LUTs.[4,5] The LUTs are built from colorometric calibration data and using both forward and inverse modeling. For real time implementations the transformations need to be very fast and accurate.

Pentahedral type multidimensional interpolations are extremely efficient for real time color transformations. Pentahedral type transformations are applied in this paper for various problems of color reproduction including colorometric characterization, gamut mapping and inverse transformations through LUTs for the reproduced media.

2. A frame work for color management

A frame work for device independent color image management in color image reproduction is shown in figure 1.

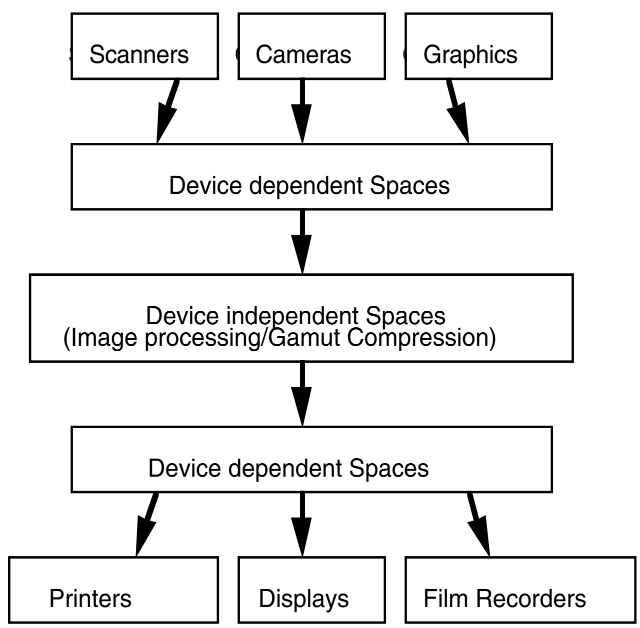

Figure 1. A general framework for color image reproduction

The images from device dependant input spaces (rgb) are converted into device independent spaces (xyz). Image processing and gamut compression are performed in the device independent space to compensate for the gamut differences between various devices and to make desired image corrections/manipulations. The images are transformed again to output device dependant spaces

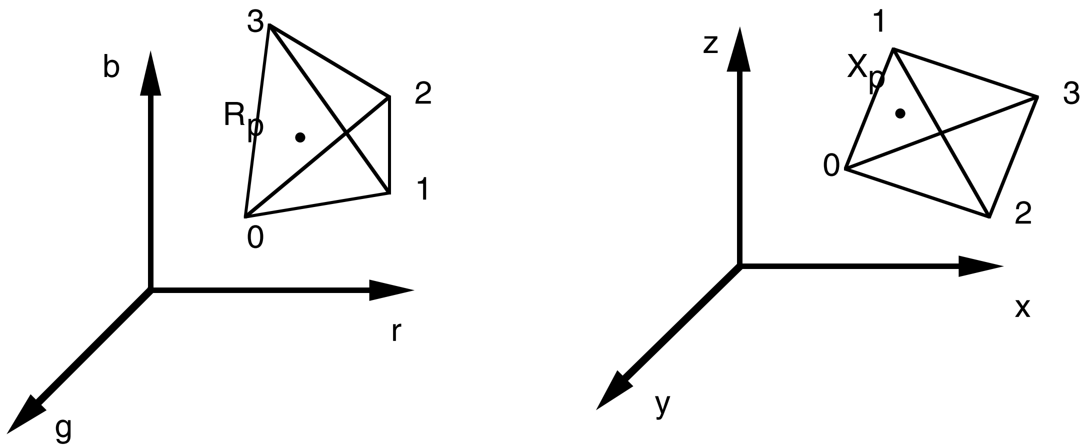

Figure 2. Corresponding Tetrahedra

(cmyk) for reproduction. The transformations between color spaces can be very efficiently performed with Pentahedral type transformations. The necessary LUTs are built using colorometric calibration data. Pentahedral type multidimensional interpolations have many advantages in estimating the optimal inverse LUTs. They can be very efficiently used in conjunction with grid search based optimization, thus, avoiding the necessity of gradient estimation from sparse data. For m -> m problems they can be used for unique inversion and in the case of m -> n situations, they can be used to formulate constrained inversion. They can also be very efficiently used for gamut compression/transformation.

3. Pentahedral type transformations

Pentahedral type multidimensional interpolations are discussed in the following for forward and inverse transformations. Decision schemes are developed for the division of space into Pentahedral type volumes. Efficient storage schemes for fast transformations with parallel access are discussed.

3.1 Multidimensional interpolation, forward and inverse estimation

Consider two corresponding tetrahedra say one in rgb space and the other in xyz space. The rgb space is uniformly gridded and at each of the grid points xyz values are measured. The corresponding Tetrahedra are shown in the Figure 2.

The forward or interpolation problem is knowing the xyz values X_i and rgb values R_i at the vertices i of the Tetrahedron, estimate the xyz value X_p at a desired point R_p. X_p is estimated from

$$Xp = \alpha\,(X_1 - X_0) + \beta\,(X_2 - X_0) + \upsilon\,(X_3 - X_0) + X_0$$

where α, β , and υ αρε coefficients and αρε obtained from

$$\alpha\,(R_1 - R_0) + \beta\,(R_2 - R_0) + \upsilon\,(R_3 - R_0) = (R_p - R_0).$$

When R_p lies with in the Tetrahedron α, β, and υ are > = 1, and $\alpha + \beta + \upsilon <= 1$. The inverse problem is knowing the xyz values X_i and rgb values R_i at the vertices i of the Tetrahedron, estimate the rgb values Rp at a point where the xyz values are X_p. That is

$$Rp = \alpha\,(R_1 - R_0) + \beta\,(R_2 - R_0) + \upsilon\,(R_3 - R_0) + R_0$$

where α, β, and υ αρε coefficients and are obtained from

$$\alpha\,(X_1 - X_0) + \beta\,(X_2 - X_0) + \upsilon\,(X_3 - X_0) = (X_p - X_0).$$

3.2. Coefficient tables and decision schemes for different space partitions

There are many ways to divide a space into Pentahedral type partitions. The interpolation coefficients and the decision schemes for the division of space into Pentahedral type volumes depend on the type of space partition. The quality and the continuity of the interpolated surfaces also depend on the type of space division. Let x_1, x_2, x_3 denote the coordinate axes. For uniform gridding, let the vertices of a cube are referenced with respect to some vertex A assumed to be at (0, 0, 0). The other vertices of the cube are referenced with respect to its reference vertex and are denoted by B(001), C(011), D(010), E(100), F(101), G (111), and H(110). If the cube is partitioned into six partitions, the interpolation coefficients and the decision scheme to locate a point $x_3\,x_2\,x_1$ of the cube in a Tetrahedral partition are as follows.

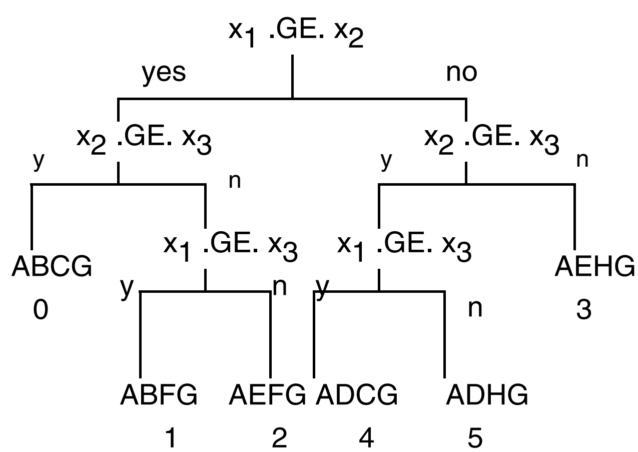

Figure 3. Decision structure for six partitions

Table 1. Interpolation coefficients for six partitions case

		A	B	C	D	E	F	G	H
0	ABCG	$(1-x_1)$	(x_1-x_2)	(x_2-x_3)				x_3	
1	ABFG	$(1-x_1)$	(x_1-x_3)				(x_3-x_2)	x_2	
2	AEFG	$(1-x_3)$				(x_3-x_1)	x_2	(x_2-x_1)	
3	AEHG	$(1-x_3)$				(x_3-x_2)		(x_2-x_1)	x_1
4	ADCG	$(1-x_2)$		(x_1-x_3)	(x_2-x_1)			x_3	
5	ADHG	$(1-x_2)$			(x_2-x_3)			x_1	(x_3-x_1)

Similarly if the cube is divided into five partitions, the interpolation coefficients and decision schemes depend on the type of partition. The decision schemes for two types of division into 5 partitions are given below.

Type A	Type B
$s=x_1+x_2+x_3$	$s=(1-x_1)+(1-x_2)+(1-x_3)$
if(s>=2) EFHC	if(s >= 2) ABDE
else if ($s<=2x_3$) EFHA	else if($s<=2(1-x_3)$) CBDG
else if ($s<=2x_2$)DACH	else if($s<=2(1-x_1)$) HGED
else if($s<=2x_1$)BACF	else if($s<=2(1-x_2)$) FEGB
else HFAC	else BDEG

Figure 4. Decision structures for five partitions

For both Types A and B, the interpolation coefficient tables are similar to the ones given in Table 1.

3.3. Efficient storage scheme for fast access

In n - variable to m - variable coordinate transformations/color corrections, the computational speed can be considerably increased by organizing the data for parallel access. As before let the coordinate axes are denoted as x_i, i = 0,1, 2, 3. The locations of the sample points along x_i are given by $n_i(r)$, r = 0, 1, 2,.., N_i, where N_i is the number of sample points. The number of sample points along coordinate axes are assumed equal, that is $N_i = N$. The sample intervals along x_i are denoted by $s_i(j)$, j = 0, 1, 2,.., J. For any point $\{x_0, x_1, x_2, x_3\}$ in the coordinate space, the coordinates xi can be written as follows:

$$X_i = I_i + f_i$$

$$I_i = \sum_{j=0}^{H_i} s_i(j)$$

and

$$H_i = h_i + b_i$$

where I_i can be considered an integer part and f_i is considered a fractional part of X_i. I_i consists of $H_i + 1$ sample intervals and the integer H_i is split into h_i and b_i, where b_i is binary and takes values 0 or 1. That is b_i is a lower order bit of H_i.

For parallel and high-speed retrieval, the data values at the sample points are stored in the tables T_i, $0 <= i <= 15$, depending on the values of b_i such that the binary representation of i is $(b_3 b_2 b_1 b_0)$. With the above scheme, each vertex of every Pentahedral type partition of the space lie in a different table and none of the tables contain more than one vertex of the same partition.

4. Pentahedral type interpolations for inverse LUT estimation

Pentahedral type multidimensional interpolations can be very efficiently used for the estimation of inverse LUTs from colorometric calibration data. In building the inverse LUTs for color transformations, the computational steps are (a) find a Pentahedral type volume of calibration data that might contain the target or that is closest to the target, (b) if the target lies within a volume, obtain inverse estimates by either direct or constrained inversion, and (c) if the target lies outside the volume of calibration data gamut compress and obtain inverse estimates either by direct inversion or constrained inversion. These computational steps are discussed in the following.

4.1. Grid search based optimization

Grid search based optimization using Pentahedral type interpolations can be very efficiently performed for locating a Pentahedral type volume either containing the target or closest to the target and for obtaining the inverse LUT estimates. The method does not require gradient estimates from sparse data. The concept is explained with reference to Figure 5 and Figure 6.

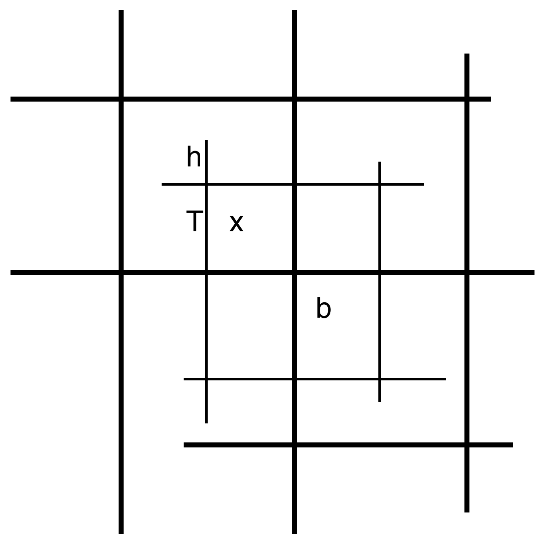

Figure 5. Input space Grid

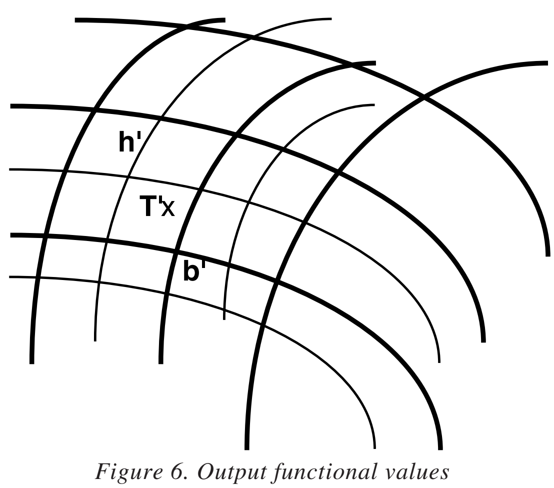

Figure 6. Output functional values

Corresponding to the target T' of the output space, the point T of the input space is searched as follows. Estimate b' closest to T' and select a set of matrix points by space division around b in the input space. Estimate h' closest to T' and repeat the procedure to locate T.

4.2. Constrained inversion

For m -> m transformations, direct inversion is discussed in section 3.1. In inverse LUT estimation for performing m -> n transformations (n > m), constrained inversion is developed in the following. Figure 7 shows corresponding Pentahedral volumes say in cmyk and xyz spaces.

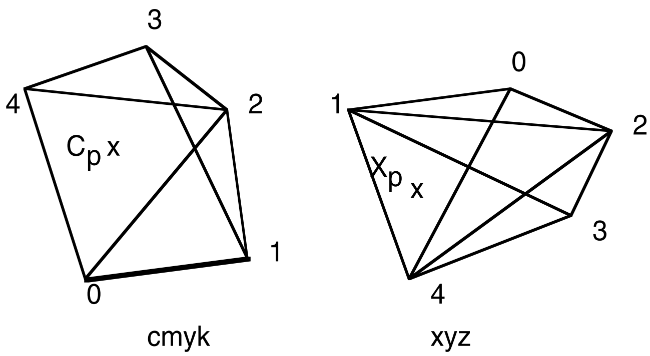

Figure 7. Corresponding Pentahedral volumes

The problem is given X_i and C_i at the vertices of the Pentahedran and X_p, the vector of xyz values at which inverse estimate C_p is required, then estimate C_p by constrained optimization. X_p might have been the result of grid search based optimization and gamut compression. From xyz space we can write

$$X_L W = X_R \tag{4.1}$$

where $X_L = (X_1 - X_0\ X_2 - X_0\ X_3 - X_0\ X_4 - X_0)$ and $X_R = (X_p - X_0)$. From cmyk space we can write

$$C_L W = C_R \tag{4.2}$$

where $C_L = (C_1 - C_0\ C_2 - C_0\ C_3 - C_0\ C_4 - C_0)$ and $C_R = (C_p - C_0)$. From equations (4.1) and (4.2), we can write

$$b\,\alpha = g \tag{4.3}$$

where $b = X_L C_L^{-1}$, $g = b\,(C_0 - C_r) + X_r$, $\alpha = C_p - C_r$ and C_r is some reference vector. The estimate of C_p can be formulated as finding C_p such that $\alpha^T\alpha$ is minimized subject to (4.3). The estimate for C_p can be shown to be

$$C_p = \alpha + C_r \tag{4.4}$$

where $\alpha_i = (1/2) \sum_{k=0}^{2} \lambda_k \beta_{ki}$ and λ_k are solved from

$$\sum_{k=0}^{2} \lambda_k d_{lk} = 2\, g_l$$

and $d_{lk} = \sum_{i=0}^{3} b_{li} b_{ki}.$

4.3. Gamut mapping

If the target lies outside the colorometric data volume, it is necessary to perform gamut mapping. Since Pentahedral type space partitions contain planar surfaces, gamut projections can be performed by repeatedly using the computations necessary for projecting a point on a plane. The intersection X_p of a line projected from X_4 toward X_0 with the plane containing non colinear points X_1 , X_2, X_3 can be estimated from

$$X_p = \eta\,(X_0 - X_4) + X_4$$

where $\eta = (1 - (a\ b\ c)\ X_4) / \delta$

$\delta = (a\ b\ c)(X_0 - X_4)$ and the quantities (a b c) are estimated from

$(a\ b\ c) = (1\ 1\ 1)(X_1\ X_2\ X_3)^{-1}$.

5. Conclusions

Accurate reproduction of color images require transformations and conversions between different color spaces of both device dependant and device independent. Differences between the color gamuts of different devices should be taken into account and it involves gamut mapping. Pentahedral type interpolations with LUTs provide very efficient means for performing color transformations. LUTs can be derived from colorometric calibration data. Grid search based optimization coupled with Pentahedral type interpolation can be very efficiently used for estimating LUTs. It avoids the necessity of estimating gradients from sparse data. The estimation of LUTs for performing m -> n transformations (n > m) is formulated as a constrained optimization problem. Pentahedral type space partitions also provide efficient means for gamut compression. The techniques have been applied for digital color proofing with excellent reproduction quality.

References

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