TWO DIMENSIONAL COLOR CALIBRATION FOR FOUR PRIMARY DISPLAYS

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ABSTRACT

The process to ensure a fixed and desired response from a color display generally consists of a per-channel calibration transform combined with a multi-dimensional characterization transformation. In this paper We focus on the former, i.e., the channel calibration. Conventional one-dimensional channel calibration strategies are inadequate for high resolution LCD displays because of inter-channel crosstalk. We address this problem by developing a color calibration strategy for a four primary LCD display, based on a two dimensional structure for channel calibration, which allows for simultaneously meeting the dual objectives of perceptual linearization of individual channels and gray balance along the device gray axes, despite inter-channel crosstalk. The two-dimensional nature of the transform represents a good balance between the dual objectives of low complexity and accurate control of key attributes of the displayed colors via channel calibration and experimental results demonstrate that the proposed scheme accomplishes its objectives offering a significant improvement over the per channel calibration for our four primary display system.

Index Terms— Color calibration, multi-primary display, LCD display

1. INTRODUCTION

The diversity of technologies for display systems, and the spread and interconnection of different digital imaging devices make necessary the use color management systems that allow the exchange of images in encodings that are device independent. Color management for display and print devices is commonly partitioned into channel color calibration and multi-dimensional characterization that maps device independent color encodings of images and videos to the calibrated device control space provided by the calibration [1,2]. Display color calibration is the focus of this paper. For color displays, the (channel) calibration aims to remap the device control space into a calibrated device control space which, apart from gamut limitations, ideally transforms linearly to a tristimulus color space, say the CIEXYZ color space [3]. If the calibration transformation accomplishes this objective with good accuracy, the subsequent multi-dimensional color characterization can be accomplished via simple linear (affine) transformations from device independent tristimulus space, specifically, a 3×3 matrix for three primary systems.

Traditional approaches for calibration[1] are one-dimensional based on the assumption of channel independence and color constancy that characterized the behavior of Cathode Ray Tubes (CRT). However, for Liquid-Crystal Displays (LCD), the channel independence assumption is challenged by the continuous reduction of the pixel size for the development of higher resolution displays. This reduction comes with the increase in the level of the interference, or crosstalk, between the electronic units, an effect that becomes strongest for spatial adjacent sub-pixels [4], affecting the channel independence and thus, the performance of traditional calibration functions [5,6].

Other challenges arise due to the introduction of multi-primary displays. The use of four or more primaries in display systems has emerged as a novel approach to widen the gamut of color devices [7–9]. Moreover, power saving [10–12], view angle improvement [7], and more recently, high resolution image representation [8], are some of the other advantages obtained by the use of multi-primary technology, which makes it an active area of research with promising results.

We develop a two dimensional scheme for calibration of a four primary display. Conceptually, the method is similar to the technique presented in [13] although the differences in the application setting and the objectives also force significant differences in our development here. Specifically, whereas the work in [13] addressed calibration for color printers and was based on a three dimensional calibrated device control space, here we address color displays and specifically four primary displays. The specifics of our calibration methodology are motivated by LCD displays and the need to address the crosstalk between the primaries, which cannot be handled by traditional one-dimensional calibration approaches. Experimental evaluation of the proposed approach on a four primary display demonstrates that it successfully accomplishes its goal of simultaneously achieving perceptual linearization of the individual channels and gray balance along the device gray axes, offering a significant improvement over the traditional one-dimensional method.

The manuscript is organized as follows. Section 2 introduces the calibration problem formulation and motivation for the two dimensional scheme proposed in Section 3. Experimental validation of the strategy for a four primary display is presented in Section 4. Section 5 concludes the paper.

2. PROBLEM FORMULATION

For our discussion, consider a display with N primaries, and a device control vector $\boldsymbol{\alpha} = [\alpha_1, ..., \alpha_N]$, an $N \times 1$ vector whose entries lie in $[0, 1]$ and represent the control signals to drive each of the primaries. Figure 1 shows the diagram for a general display system, where the display response, $\mathbf{d}(\boldsymbol{\alpha})$, to the control vector $\boldsymbol{\alpha}$, is modeled in the CIEXYZ color space as,

$$\mathbf{d}(\boldsymbol{\alpha}) = \mathbf{P} f(\boldsymbol{\alpha}), \tag{1}$$

where $\mathbf{P}$ is a $3 \times N$ matrix whose columns contain the color coordinates of the display primaries in the CIEXYZ color space. The

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[1]Throughout this paper, we use the term calibration to refer to channel color calibration, even though the term is often used elsewhere to refer to both channel calibration and the characterization.

function f transforms the control values according to the physical characteristics of the display. The physical model for most display technologies includes nonlinearities that affect the output for each color channel, as well as cross channel coupling, e.g.,crosstalk.

To introduce the idea of calibration, we begin with the very general situation shown in Fig 2, where an input control vector $\boldsymbol{\alpha}'$ is transformed by the calibration transformation, $\mathcal{C}$, to the display control vector, $\boldsymbol{\alpha} = \mathcal{C}(\boldsymbol{\alpha}')$ that actually drives the display. Thus, the response for the calibrated system can be expressed as,

$$\mathbf{d}(\boldsymbol{\alpha}') = \mathbf{P}f(\mathcal{C}(\boldsymbol{\alpha}')). \tag{2}$$

Success in the calibration process relies on the definition of $\mathcal{C}$. If the transformation $\mathcal{C}$ forms a (right) inverse of the function $f(\cdot)$, then the calibration accomplishes the objective of rendering the device linear in the calibrated space, in the sense that the primary matrix $\mathbf{P}$ defines a linear mapping from the calibrated device space to the CIEXYZ space[2]. Better use of the device quantization levels can be obtained through a slight generalization which changes the objective of calibration to make $f(\mathcal{C}(\cdot))$ a diagonal transform where the quantization levels are distributed according to a $1/2.4$ power law nonlinearity that approximates the perceptual nonlinearity in the visual system mapping luminance to lightness [16]. Note that in this situation, in the calibrated device coordinates, the device is also "gray balanced" along the device gray axis corresponding to equal amplitude of the primaries in the calibrated space, i.e,

$$\alpha_i' = \alpha_j', \;\; 1 \leq i, j \leq N. \tag{3}$$

A general $N \times N$ calibration transformation can accomplish the afore-mentioned desired objectives. However, computational complexity trade-offs mandate simpler implementations in which the transformation $\mathcal{C}$ is constrained. Under these settings, the afore-mentioned objective can only be accomplished approximately and common goals for calibration are perceptual linearity and gray balance, with the former being desirable along both individual primary axes and along the device gray axes in calibrated control space. We also use these more protracted objectives for evaluating the calibration transforms that we develop in this paper.

In the case of CRTs, where channel independence and color constancy holds, the function f is (almost) channel-wise separable, i.e.,

$$f(\boldsymbol{\alpha}) = [f_1(\alpha_1), ..., f_N(\alpha_N)]^T, \tag{4}$$

and represents the nonlinear relationship between voltage grid and beam current in the CRT, usually approximated by a power function, $f_i(\alpha_i) = \alpha_i^\gamma$, for some parameter $\gamma > 0$ [17, 18]. The calibration function is therefore, defined channel-wise as, $\mathcal{C}_i(\alpha_i') = \alpha_i'^{1/\gamma}$, so the composition $f(\mathcal{C}(\cdot))$ is actually the identity transform. The dual objective of channel linearization and gray balance is accomplished in practice, by the use of 1-D look-up-tables (LUTs), commonly referred to as tone response curves (TRCs).

The simplicity for the calibration of CRTs can not be extended for high resolution LCDs, where channel coupling needs to be considered, preventing a separable model. Instead of defining a general N dimensional calibration to consider all possible channel interactions, we propose an intermediate approach, using two dimensional functions[3], a strategy that is described in Sec. 3 for a four primary display.

[2] And in the three primary setting, the inverse of $\mathbf{P}$ defines the mapping from CIEXYZ space to the calibrated device control space. Segmented affine calibrations can also be obtained for the more general multiprimary settings [14, 15].

[3] In the color printing scenario the 2D calibration is motivated by similar reasons in [13].

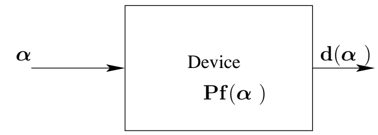

Fig. 1. General diagram for a display system

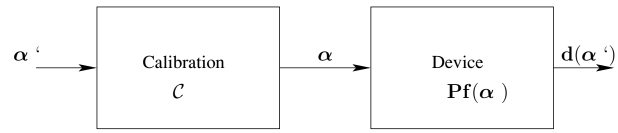

Fig. 2. Diagram for a calibrated display system

3. TWO DIMENSIONAL COLOR CALIBRATION

We propose a scheme for channel calibration that is composed by two stages, as observed in Fig.3 for the particular case of a 4-primary display. The first stage is described by a function denoted as $\boldsymbol{\nu}$, and transforms the display control parameters from a N dimensional *device control space*, to a two dimensional *calibration control space* for each of the N device channels. On the latter space, a two dimensional calibration function $\boldsymbol{\Phi}$ is defined, so the overall channel calibration is expressed as,

$$\mathcal{C}_i(\boldsymbol{\alpha}) = \boldsymbol{\Phi}_i\left(\boldsymbol{\nu}_i(\boldsymbol{\alpha})\right), \;\; i = 1, ..., N. \tag{5}$$

This two step approach allow us to reduce the implementation complexity for the calibration, while also approximating different channel couplings.

For the rest of the paper, we consider a display system with 4 primaries, R, G, B, Y, although the calibration strategy proposed here is not limited to any particular choice of primaries. We use this system as reference, and present for it definitions for the functions $\boldsymbol{\nu}$ and $\boldsymbol{\Phi}$.

There is considerable freedom in the choice of the calibration space, and the function $\boldsymbol{\nu}$ that defines it. We use a specific choice that enables us to achieve our dual objective, perceptual linearity and gray balance for a four primary configuration. Specifically, we chose the parameter transformations for each of the channels to be,

$$\begin{aligned} \boldsymbol{\nu}_R(r, g, b, y) &= [r, \; g + b + y]^T, \\ \boldsymbol{\nu}_G(r, g, b, y) &= [g, \; r + b + y]^T, \\ \boldsymbol{\nu}_B(r, g, b, y) &= [b, \; g + r + y]^T, \\ \boldsymbol{\nu}_Y(r, g, b, y) &= [y, \; g + b + r]^T \end{aligned} \tag{6}$$

Let us consider the particular case of the R channel calibration to describe the benefits of the functions defined in (6). Consider also the conceptual representation of the device calibrated device space defined by $\boldsymbol{\nu}_R$, shown in Fig. 4. Note that the any point on the primary axis, in the control parameter space $[r, g = 0, b = 0, y = 0]$, is mapped to the point $[r, 0]$ in the calibration space, located on the vertical axis of the two dimensional representation. Note also, that the device neutral axis, $r = g = b = y$, is mapped to the axis $[r, 3r]$, represented by the main diagonal in Fig. 4. Under these conditions, it is possible to obtain independent control over both axes, and thus, to define a calibration function $\boldsymbol{\Phi}_R$ to obtain simultaneously, perceptually linear response on the red primary and gray balance display response.

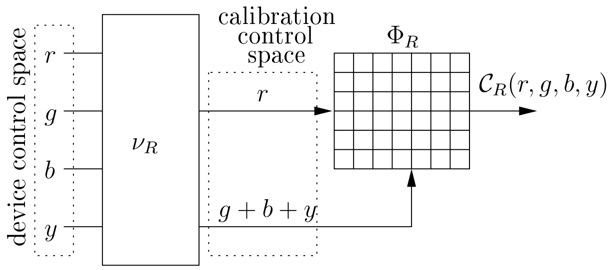

Fig. 3. Architecture for the 2-D calibration (red channel shown).

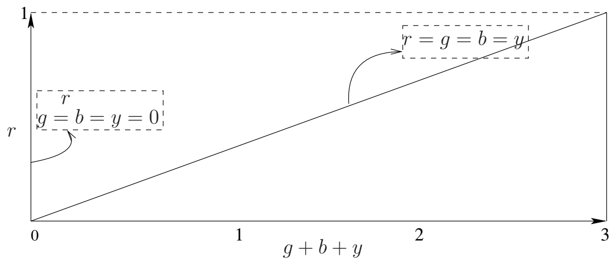

Fig. 4. Conceptual representation of the 2-D calibration control space defined by ν_R. The mappings of the primary and gray axes are shown.

The two dimensional structure gives us the possibility to get an accurate and desired response over more regions. We propose the selection of seven axis, as shown in the representation of Fig. 5, which include some secondaries and tertiaries consisting of equal combinations of two and three primaries, respectively, with other primaries set at zero. The selected axes and their mappings, are distributed over the control and calibration spaces, respectively, assuring the smoothness of the calibration function, a feature that benefits the performance of the calibrated system under device drift.

In this way, $\mathbf{\Phi}_R$ is defined on each axis as the one dimensional calibration function that satisfies a desired performance, while interpolation is used to define the function on the remaining domain.

The analysis presented in this section applies in a similar way to the remaining channels. However, in contrast to the one dimensional calibration, the channel calibration functions are not independent. For example, having an accurate calibration on the secondary axis $g + b$ requires that both, Φ_R and Φ_G, include that axis for their definition. For this reason, only a reduced set of axis is selected, so a complete control over them is guaranteed. A description of the selected axes, is found in Table 1.

3.1. Implementation

For each of the color channels, the set of one dimensional TRCs that calibrate the selected axes are placed in a two dimensional array, following the structure shown in Fig. 5. A two dimensional cubic interpolation is used to fill the remaining spaces of the 2D LUTs. Details for the computation of the axis calibration follows.

3.1.1. Linearization to ΔE

The objective is to provide a display response for a given axis in the control space, such that variations along the axis are proportionally perceived by an observer. A perceptual response can be expressed

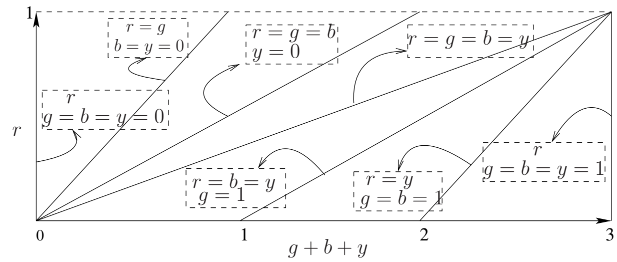

Fig. 5. Conceptual representation of the 2-D calibration control space defined by ν_R. The mappings of the seven selected axes for color calibration are shown

	Φ_R	Φ_G	Φ_B	Φ_Y
1	r $g=b=y=0$	g $b=y=r=0$	b $y=r=g=0$	y $r=g=b=0$
2	$r=y$ $g=b=0$	$g=b$ $y=r=0$	$g=b$ $y=r=0$	$r=y$ $g=b=0$
3	$r=g=b$ $y=0$	$r=g=b$ $y=0$	$r=g=b$ $y=0$	$y=r=g$ $b=0$
4	$r=b=y$ $g=1$	$r=g=b$ $y=1$	$r=b=y$ $g=1$	$r=b=y$ $g=1$
5	$r=y$ $b=g=1$	$g=b$ $r=y=1$	$b=g$ $y=r=1$	$r=y$ $b=g=1$
6	r $g=b=y=1$	g $b=y=r=1$	b $y=r=g=1$	y $r=g=b=1$
7	$r=g=b=y$	$r=g=b=y$	$r=g=b=y$	$r=g=b=y$

Table 1. Description of the selected axes considered for definition of Φ_R,Φ_G,Φ_B,Φ_Y.

using uniform spaces like CIELAB [3, 19], which euclidean metric, ΔE^*_{ab}, is usually used to quantify perceptual differences [3, 20].

A linearization methodology can be generalized for perceptual response on any axis in the control space with extreme points coordinates $\boldsymbol{\alpha}_o$ and $\boldsymbol{\alpha}_f$. If we denote by $\mathcal{F}$ the transformation from CIEXYZ to the perceptual space CIELAB [3], then, the perceptual difference of the display response to any level $\boldsymbol{\alpha}'$ and the reference $\boldsymbol{\alpha}_o$ is denoted by $\mathcal{E}_{\boldsymbol{\alpha}_o}(\boldsymbol{\alpha}) = \Delta E^*_{ab}\left(\mathcal{F}(d(\boldsymbol{\alpha}')), \mathcal{F}(d(\boldsymbol{\alpha}_o))\right)$. The ideal perceptually linear response for any point $\boldsymbol{\alpha}'$ on the axis can be computed as,

$$\mathcal{E}_{\boldsymbol{\alpha}_o}(\boldsymbol{\alpha}') = \frac{\|\boldsymbol{\alpha}' - \boldsymbol{\alpha}_o\|}{\|\boldsymbol{\alpha}_f - \boldsymbol{\alpha}_o\|}\mathcal{E}_{max}, \tag{7}$$

where the maximum perceptual difference on the axis is given by $\mathcal{E}_{max} = \mathcal{E}_{\boldsymbol{\alpha}_o}(\boldsymbol{\alpha}_f)$.

3.1.2. Gray-Balanced Calibration

In the perceptual space CIELAB, the response to the neutral axis for gray-balanced device is located on the L^* axis, where $a^* = b^* = 0$. Perceptual linear response and white balance, can be expressed jointly by constraining the device gray axis to respond uniformly on L^* axis in the $CIELAB$ color space ($a^* = b^* = 0$). For the 4-primary system, more than one solution is possible. To facilitate the computation of a solution, the problem is reformulated in terms of a three primary system with primaries r_t, g_t, b_t, such that,

$$\begin{aligned} y &= min(r_t, g_t), \\ r &= 2r_t - y \\ g &= 2g_t - y \\ b &= b_t. \end{aligned} \tag{8}$$

The transformation in (8) guarantees that points $r_t = g_t = b_t$ in the reduced space are mapped to line $r = g = b = y$ in the four dimensional space.

4. RESULTS

We use the method presented in Sec. 3 to compute the two dimensional channel calibration functions for an LCD display with red, green, blue, and yellow primaries. In particular, Fig. 6, shows the channel calibration curves for the gray axis. Note that the curves from the G and Y channels are the same, as consequence of the the transformation (8), and the fact that the TRC for the G channel is always lower than for the R channel. We evaluate the proposed calibration strategy on the red and gray axis, and compare it with the traditional 1-D approach. Taking as reference the ideal linear display response, Fig. 7 shows the perceptual difference on the R axis in ΔE_{Lab} units, with respect the uncalibrated response (dashed line), the calibrated response using the proposed approach (solid line), and the calibrated response using a 1-D strategy computed for device-axis gray balance (dot-dashed line). Observe that perceptual linearization on the R axis is achieved with the proposed 2-D method. Similarly, when considering the response over the gray axis, and a 1-D calibration designed to obtain linear response on the red channel, Fig. 8, shows the measured Chroma, C_{ab}, for the uncalibrated response, the proposed 2-D calibration, and for the 1-D per channel linear calibration. The proposed 2-D calibration maintains gray-balance, whereas the 1-D calibration exhibits significant chroma magntiudes.

The results demonstrate that the proposed 2-D calibration strategy provides a significant improvement over the 1-D calibration alternative. The scheme does require a modest increase in memory and a small increase in computation. The memory requirement is, however, significantly below the requirement for a full-fledged 4-D LUT and the scheme therefore represents a reasonable trade-off for practical implementations. Table 2 compares the computation and memory requirements for the different alternatives.

5. CONCLUSION

We presented a framework for four-primary display calibration based on a two dimensional scheme for channel calibration. We use this framework to develop and evaluate a particular methodology for calibration of a four primary display. In contrast to the calibration based on single TRCs, the two dimensional structure acknowledges the inter-channel dependency, common in high resolution LCD displays, and enables us to get simultaneous control over different regions of the device control space. For the calibrated system designed in this paper, we obtain perceptual linear channel response as well as gray balance. The two dimensional structure provides a good trade-off between accuracy of color control and implementation complexity, making the proposed approach an attractive alternative for use in multiprimary displays.

	Memory		Computation	
	8bit	10bit	Adds	LUT access
1D Calibration	1KB	4KB	0	4
2D Calibration	256KB	4MB	24	4
4D Calibration	16GB	4TB	0	4

Table 2. Comparison of the memory and computational requirements for the overall calibration, using the traditional 1D approach, the proposed 2D scheme, and the full 4D calibration

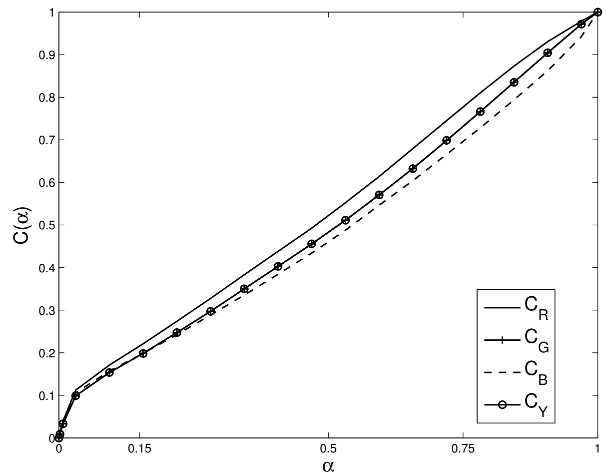

Fig. 6. Tone Response Correction (TRC) for Gray Level Axis

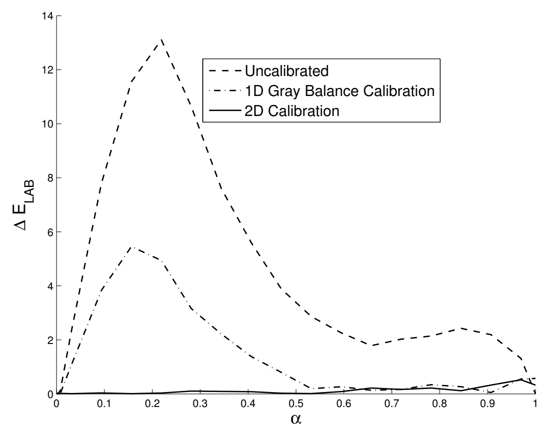

Fig. 7. Perceptual difference ΔE_{ab} on the red axis, between the ideal perceptual linear display response and the display response of the display without calibration, one dimensional gray balance calibration, and two dimensional calibration.

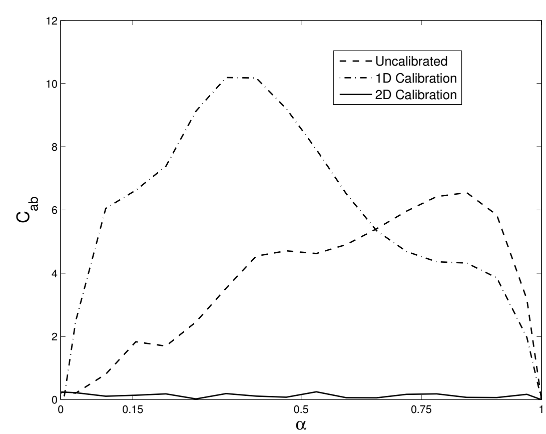

Fig. 8. Chroma in CIELAB space, C_{ab} of the display response over the gray axis, without calibration, when a one dimensional calibration for linear channel response is applied, and the two dimensional calibration.

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