A camera-based method for calibrating projection color displays

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Abstract

Almost all presentations today are given electronically using projection display technology. In such presentations, color images often do not reproduce correctly due to lack of projector calibration. In cases where the color imagery is intended to convey an important message, this problem can severely diminish the value of a presentation. Examples include technical, educational, and marketing presentations attempting to demonstrate color and image quality effects. Depending on the severity of the miscalibration, important information such as text and graphical elements can change color name or become difficult to discern. We propose a simple technique for calibrating projection displays using a digital camera as a color measurement device. The camera is first calibrated via visual luminance matching of projected colors. A target of known RGB values then is projected on the screen, and captured with the digital camera. The camera signals are processed through the camera calibration to produce luminance signals, and the latter are used to calibrate the tone response of the projector. The approach produces a tone response correction that is satisfactory for many applications, and most importantly, eliminates the need for costly and tedious measurement of colors projected on a screen.

Introduction

Display devices conform to an additive color mixing model. According to this model, the relationship between RGB signals driving the device and XYZ tristimulus values produced by the display is as shown in Fig. 1. The first step is tone response calibration, which linearizes each of the R, G, and B channels to luminance. In the second step, the linearized signals, R', G', B' are related to XYZ tristimulus values via a 3-D characterization transform. Under the assumptions of additivity and chromaticity constancy, this transform can be represented by a 3x3 matrix, determined by the chromaticity coordinates of the R, G, and B phosphors and the tristimulus values of the display white point. For greatest accuracy, both the tone calibration and the 3x3 matrix must be derived for each display. However for many practical applications, sufficient accuracy can be achieved by deriving only the tone calibration, and using a fixed generic 3x3 characterization matrix such as the sRGB standard [1]. This paper focuses only on tone response calibration.

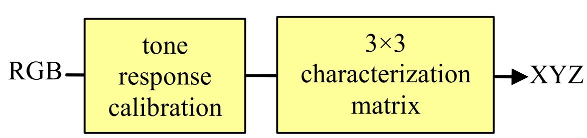

Figure 1: Color calibration and characterization of display devices.

Cathode Ray Tube (CRT) Displays

The tone response of a typical CRT is accurately modeled by a gamma-offset-gain (GOG) model [2]. A common simplification is to assume offset=0, gain=1. This reduces the model to:

$$R' = R^{\gamma},\ G' = G^{\gamma},\ B' = B^{\gamma}, \qquad (1)$$

where R,G,B and R',G',B' are normalized to the range 0-1. Due to the predominance of CRT displays in past years, it has been common practice to prepare electronic RGB images for rendition to such devices. In recognition of this fact, the sRGB color space was developed to represent an average CRT display, and serves today as the main de-facto standard for electronic RGB imagery. Indeed many scanner and digital camera manufactures apply post-processing to the captured images to transform them approximately to sRGB. The sRGB tone response can be approximated closely by $\gamma = 2.2$.

Projection Displays

Digital projection displays are the prevalent method for giving electronic presentations. Several technologies are available, of which liquid crystal displays (LCD) are perhaps the most common. Although LCDs conform to the same basic additive model shown in Fig. 1, their tone response characteristics can be markedly different from that of CRTs. Fig.2 compares the tone response of a portable Sharp LCD projector with that of a CRT with $\gamma = 2.2$. The projector tone response was derived from radiometric measurements of 11 neutral (R=G=B) patches projected on the screen under dark-room conditions. The difference between the tone response of the projection LCD and CRT is quite apparent. The consequence is that if an sRGB image prepared for display on a CRT is rendered directly to a projection LCD (as is commonly done today), the reproduction is grossly incorrect, and produces a level of image quality that may be unacceptable, especially in applications where the color reproduction is critical to the value of the presentation. Examples of such applications include technical and educational forums (such as this conference!) and marketing presentations attempting to demonstrate color and image quality effects.

A method is therefore needed to accurately calibrate the projector's tone response, which involves the following basic steps:

- Establish the built-in projector settings (typically default) and viewing environment (typically dim or dark-room).
- Generate a color target of known device values. The target should comprise ramps in gray (R=G=B) and/or the primary R, G, B axes.
- Project the target onto the screen and take device-independent color measurements of the patches.
- Relate the device values to the device-independent values via a tone response calibration function.

Several techniques exist to accomplish the above steps; these are discussed in the next section.

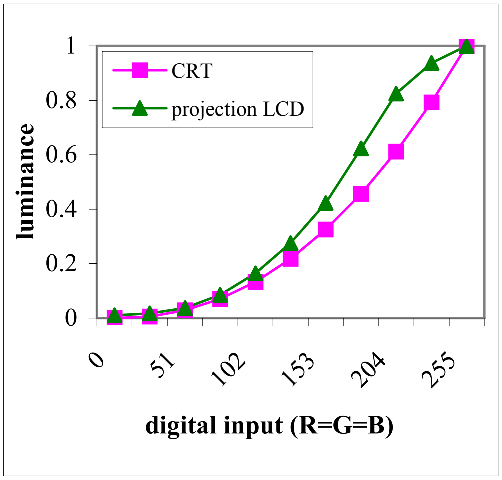

Figure 2: Luminance response of CRT (γ = 2.2) and projection display along the neutral R=G=B axis.

Display Calibration Techniques

The standard approach for determining the projector's tone response is to make device-independent measurements of R, G, B ramps with a spectroradiometer, and derive a tone response function that relates digital input value to luminance by fitting or interpolating the measured data [3, 4]. Hardeberg et al. [3] augment the spectroradiometer with a calibrated digital camera to correct for spatial nonuniformity in the projected image. This approach is expected to produce a highly accurate correction. However, making spectroradiometric measurements is a very expensive, time-consuming and tedious process. Indeed this is the reason why projection display calibration is usually avoided, and we live with "What you get is what you get" or WYGIWYG color on the screen!

An alternative to measurement-based approaches is visual calibration [5-7]. A classic example of visual calibration for CRTs is shown in Fig. 3. The left field contains a pattern of alternating lines of black and the full-strength primary. The average luminance of the left field is 50% between that of black and full primary, and is thus a known constant. The user is asked to adjust the digital input to the right field until the two fields match visually in luminance. This task establishes one [x-y] pair on the display tone response curve. If one assumes the simplified CRT model in Eq. (1), this information is sufficient to determine the □ parameter, which in turn defines the entire tone response. The process can be repeated for each of the R, G, B primaries to estimate separate □ values for each channel.

The visual task in Fig. 3 has been demonstrated successfully for CRT calibration [5]. However, as noted earlier, projection displays often exhibit an "S-shaped" tone response rather than a power-law. Therefore an attempt to fit a power-law model to a projector response using the technique in Fig. 3 will produce an incorrect tone calibration.

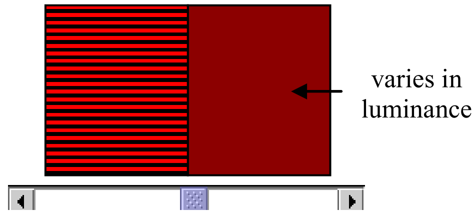

Figure 3: Standard visual display calibration task for determining gamma for the red (R) channel. The slider is adjusted until the luminance of the right field matches the average luminance of the halftone pattern on the left. The process is repeated for G,B.

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The aforementioned visual technique can be extended to estimate multiple points on the tone response curve. However, this involves repetitions of the visual tasks in Fig. 3, which can become tedious and error-prone.

New Projector Calibration Technique

A method is proposed for projection display calibration that addresses the problems present in previously published techniques. The same four basic steps in Sec. 1.2 are followed. The main novelty is that a digital camera is used instead of a spectroradiometer to obtain target measurements in Step 3. Our approach is distinct from the technique in Ref. [3] in that the digital camera is the *only* measurement device used for calibrating the projector. Furthermore, the proposed method does not require a sophisticated camera - a consumer device will suffice. Advantages with this approach are:

- i. consumer digital cameras abound today as an inexpensive commodity item;
- ii. digital cameras are easy to use in comparison to spectral measurement devices;
- iii. digital cameras can capture a fairly large spatial footprint, thus allowing for measurement of a large number of patches, and/or greater spatial averaging.

Issues to address with this approach are:

- i. since device-independent measurements are needed, the camera itself needs to be calibrated for the projected medium it is capturing;
- ii. the camera may drift over time, thus invalidating the data it captures.

In the next section, a novel technique is described for camera calibration that addresses both these issues.

Camera Calibration

Digital camera calibration and characterization has engendered a large body of research literature [1]. As mentioned earlier, manufacturers of consumer cameras often incorporate a built-in correction to produce images in a standard space (often sRGB). To test this assumption, Fig. 4 compares the sRGB tone response (magenta curve) with the tone response of the green channel from a Kodak LS443 digital camera (black curve). The latter was obtained by displaying a gray ramp with the Sharp projector, and capturing both a digital camera image, and luminance measurements with a PhotoResearch SpectraScan PR705 spectroradiometer. Clearly, the camera tone response deviates noticeably from the sRGB assumption. Furthermore, the response is likely to vary with the particular camera model, camera settings, image capture conditions, and over time. While these factors may not be an issue for casual consumer needs, they may pose a problem in the application at hand, where the camera is used as a measurement device. It is therefore preferable to perform some form of "on-site" camera calibration with a projected target.

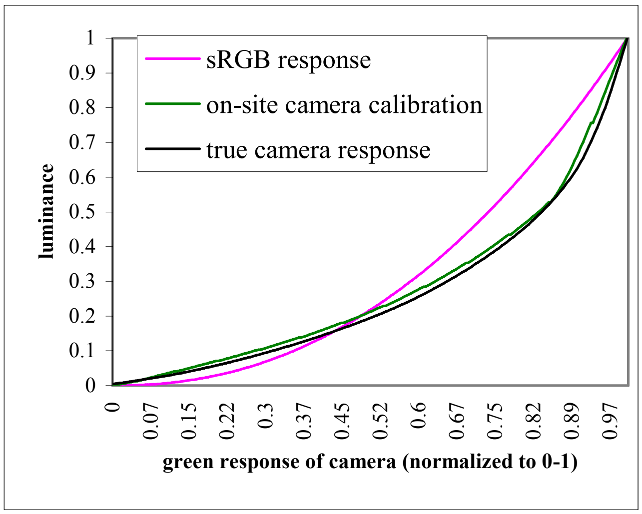

Figure 4: luminance tone response of the green channel of the Kodak LS443 camera.

The standard approach for camera calibration is to capture a target of known colorimetric or spectral measurements, and relate the captured device signals to these measurements. However recall that the goal of our approach is to eliminate colorimetric and spectral measurements in the first place. A key observation we have made from examining a number of digital cameras is that the shape of a typical camera tone response, while not necessarily conforming to the sRGB gamma function, can be represented by a simple parametric form requiring very few calibration points. This is exemplified by the black curve in Fig. 4. Now recall that in Sec. 1.3, we described a visual calibration technique that determines the 50% luminance point for the projector. While this single point may not be sufficient to accurately calibrate the projector's response, we hypothesize that it is sufficient for calibrating the camera tone response. To this end, we use the visual calibration technique to calibrate the camera tone response, and then use the calibrated camera to determine the entire tone response of the projector.

To illustrate the idea, consider the target in Fig. 5 comprising a ramp of 15 neutral (R=G=B) patches from white to black. The middle row and the last column of patches are the calibrated 50% point derived from the visual matching task of Fig. 3. (The patch is duplicated in the x- and y- directions in order to correct for spatial non-uniformity in the projected image; this issue is discussed in Sec. 2.3.) This target is displayed with the projector, captured with the digital camera, and the camera RGB values are retrieved. Three points from the target are used to calibrate the camera: namely white, black, and 50% gray. In addition, perfect black (i.e. zero luminance) is used to pin the one endpoint of the camera response.

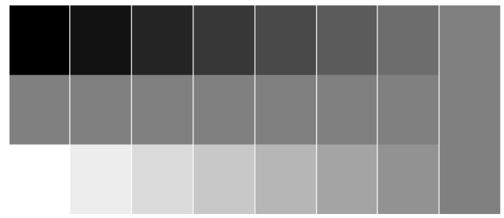

Figure 5: target used for calibrating the camera and projector.

Table 1 summarizes the data used to calibrate the camera response. Luminance is normalized to that of projector white, so that by definition, Yw=1. The only unknown parameter is the luminance of the projector black point, Yb. This flare factor is affected by the characteristics of the projector, screen, and ambient illumination. We assume 2% flare (i.e. Yb = 0.02) based on a priori radiometric measurements from different projectors in a dim surround. (This parameter can be tuned based on additional knowledge of the projector and viewing environment.) The four points in Table 1 can be interpolated to derive a camera response curve that relates each of R, G, B camera signals to luminance. Many interpolation techniques can be used; in our implementation, the choice was cubic spline interpolation.

Table 1 Data used to calibrate the tone response of the digital camera

Patch	Luminance	Captured camera signal
Projector white	Y_w=1	R_1, G_1, B_1
Projector black	Y_b	R_2, G_2, B_2
Mid-gray	$(Y_w+Y_b)/2 = (1+Y_b)/2$	R_3, G_3, B_3
Perfect black	0	0, 0, 0

The green plot in Fig. 4 shows the camera tone response derived from this approach. Comparing this to the true camera response (black curve), we note that the technique is very accurate.

Camera-based projector calibration

Once the camera is calibrated, it is effectively turned into a luminance measurement device. Thus the luminance of all 15 patches in the projected gray ramp in Fig. 5 can be derived. These luminance values and the corresponding digital values driving the projector are then used to generate a tone response calibration for the projector using straightforward interpolation techniques. In our implementation a cubic spline was used to interpolate among the 15 points from the target.

The benefit of this approach is that, since the same target is used to calibrate both the camera and the projector, the dependence of the camera response on capture conditions (i.e. projection media, image content, camera settings, etc.) are effectively calibrated out. The correction technique is thus robust to projection and capture conditions.

Spatial non-uniformity correction

Many projectors exhibit significant spatial non-uniformity, especially in luminance. Correction for this effect is therefore an important aspect of projector calibration. The correction should ideally be a spatial function. However, this approach cannot be implemented with standard color management architectures such as ICC. A simpler alternative is to pre-correct the calibration data to approximate the effect of displaying each patch at a single reference location. This allows calibration to be derived from well-behaved data, although it is strictly valid only at the reference location.

A simple technique is to repeat a given patch at multiple spatial locations on the target, and average the data from the multiple locations. A more effective technique is to explicitly profile the non-uniformity with a set of constant-color patches in the x and y direction, as shown in Fig. 5. An example of a correction that is separable in the x- and y- directions is given by:

$$M'(x,y) = M(x,y)*C1(x)*C2(y) \,, \qquad (2)$$

where M is the original measurement, M' is the corrected measurement, and C1 and C2 are spatial corrections in the x and y directions, derived from measurements of a constant-color row and column respectively. For example, C1(x) is derived from the middle row of gray patches in Fig. 5:

$$C1(x) = G(xo)/G(x) \,, \qquad (3)$$

where G(x) is the constant-gray measurement at location x, and xo is a reference location. An analogous formulation applies in the *y* direction. This technique has been tested successfully for projection calibration.

In summary the following steps are carried out for projector calibration:

- A calibration tool projects a visual pattern (e.g. Fig. 3) on the screen.
- The user performs a visual luminance matching task to establish the 50% luminance point.
- The calibration tool displays on the screen a target (e.g. Fig. 5) comprising neutral ramps with known input RGB values. The 50% luminance point is included in this target.
- The user captures an image of this target with a digital camera, and downloads to the host computer.
- The calibration tool a) extracts camera RGB values corresponding to the projected ramp; b) derives a camera tone response function using the white, black and the 50% luminance point from the target; c) processes the camera RGB values for all ramp patches through the camera tone response function to create luminance values; d) derives a tone response calibration for the projector using the input projector RGB values and the corresponding luminance values.

Experiment

The proposed technique was tested with two projectors and two digital cameras. The projectors were a Sharp PG-C30XU portable LCD projector, and a JVC DLA-G15 projector. The cameras were a Kodak LS443 and a Nikon CoolPix 990. In all cases, radiometric measurements were made with the PhotoResearch PR705 to validate the results. For brevity, data is reported only for the Sharp projector and Kodak camera, noting that similar results were found in the other cases.

Prior to calibration, the projector was warmed up for at least 30 minutes. All built-in projector settings were at their default state. A dim surround was maintained (i.e. no room lights, only indirect light from windows). The capture distance for both camera and spectroradiometer was approximately 3h, where h is the height of the projected image on the screen. The Kodak camera settings were:

- Illuminant: Daylight
- Picture quality: Best
- Exposure: Center-weighted

Results

To test the quality of tone response calibration, a neutral ramp of R=G=B input values was processed through the given calibration function, projected on the screen, and the resulting luminance measured. A perfect calibration would result in a perfectly linear relationship between input digital values and resulting luminance.

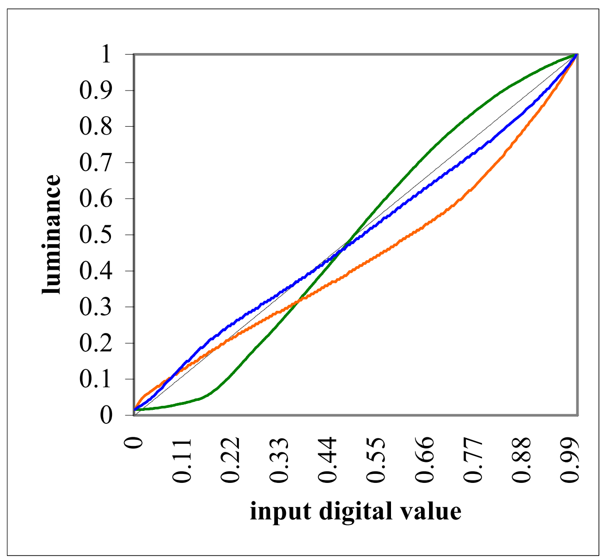

Figure 6: gray luminance tone response of Sharp projector using different calibration techniques: green is visual calibration, orange is camera-based calibration assuming sRGB camera, blue is proposed on-site calibration, dashed black is the reference linear response function.

Figure 6 is a plot of the luminance response for the Sharp projector calibrated with different techniques. For reference, the linear plot representing perfect calibration is included as the black dashed line. The visual calibration technique is clearly inadequate; the reasons for this are explained in Sec. 1.3. Camera-based calibration, wherein the camera is simply assumed to be an sRGB device, also does not adequately linearize the projector. (The validity of the sRGB assumption will vary across different cameras, and may improve over time with advances in built-in correction algorithms.) Finally, we note that the on-site camera calibration achieves superior performance in terms of linearizing the projector.

Table 2 compares ΔE^*_{ab} from the various calibration techniques for 6 neutral (R=G=B) patches that do not include white or black. Clearly both the camera-based approaches offer superior accuracy, with the on-site camera calibration performing the best.

Table. 2: ΔE^*_{ab} results for 6 neutral (R=G=B) patches in Fig 6, excluding black and white. The errors are only along L*.

Calibration Technique	ΔE^*_{ab}	
	Average	Maximum
No calibration (assume input = sRGB)	17.4	23.1
Visual calibration	6.3	19.7
Camera-based calibration (assuming sRGB camera)	4.6	7.2
Camera-based calibration, (on-site camera calibration)	1.9	4.5

Conclusions

A simple projector calibration technique has been proposed that requires only a consumer digital camera, and involves no radiometric or colorimetric measurement. The key novelty is that a visual luminance matching task that is normally used to calibrate a display is used instead to calibrate a digital camera. The calibrated camera is then used to generate the tone response calibration for the projector. The new calibration procedure is considerably simpler and cheaper than methods involving radiometric measurements. Several extensions can be conceived. Ramps of pure R, G, and B can be used instead of, or in addition to, the gray ramp in Fig. 5. In this case, the R, G, and B tone responses would be individually linearized, giving rise to three distinct tone correction curves for the projector. The number of steps in a given ramp can be varied, depending on the desired accuracy of the tone correction. In addition to calibrating the projector tone response, our approach could be used to estimate the 3x3 characterization matrix. This would require that the target includes other RGB combinations, and also calls for additional knowledge of the camera colorimetry. We note one limitation of the proposed technique in that the fundamental assumptions of additivity and chromaticity constancy may not strictly hold for certain display technologies. Finally, the digital camera could either be a standalone device, or embedded in a mobile device such as a cell-phone or PDA.

Acknowledgements

We thank Pravin Rao for his assistance in acquiring experimental data.

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