Color Calibration of Multi-Projector Displays through Automatic Optimization of Hardware Settings

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Abstract

We describe a system that performs automatic, camera-based photometric projector calibration by adjusting hardware settings (e.g. brightness, contrast, etc.). The approach has two basic advantages over software-correction methods. First, there is no software interface imposed on graphical programs: all imagery displayed on the projector benefits from the calibration immediately, without render-time overhead or code changes. Secondly, the approach benefits from the fact that projector hardware settings typically are capable of expanding or shifting color gamuts (e.g. trading off maximum brightness versus darkness of black levels), something that software methods, which only shrink gamuts, cannot do. In practice this means that hardware settings can possibly match colors between projectors while maintaining a larger overall color gamut (e.g. better contrast) than software-only correction can.

The prototype system is fully automatic. The space of hardware settings is explored by using a computer-controlled universal remote to navigate each projector's menu system. An off-the-shelf camera observes each projector's response curves. A cost function is computed for the curves based on their similarity to each other, as well as intrinsic characteristics, including color balance, black level, gamma, and dynamic range. An approximate optimum is found using a heuristic combinatoric search. Results show significant qualitative improvements in the absolute colors, as well as the color consistency, of the display.

1. Introduction

Hardware display controls are familiar to anyone who has ever adjusted the brightness setting on a television. They are just as prevalent on digital light projectors. A significant amount of research has focussed on color and intensity calibration of projectors [1, 6, 8, 5, 3] but the corrections are typically performed in software; the hardware display controls are ignored. There are reasons for this. It is difficult to perform automatic calibration using hardware settings, because they are typically designed to be adjusted manually using dedicated pushbuttons built into the display device; they are not easily manipulated from a program running on a host PC. Only high-end projectors provide functions for computer control of the hardware settings via a serial link and even for them the amount of available control is usually limited. As a result, software-correction methods start with the hardware controls either left unchanged or kept identical.

Performing multi-projector color calibration from unchanged hardware settings is not optimal – even identical settings on the same-model projectors can have significantly different color appearance. Therefore there are significant advantages to using projector hardware settings for color calibration. Because the hardware settings are applied directly by the display device, they are entirely transparent to the host PC's graphics adapter and rendering software. The video output adjustments are applied without rendering overhead or impact on the APIs for rendering software. This is unlikely to be true for software-based correction.

Another advantage to using hardware settings is that they are capable of expanding or shifting projector color gamuts. Software methods, by contrast, can only produce a modified gamut that is a subset of the original one. Strict gamut matching with software-only correction leads to a common gamut that is the intersection of all individual gamuts; in practice this intersection can be very small, leading to washed-out pictures with poor contrast. Hardware settings, however, are capable of shifting or expanding a color gamut beyond its previous boundaries. For example, increasing a brightness setting, on some projectors, will increase bulb brightness, leading to increased dynamic range at the cost of reduced darkness of black levels.

Inspired by Ilie and Welch's work on hardware-based adjustment for camera color matching [4] we present in this paper an approach to fully automatically adjust projector hardware settings to best match the color consistency across

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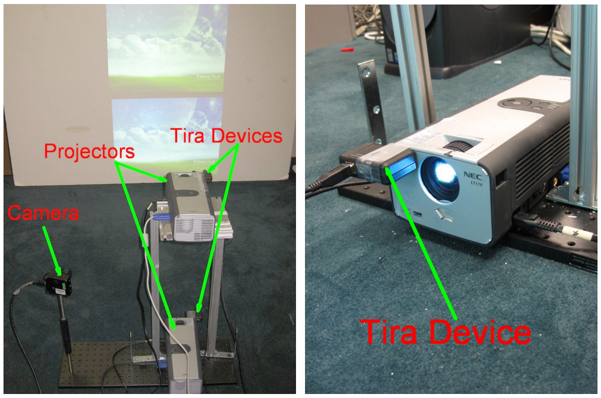

(a) (b)

Figure 1. System overview. (a) The system consists of one host pc, two projectors attached with two Tira devices and one Point Grey camera. (b) Close-up front view of a projector with Tira device attached.

multiple projectors. We attach a learning universal remote to each commodity projector so that it can be computer-controlled, independent of its make or model. A standard off-the-shelf camera is used to measure projectors' color response curves under different hardware settings. A cost function is designed to quantify the consistency among all projectors. The hardware settings are changed until an optimal match is found.

This paper's contributions are two-fold. First we propose this concept of automatically changing hardware adjustment to achieve better photometric calibration in a multi-projector setup. Secondly we develop a color consistency cost function that takes into consideration several incompatible factors including color balance, black level, gamma, and dynamic range.

Our method should not be considered as a replacement for software-based correction methods. Since photometric controls on commodity projectors are usually global, it is unable to correct inconsistency on a per-pixel basis. For example, intensity blending or intensity uniformity correction has to be carried out in software. Nevertheless, hardware-based adjustment provides a much better starting point for these tasks.

2. Technical Details

2.1. System Overview

The prototype system consists of two projectors and a camera connected to a computer. The setup is shown in Fig. 1 Two USB universal remotes are attached to the PC; each one is aimed at a projector's IR port.

The remotes we use for our experiments are Tira-2.1 [7], which can both receive and transmit IR codes. The IR codes that are needed to control the projectors are pre-captured from the projectors' dedicated remotes. The Tira devices are used to change the projector's hardware settings by programmatically activating and manipulating the firmware user menu. While the program is running, it simply decides which parameters should be changed and how much they should be changed and then find the very places to finish this process. This process is to some extent time-consuming, however fully automatic.

Projector responses are measured with a Point Grey Dragonfly2 camera. Since it is a camera designed for computer vision tasks, its intensity response is linear. No camera color calibration procedure is needed. The 3-channel response curve of the projector is measured for multiple displayed intensities by showing a sequence of graylevels for a given hardware setting, and computing the average RGB response in the camera. Because the projectors' dynamic ranges exceed the camera's, high-dynamic range imaging techniques [2] are used; multiple images are acquired with varying exposure times. The long exposure times allow accurate measurement of projector black levels; short exposure times allow measurement of the top of the color gamut without saturating the camera.

2.2. The Cost Function

The cost function is intended to reward hardware settings in which the projectors' responses are similar to each other. There are other criteria that are often desired in a display: accurate white balance, large dynamic range, dark black-levels, a consistent gamma curve. The cost function includes a number of terms to accommodate each criterion. Because in general they cannot all be satisfied simultaneously, they must be independently weighted to represent their importances relative to each other.

The relative dissimilarity term consists of a summed squared distance between each color g_k as displayed in projector p_i and observed in the camera, versus the appearance of g_k as displayed by projector p_j and observed in the camera.

$$Dissimilarity = \sum_{i,j,k} d\Big(c\left(p_i\left(g_k\right)\right)\,,\,c\left(p_j\left(g_k\right)\right)\Big)^2 \quad (1)$$

Here $d(\cdot,\cdot)$ is a perceptually-meaningful distance measure between colors c seen in the camera. In our case, we compute $d(\cdot,\cdot)$ by first applying an inverse gamma function ($\gamma = 0.45$) to each of the R, G, and B values of each color, followed by the 3D Euclidean distance between each of the two resulting colors. Raising the channels to a fractional power has the effect of boosting the effect of discrepancies for lower intensities; this is important because the human visual system is more sensitive to absolute gradients in dark regions than in bright regions. (The distance could alternatively be computed in a different color space such as CIE

LAB; however, because our camera, rather than measuring points in a standard space like sRGB, is linear without any absolute calibration, the accuracy of a conversion to CIE LAB would be questionable.)

While the relative dissimilarity term encourages projectors to have similar responses, it has nothing to say about the color balance of the projectors. We also consider a color balance term, based on the YCbCr space. The chrominance components Cb and Cr are given by

$$\begin{aligned} Cb &= -0.168736R - 0.331264G + 0.5B \\ Cr &= 0.5R - 0.418688G - 0.081312B \end{aligned} \tag{2}$$

The color balance term is obtained by summing up the squared values of all the Cb and Cr Components seen in the camera (the displayed images are white).

$$Color = \sum_{i,k} Cb\Big(c\left(p_i\left(g_k\right)\right)\Big)^2 + Cr\Big(c\left(p_i\left(g_k\right)\right)\Big)^2 \tag{3}$$

Additionally, there is an absolute response term that penalizes projectors to the extent that their objective response curves deviate from a standard gamma function.

$$Absolute = \sum_{j,k} d\Big(ag_k,\, c\left(p_j\left(g_k\right)\right)\Big)^2 \tag{4}$$

The quantity a is actually chosen so as to minimize Eq. (4); this means that the absolute term does not dictate a specific brightness for the display; it specifies the shape of the response curves but not their size.

A fourth term, called the inflation term, is simply given by the negative of the scale needed to align the standard gamma curve with the actual projector response. It is negative so that the cost is reduced for brighter displays. This term is designed to favor displays with large dynamic ranges.

$$Inflation = -a \tag{5}$$

The total cost function is given by a weighted sum of each of the above terms.

$$\begin{aligned} cost = {} & W_m(Dissimilarity) + \\ & W_b(Color) + \\ & W_g(Absolute) + \\ & W_i(Inflation) \end{aligned} \tag{6}$$

The relative weights of the parameters W_m W_b, W_b, and W_i must be chosen a priori by the user; they reflect how the optimization procedure should prioritize the various criteria of inter-projector appearance matching, color balance, desired gamma (and zero blacklevel), and dynamic range. There is more discussion about the effects of these parameters in the Results section (3).

2.3. The Optimization Algorithm

A number of search algorithms can be used to find the optimum of the cost function. An iterative local search strategy is perhaps the most obvious first choice. In particular, Powell's method and the Downhill Simplex method seem particularly appropriate, as they do not require derivative evaluations.

However, we have found that the parameter space tends to be quite smooth; we can sample it at a low rate and obtain very good results with interpolation. This helps to limit the number of times that the projector hardware settings need to be changed, an expensive operation that takes on the order of 10 seconds. In our current implementation, we use pre-captured data and a brute-force search method to quickly evaluate the fitness of the cost function.

The pre-captured data is combinatoric in the number of parameters per projector, but it is only linear in the number of projectors. This is because the hardware settings of a projector p_i do not affect the response curve of a different projector p_j. (It is assumed that the camera is able to see a non-overlapping region for each projector.) The settings only interact when it is time to compute the cost function over the two projectors' response curves, but the cost function can be computed many orders of magnitude faster than the response curves. For a moderate number (say 4) of parameters per projector, the problem of sampling the response curves is quite tractable.

Given that the changes of response curves under different hardware settings are usually smooth, we can apply linear interpolation to increase the sampling rate of the measurements. This can add a great many additional response curves to the observation set. However, when the number of curves approaches hundreds of thousands, even the cost function becomes expensive to compute due the combinatory search. To keep the computations manageable, we apply a hierarchical refinement strategy. Once a global optimum is found at a coarse level, we change the parameter space to be a narrow region around the best candidate. At this finer level, we can perform a new round of interpolations, and find the optimum over this new, smaller but more finely sampled parameter space. This process is repeated until we can reach the precision the hardware supports.

3. Results

We tested our algorithm on a pair of NEC LT170 DLP projectors. Although they are the same model, the bulbs have different ages; the older (more heavily used) projector has a somewhat dimmer and yellower light output. These projectors have eight hardware controls: a global brightness, a global contrast, a three-channel brightness, and a three-channel contrast. For this experiment, the three-channel contrast controls were optimized; the other settings were kept at their default values.

The measured response of the projectors is compared in the top row of Fig. 2. The left, center, and right columns compare, respectively, the projector response for the red, green, and blue channels. The response shown is the observed camera value divided by the exposure time, raised to a power of $\gamma = 0.45$. (Other camera settings such as aperture and gain were held fixed for all the data shown in the figure, so all the projector responses shown here are directly comparable.) The newer projector's response is shown in each color of red, green and blue; the older projector's response is shown in black. The response curves show that the older projector's overall light output is less than the newer projector's. Both projectors show a blue channel that is slightly weaker than the other two, but this effect is somewhat more pronounced with the older projector.

The second row of Fig. 2 shows the optimum for the cost function with $W_m = 1$, $W_b = 0$, $W_g = 0$, and $W_i = 0$. This criterion aims to match the two projectors' response curves without regard to any other consideration. Notice that the curves do match quite well, but the overall color balance of the two projectors is actually made worse, as both blue channels are reduced more than the other colors.

The third row of Fig. 2 shows the optimum of the cost function with $W_m = 1, W_b = 1, W_g = 1$, and $W_i = 1$. The overall color balance between the channels is better than in the second row, although it is not necessarily an improvement over the default settings. The $W_g = 1$ setting attempts to force the (gamma-corrected) response curve to be a line through the origin. Although the curves do not satisfy this constraint, they do appear to be noticeably straighter than the other examples. Also, the inflation parameter seems to have succeeded in boosting the dynamic range of the output. Unfortunately, these successes seem to have come at the cost of accurate matching of the projectors' response curves to each other. These particular projectors, with these particular hardware settings, are apparently unable to satisfy all of the optimization criteria simultaneously.

The fourth row of Fig. 2 shows an optimization that is aggressive enough to enforce subjectively satisfactory results, and conservative enough to be successfully satisfied by the hardware controls. The cost function parameters were $W_m = 1$, $W_b = 1$, $W_g = 0$, and $W_i = 0$. The response curves match each other accurately and the color balance is better than in any of the other examples.

Fig. 3 shows the results for some images displayed with these hardware settings. The top row shows three images displayed with the default settings. The older projector (top) is noticeably yellower or redder than the newer projector displaying its image immediately below, although it is difficult to say whether the older projector is perceptibly dimmer overall. The middle row shows the results for optimizing only the W_m criterion. The projectors match each other accurately, but the overall color balance is noticeably more yellow than our chosen white point. The bottom row shows the result for optimization with $W_m = 1$, $W_b = 1$, $W_g = 0$ and $W_i = 0$. The images match each other very closely, and the colors are also well-balanced.

4. Conclusion

We have described a method for camera-based automatic calibration of projectors using the built-in hardware adjustments for color and intensity correction. Initial results have successfully achieved high-quality white balancing and color matching across projectors even by adjusting a very limited set of parameters.

Looking into the future we plan to experiment with all control parameters. The major roadblock seems to be the lack of an efficient control interface. With the demonstrated success here we hope projector venders can provide easy-to-use fast PC control interface even on their low-end projectors. In the meantime we plan to study in more depth about the dependency of these parameters and develop an efficient optimization method that requires fewer measurements.

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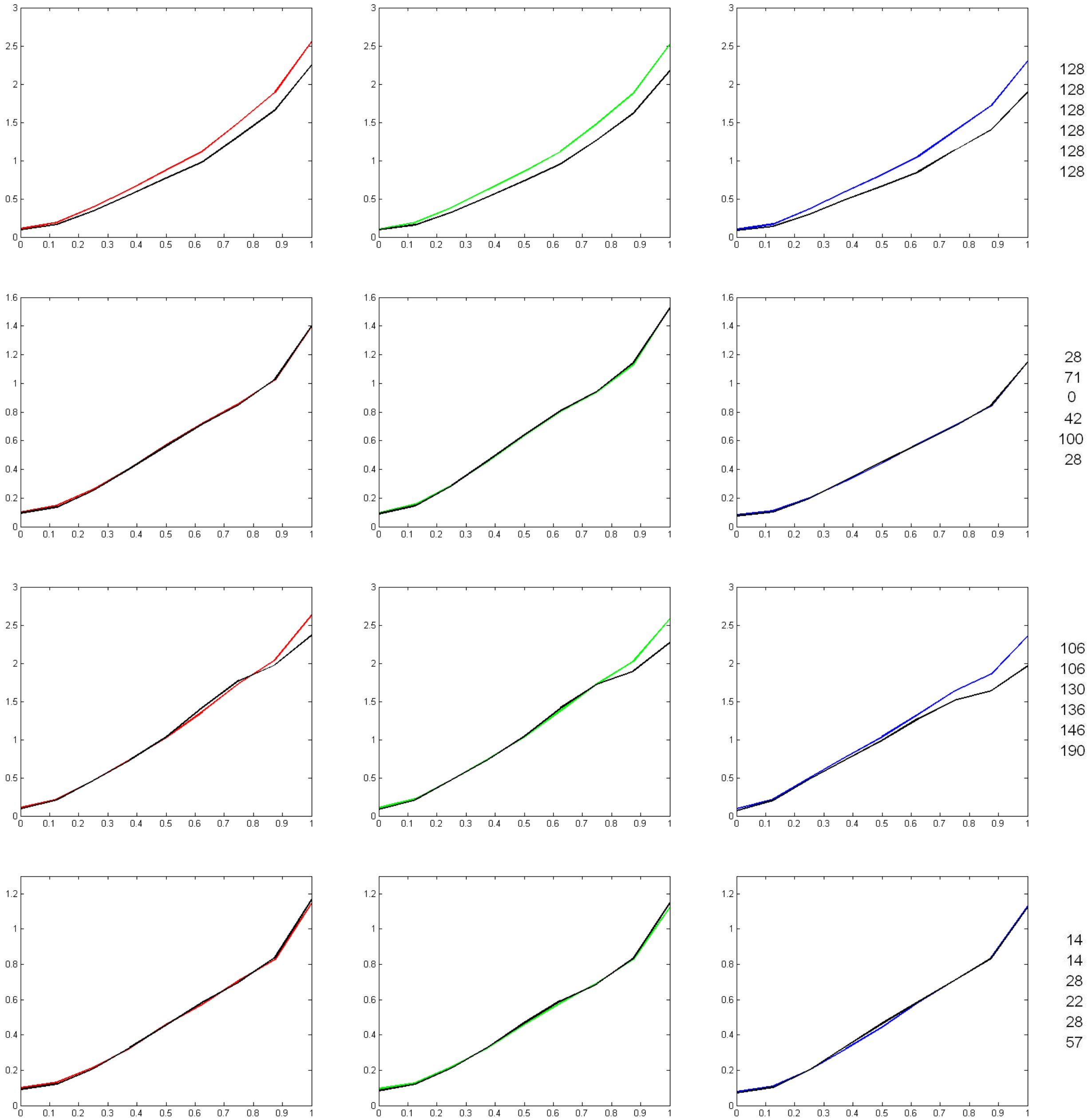

Figure 2. Projector response curves. Single-color responses are plotted against displayed graylevels. Plots for red, green, and blue responses, respectively, are shown in the left, center, and right columns. The responses for the bottom projector in Fig. 3 are shown in the color of its respective channel; the corresponding response for the top projector is shown in black. The far right column shows the 3-channel contrast settings for each of the two projectors. (Top) Curves for the default parameter settings. (Second from Top) Curves for optimum for $W_m = 1$, $W_b = 0$, $W_g = 0$, and $W_i = 0$. (Third from Top) Curves for optimum for $W_m = 1$, $W_b = 1$, $W_g = 1$, and $W_i = 1$. (Bottom) Curves for optimum for $W_m = 1$, $W_b = 1$, $W_g = 0$, and $W_i = 0$.

Figure 3. Comparison of displayed results for several hardware adjustment settings. Each of the three rows shows the results for a pair of projectors stacked on top of each other. Three different images are shown in each row for comparison. The older projector illuminates the upper half of each image; the newer projector displays the lower half. The far right column shows the 3-channel contrast settings for each of the two projectors. (Top Row) Images are shown with the default hardware settings. (Middle Row) Hardware settings for optimum of cost function with $W_m = 1$, and all other weights zero. Notice that the projectors match each other better than with the default settings, but the results appear yellowish. (Bottom Row) Hardware settings for optimum of cost function with $W_m = 1$, $W_b = 1$, $W_g = 0$, and $W_i = 0$. The projectors match each other well and a white balance close to the desired one is achieved.