

A Comparison of Methods of Sensor Spectral Sensitivity Estimation

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Abstract

An experiment is described to obtain estimates of the spectral sensitivities of a digital image capture device by photographing a wide range of input color signals. Given the red, green, and blue signals from the device and the spectral power distributions of the color signals, we apply the methods of simple linear regression, rank-deficient pseudo-inverse, and Wiener estimation. Nominal data and the results obtained by the methods are presented and compared.

Introduction

There are considerable benefits to converting image data into representations that are independent of the image capture device. Device-independent representations are nonetheless dependent on our ability to calibrate input devices. To subtract out the effects of an image capture device, we first must be able to characterize how the device transforms the input. Accurate estimates of the spectral responses of an input device plays a vital role in the reproduction of color by any imaging system¹.

Color calibration of input devices is possible if the device responds linearly to the input, if the spectral sensitivities of the input device are known, and if the spectral power distribution of the illuminant is known. CCDs are inherently linear sensor devices and optical image transformations are linear operations. Thus it should not be surprising that image capture devices based on CCDs, such as scanners, digital cameras, and video camcorders, can be modeled as linear devices². Unless we manufacture these devices, however, we do not know the spectral sensitivities of their sensors.

In this paper we report on results of applying sensor estimation methods to experimental data collected from a digital camera. By using known illuminants and surfaces that give color signals of high dimensionality, we can get a good estimation of the spectral sensitivities of the input device.

Experimental

To test the camera under consideration, we use an experimental configuration that gives high dimensionality of the input (Figure 1). We illuminate the Macbeth ColorChecker with a tungsten halogen light filtered with 8 broadband and 16 narrowband filters spanning a 400 to

700 nm spectral range. In some cases, it was necessary to include a neutral density filter so that the level of illumination was within the dynamic range of the camera being tested.

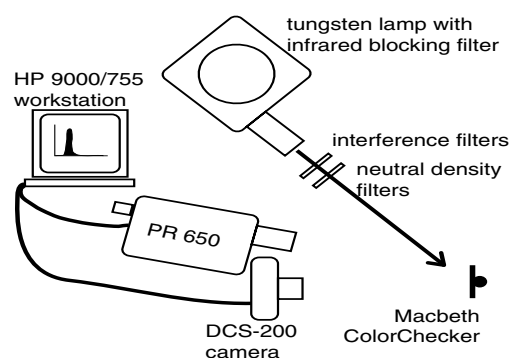


Figure 1. Set up for photographs of Color Checker and measurements of color signals

We used the Kodak DCS-200 digital camera to photograph the ColorChecker illuminated by the source passing through each of the filters. The raw data (not interpolated) was collected and subsampled by an HP 9000/755 workstation. In each image, average red, green, and blue values were calculated over an area for each patch of the Color Checker. Along with the photographs, the spectral power distribution of the color signal from each patch of the Color Checker was recorded and transferred to the computer using a Photo Research-650 spectrophotometer. The data was organized as two large matrices which held the rgb and the spectral data from the images of the Macbeth ColorChecker.

Linearity of Data

For each illuminant, we test for device linearity by measuring sensor responses to the six gray patches in the Macbeth ColorChecker. If device linearity holds for that illuminant condition, we include the data in our analysis. We tested this by plotting r , g , and b as a function of reflectance of the gray patches under a given light. For each light, r , g , and b increased linearly with the amplitude of the color signal.

Because of the limited dynamic range of the device, there were two exceptions to linear behavior: an offset due to noise, and clipping due to saturation of the CCD.

Clipping was avoided in most cases by the use of the neutral density filter in the experiment. A few patches still managed to saturate one of the channels and so were removed from the data set. From the plots we determined the mean noise level by using line fitting techniques and compensated the data for the offset.

Sensor Estimation

Due to the brevity of this paper we have chosen to refer the reader to other publications for the mathematical descriptions of sensor estimation methods. Here we will report on how the methods worked for our particular experiment, when applied to a real set of data.

Figure 2 shows a simplified diagram of the sensor estimation problem. In our case, where the large set of data includes both broadband and narrowband color signals, we can apply the methods to either the entire set of data or a subset (just the narrow band data, for example).

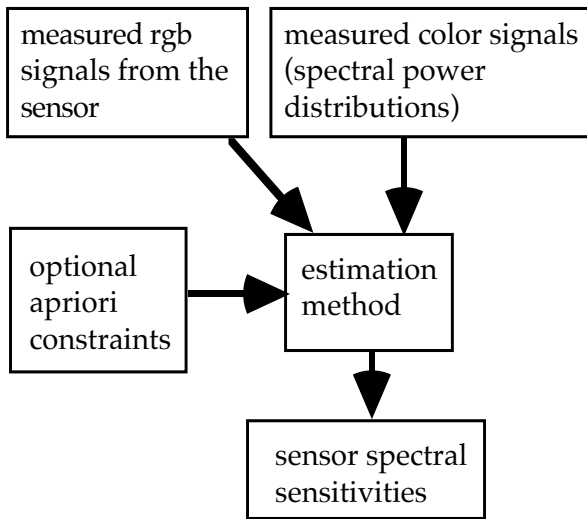


Figure 2. The simplified diagram of the sensor estimation problem

The most obvious method of sensor estimation is to ask the manufacturer. The spectral response curves for the Kodak KAF-1600C CCD sensor³ used in the DCS-200 digital camera are shown in Figure 3. Unfortunately, we were not able to obtain the spectral reflectance curve for the infrared blocking filter mounted in the camera. The primary differences between our estimations (described later) and the Kodak supplied data (Figure 3) can be attributed to the absence of this filter response in the supplied data set.

Simple Method

The simplest method to determine the spectral sensitivity of the sensors uses the camera’s response to the narrowband data. Because this data is non-overlapping and spaced every 20 nm throughout the spectrum, we can simply regress the sensor responses against the amplitudes of the color signals at the corresponding wave-

lengths. Although the coarse sampling of the filters limits the detail of the curves, the results are a dependable starting point. Figure 4 shows the data from this simple averaging method.

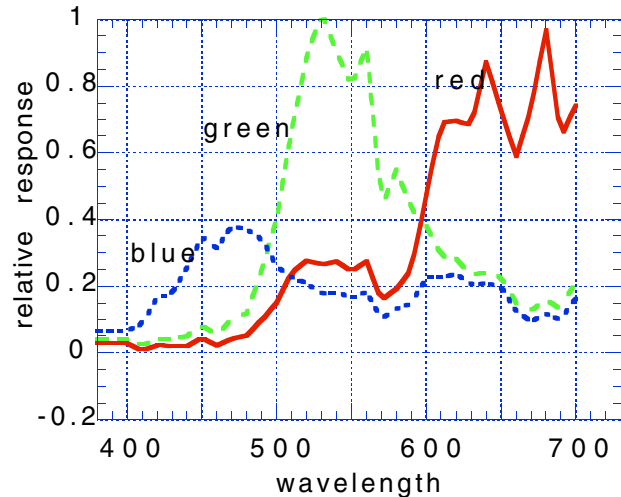


Figure 3. Spectral response of the Kodak KAF-1600C sensor used in the DCS-200 camera as supplied by Kodak

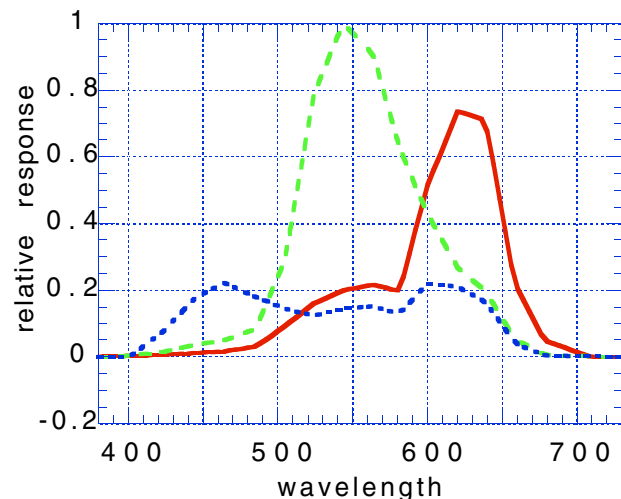


Figure 4. Spectral response of the camera’s sensors calculated from the narrowband data

Rank-Deficient Pseudo Inverse Method

The rank-deficient pseudo inverse method^{2, 4, 5, 6} gave the curves shown in Figure 5 when applied to the full set of data. Clearly, this method suffers from the lack of a smoothness constraint to compensate for the spikes caused by the nature of the narrowband interference filters. We ran this method with subsets of the data, but achieved an unsatisfactory tradeoff between the spikiness from the narrowband data and unrealistic fluctuations from the broadband data. Another factor that we found to be critical in this method is sensitivity to noise. When we ran the regression using simulated data without noise, the results were excellent, but when noise was added (~1%) results similar to Figure 5 were obtained.

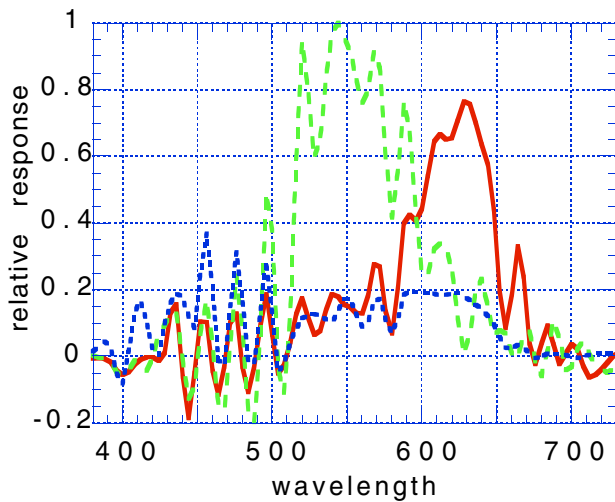


Figure 5. Estimated sensor responses generated using the rank-deficient pseudo inverse method

Wiener Estimation Method

It is clear from the previous result that some kind of smoothness constraint is necessary for obtaining realistic results. The Wiener estimation method⁷ was applied by Mancill^{8,9} to a similar problem. In Figure 6 we have applied the Wiener estimation method to the narrow band data and in Figure 7 to the broadband data. These curves were obtained by using a rank that corresponded to the number of filters used in each case, and a correlation coefficient of $\rho = 0.9$. The similarity of these two sets of curves supports the accuracy of the estimations as described by Mancill. A plot similar to Figure 6 was obtained when the Wiener estimation was applied to the full set of data.

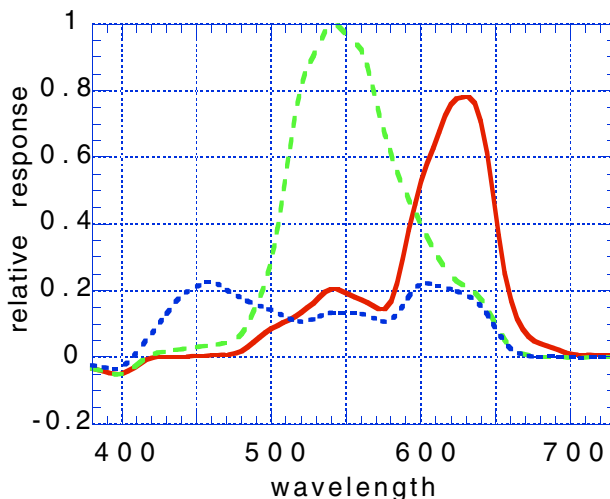


Figure 6. Estimated sensor responses generated using the Wiener estimation method on the set of narrowband data

Other Methods

Although the Simple and Wiener methods applied to the narrowband data have given us what we believe are good

estimations for the spectral responses of the sensors, it would be advantageous to analyze a method that gives good results when using a smaller set of color signals (such as just the broadband data). The side lobe and negative fluctuations in Figure 7 could potentially be reduced by using a method such as projection onto convex sets (POCS)^{5,6}. We have found that using POCS to constrain the set to non-negative numbers decreases the rms error, but further constraints need to be added to the analysis.

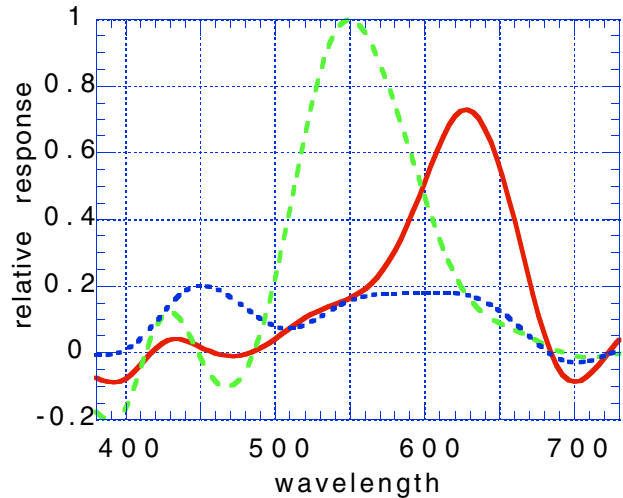


Figure 7. Estimated sensor responses generated using the Wiener estimation method on the set of broadband data

Conclusions

Because the data in Figures 4, 6, and 7 are in good agreement we believe that these are good estimates for the spectral responsivities of the camera's sensors. In Table 1 we show the average rms errors for measured rgb camera signals versus the rgb signals calculated using the curves estimated by the various methods. Although the rank-deficient pseudo inverse estimation gave the lowest error, it is clear from Figure 5 that the curves are very dependent on the data used in the derivation: if this method is applied to just the wide band data, the error jumps to above 25. The Wiener method gave good results and produced more realistic curves. As expected, these methods produce lower errors than the Kodak supplied data, mainly due to the absence of the infrared blocking filter response.

In Figure 8 we plot our best estimates of the sensor responses along with the data supplied by Kodak. From these curves it is clear that the major discrepancy – the red responses above 650 nm – is due to the absence of the infrared blocking filter response in the supplied data. Even with the infrared filter added, the result may not be as reliable as our estimates. The response of the camera lens and the chip to chip variation typical of CCDs surely affects the dependability of this data. Our estimates, derived from data carefully measured from the entire imaging system, would likely be more reliable for the particular device under consideration.

Table 1.

Estimation method	RMS error
Simple linear regression	8.472
Rank-deficient pseudo inverse estimation	3.717
Wiener estimation	5.9220

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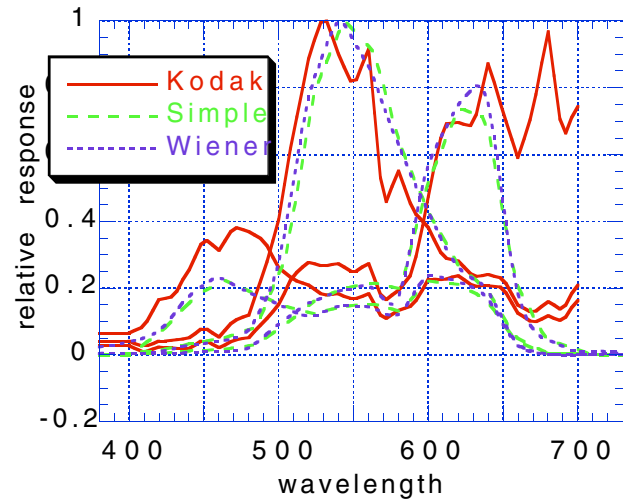


Figure 8. Estimated sensor responses of the various methods compared with the Kodak data

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