Camera Calibration for Colour Research

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In this paper we introduce a new method for determining the relationship between signal spectra and camera RGB which is required for many applications in colour. We work with the standard camera model, which assumes that the response is linear. Since our Sony DXC-930 CCD colour camera has a slight non-linearity, we also discuss the implications of such a non-linearities, and report on the method used to deal with them.

The fitting procedure itself is an extension to that documented in [Bar95], which itself was inspired by [ST93]. We find it superior to the pseudo-inverse method as well as the Wiener method (both tested in [HSF92]), as both these methods can find sensors which are not physically possible. For example, they both can find sensors which have negative sensitivities. The pseudo-inverse method is especially notorious for finding solutions which are not smooth, since the only objective of the fitting method is to minimize error.

The basic idea of our method is to minimize squared error subject to linear constraints, which enforce positivity and range of the result. In [Bar95] we constrained the smoothness; however, we have subsequently found that it is better to add a regularization expression to the objective function to promote smoothness. With this method, smoothness and error can be traded against each other without being restricted by arbitrary bounds. Nonetheless, with our method it is easy to set a maximum possible error or minimally acceptable smoothness as additional constraints.

The method is easily implemented as it is an example of a quadratic programming problem, for which there are many software solutions available. These include the fortran subroutines DLSEI and DBOCLS from the SLATEC library freely available by FTP from ftp.netlib.com, and the "qp" facility in Matlab's optimization toolbox.

In recent work Finlayson and Hordley also advocate a fitting procedure based on quadratic programming [FH98]. In that work, however, they handle smoothness by constraining the sensors to be linear combination of the first 9-15 Fourier basis functions. They also propose constraining the sensor response curve modality, but doing so requires both knowing the modality, and trying all possible peak locations, as the modality constraints are expressed in terms of peak locations.

We now provide some more details of both the overall camera model and the fitting procedure. Both input spectra and camera sensors are assumed to be continuous functions of wavelength, but we use the common simplification of representing them as vectors, with consecutive components being the samples at consecutive sampling wavelengths. In our case, we use vectors with 101 components representing samples from 380 to 780 nano-meters at 4 nano-meter intervals. This choice matches the PhotoResearch PR-650 spectraradiometer used for calibration.

We model the camera as $F(\rho_i) = \mathbf{R}_i \cdot \mathbf{C}$, where ρ_i is the response of the i'th sensor to the signal $\mathbf{C}$, given camera response $\mathbf{R}_i$, and F is a function compensating for any non-proportionality in the camera. In [VFTB97a] F is fit in a separate experiment where only the intensity of the input spectra is varied. This is an effective approach, but in this paper we describe an alternative which we find more convenient. We use a similar separate experiment to investigate the nature of F, and then fit for the relevant parameters (coefficients) in F at the same time as the fit for $\mathbf{R}_i$. For example, our camera has only a slight non-proportionality which is well approximated by $F_i(x) = a_0^{(i)} + a_1^{(i)} e^{-k_i (x - b_i)}$, where b_i is the camera black. Thus we can solve for $a_0^{(i)}$ and $a_1^{(i)}$ simultaneously with $\mathbf{R}_i$. The additional constant k_i cannot be solved for, but is quite stable, and is easily found by trial and error.

With the above camera model, prediction of complete RGB is aperture dependent, but the prediction of chromaticity is aperture independent. Fortunately, for most applications, chromaticity predictions is sufficient. Some examples of applications where this is the case are in [Fin95] and [FCB97]. In fact, since the overall brightness is usually arbitrary in colour constancy, similar considerations apply to practically all colour constancy applications.

References

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