Practical Camera Characterisation for Colour Measurement

M. R. Pointer, G. G. Attridge and R. E. Jacobson
The Imaging Technology Research Group
University of Westminster, Harrow, United Kingdom

Abstract

This paper reviews the major issues involved in the use of digital cameras to derive the CIE *X*, *Y*, *Z* tristimulus values of the objects in real scenes. Both practical and theoretical investigations have been carried out to gain experience in this specialised field of imaging. The practicalities of camera characterisation described include: lighting - spectral power and uniformity, test target - choice and number of colours, camera signal processing - linear or gamma corrected, colour analysis - filter transmittance and infra-red filtration, characterisation method – linear or higher order, quality measure - CIELAB, CMC, CIE94 colour difference, and quality statistic - mean, median etc. It is shown that the choice of colour separation filtration is the most sensitive variable. If a 'colour' camera is used, then it needs to be carefully selected: a more adaptable choice, however, may be a monochrome camera with external filters. In addition, the illumination uniformity of the test target is shown to be important: that it is never perfectly uniform must be considered in the characterisation process. With careful selection of system components, a median value of less than 1.0 CIELAB colour difference between the required and the predicted colorimetry can be obtained.

Introduction

The growing availability of digital cameras has stimulated interest in their use in a wide range of applications. Some of these applications are essentially instrumental in that the final requirement is not necessarily an image on a computer display but an array of CIE colorimetric coordinates in a data file. In machine vision applications for example, there may be no conventional 'image" beyond the optics of the camera, and the remainder of the imaging chain involves the manipulation and analysis of an electronic virtual image, which possess no immediate visual significance.

Computer modelling of such a process requires consideration of a virtual image produced by a virtual camera of stipulated properties. This has the advantage of possibly avoiding considerable experimental work while offering direct verification of results from experimental studies.

Camera Characterisation

To use a digital camera as a tristimulus colorimeter requires signal processing to obtain *device-independent coordinates*, CIE tristimulus values,[1] from the *R*, *G*, *B* output data and it is the form and efficiency of this *characterisation process* that dictates the overall accuracy of the device as a colorimeter. The basic response value, *R*, *G* and *B*, of a specific pixel in an image can be calculated from a knowledge of the spectral power distribution of the light coming from the equivalent location in the original scene. Assuming the light is present by reflection, then this power distribution can be substituted by the product of the spectral power distribution of the light source, $P(\lambda)$, and the reflectance of the object in the scene element, $R(\lambda)$ to give:

$$R = \int P(\lambda) R(\lambda) D_r(\lambda) d\lambda$$

$$G = \int P(\lambda) R(\lambda) D_g(\lambda) d\lambda \qquad (1)$$

$$B = \int P(\lambda) R(\lambda) D_b(\lambda) d\lambda$$

where $D_r(\lambda)$, $D_g(\lambda)$, $D_b(\lambda)$ are the spectral responsivities of the camera colour channels, and the integration is taken over a suitable wavelength range in the visible part of the spectrum, for example, from 380 to 750 nm.[2]

The values of *R*, *G* and *B* calculated using the above equations are *device-dependent* in that they will be different, for example, for a camera having a different spectral responsivity. Thus, the problem to be solved is how to transform these device-dependent coordinates into *device-independent coordinates*. The device-independent coordinates usually chosen are the CIE tristimulus values, *X, Y, Z*, which are defined in a similar manner to the *R*, *G*, *B* values above[1]:

$$X = \int P(\lambda) R(\lambda) X(\lambda) d\lambda$$

$$Y = \int P(\lambda) R(\lambda) Y(\lambda) d\lambda \qquad (2)$$

$$Z = \int P(\lambda) R(\lambda) Z(\lambda) d\lambda$$

The difference is that the $X(\lambda)$, $Y(\lambda)$, $Z(\lambda)$ functions are unique and represent the colour matching functions of the CIE standard observer. Thus the problem becomes one of finding a mathematical relationship between the values of *R*, *G*, *B* and their corresponding *X*, *Y*, *Z* values.

Characterisation Methods

Spectral Responsivity

Investigation of the above equations shows a certain similarity between those for deriving the camera responses *R*, *G*, *B* and the CIE *X*, *Y*, *Z* tristimulus values, the difference being the spectral responsivities. Thus if a relationship can be found between the camera spectral responsivities and the CIE colour matching functions then this same relationship can be used to transform *R*, *G*, *B* values to *X*, *Y*, *Z* values.[3] The usual place to start when looking for such a relationship is to assume that the camera responses are a linear combination of the CIE colour matching functions. Because this is an assumption, rather than a fact, it is reasonable to investigate the use of more complex forms of equation to model the relationship.[4]

Colorimetry

This may be regarded as an extension of the above solution in that the regression procedures are applied, not to the data comprising the spectral responsivities, but to the *R*, *G*, *B* and *X*, *Y*, *Z* data of a suitable number of test colours.[5-9] Thus, a number of test colours are illuminated by a suitable light source and images captured using the camera to be characterised. *R*, *G*, *B* values are obtained from these images. It is also necessary to be able to calculate the *X*, *Y*, *Z* tristimulus values of the coloured samples, and this can be done, either by measuring the spectral power distribution directly using a tele-spectroradiometer, or by measuring the spectral power distribution of the light source using a spectroradiometer and also measuring the spectral reflectance of each of the coloured samples using a spectrophotometer. The *X*, *Y*, *Z* values are then calculated using the equations described above. Regression analysis can be applied in a manner similar to that applied to the values of spectral responsivity. Some regression techniques offer the further advantage that they are constrained to permit, for example, a white sample to be correctly reproduced with defined colorimetric values.[10]

Practical Approach

The initial step was the careful selection of a set of test colours. These should span the range of colours of interest and should be standardised, preferably by spectral data. Arrays of useful colours include the IT8 target,[11] comprising 264 colours and used for example, to in creating device profiles for digital scanners, a colour atlas, for example, the Munsell Book of Color in its various guises, with 225 colours in its simplest form,[12] and the Macbeth ColorChecker with 24 colours.[13] It is arguable that the visual importance of the grey scale is reflected in the use of all six neutral samples when the ColorChecker is used, together with its complement of colours representative of real scenes and subjects.

Because of metamerism it must be recognised that two targets could be colorimetrically identical, that is each sample have the same *X*, *Y*, *Z* values, but give different *R*, *G*, *B* values when imaged by a camera.[12] The issue of metamerism also indicates the importance of the illuminant. Ideally, it should have a defined spectral power distribution but in practice, a variety of distributions may be encountered, even when supplied as matching CIE specifications such as Illuminant D65. This power distribution may be approximated colorimetrically for example, using filtered tungsten halogen lamps or specified fluorescent lamps as sold fitted in colour-matching booths. The spectral power distributions are not usually identical: mercury emission lines are seldom completely excluded from the output of the fluorescent lamps. In this practical study, filtered tungsten light sources were used to achieve a close colorimetric match to CIE Standard Illuminant D65.

Uniformity of illumination of both the sample and the sensor is important if objectively correct colour reproduction is required. The sample may appear to be uniformly illuminated but measurement can reveal considerable variation. If the unevenness of illumination is determined as the spatial non-uniformity of the sensor output when the camera records a uniform white card, then it is possible to factor out the non-uniformity as part of the characterisation process. It is most rigorous when carried out at exposure because it then includes any off-axis fall-off in photometric efficiency of the camera objective, as well as deficiencies in the illumination system and in the sensor device itself. The practical study used two directional light sources at 45° to the subject plane to achieve near-uniform illumination, and a uniform white card was recorded as a photometric calibration of the image uniformity.

The practical system assembled avoided the colour balance problems of commercially available equipment. It employed a Kodak DCS420 monochrome CCD camera, fitted with a "hot filter" to exclude infrared radiation. The camera was additionally equipped with tricolour separation filters typical of traditional photographic practice, and colour balancing could be carried out during computer assembly of the images. Spectral sensitivities of the filtered camera are shown in Fig. 1.

Colorimetric data were obtained from the sample sets by measuring the spectral reflectance and CIE tristimulus values were then calculated using the 1931 CIE Standard Observer (the 2° observer), and CIE Standard Illuminant D65 as representing a standard daylight. It should be noted that this was not the illuminant used physically to illuminate the test targets; it represents the illuminant for which the output colorimetry is required after the camera characterisation process. The R, G, B values were obtained from images of the test charts using the Scion Image software package.[14]

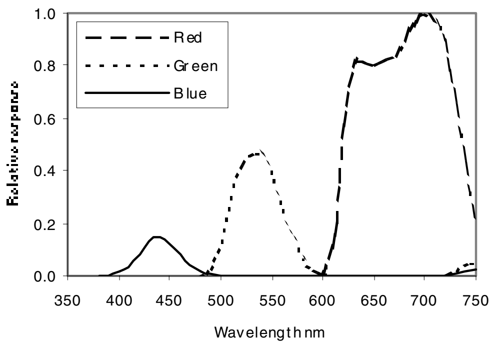

Figure 1. Spectral responsitivities of the CCD camera.

An imaging system may carry out some image processing within the image acquisition device or in the host computer. Such manipulations are designed to optimise images according to criteria that may be concealed from the operator. Examples include manipulation by a 1/γ function to compensate for the power law transfer characteristic of a typical cathode-ray tube monitor.[15]

Experimental Results and Discussion

The initial, linear, approach was replaced by polynomial regression to optimise the matrix relating the measurements of the sample and reproduction sets of colours. CIELAB, CMC and CIE94 colour difference formulae were used to quantify differences, Δ*E**, between subject and reproduction.[12] Inclusion of the median value of colour difference as a measure of central tendency was made having regard to the non-Gaussian distribution of the Δ*E** values, which are not directed numbers. The median alone was judged inadequate for the investigation which invariably detected outliers in the distributions found, so the maximum Δ*E** was also evaluated.

Table 1 summarises linear characterisation results for the digital camera system with two different input colour sets. The most important figure of merit given is the median colour difference for each characterisation relating *R*, *G*, *B* responsivities to the required colorimetry of sample sets.

This allowed the optimum relationship to be determined and the computation of equivalent results for any chosen sub-set. From these data, it was hoped to determine whether a large colour set was beneficial, and whether an optimum colour set was likely to exist for camera characterisation. Table 1 shows data from 225 Munsell samples and a linear matrix for *R*, *G*, *B* data, with and without pre-linearisation of the *R*, *G*, *B* data using the transfer characteristic of the camera. Pre-linearisation through the transfer characteristic improved median Δ*E** values, and reduced Δ*E** values for major outliers. Table 2 shows that similar results were obtained using the Macbeth ColorChecker as an input test target.

Table 1. The results of applying a linear characterisation model to Munsell samples, with and without pre-linearisation.

Model	Pre-linear	Formula	Median
Linear	Without	CIELAB	5.4
		CIE94	3.5
		CMC	4.1
Linear	With	CIELAB	5.3
		CIE94	3.4
		CMC	3.9

Table 2. The results of applying a linear characterisation model to Macbeth ColorChecker samples, with and without pre-linearisation.

Model	Pre-linear	Formula	Median
Linear	Without	CIELAB	8.8
		CIE94	5.3
		CMC	5.9
Linear	With	CIELAB	5.1
		CIE94	4.1
		CMC	4.7

High values of colour difference, Δ*E**, obtained for the maximum values, are usually attributable to high chroma colours that are very dark (a relatively high value of *C** and a low value of *L**) but also to very dark neutral colours, for example the black of the Macbeth ColorChecker. Both these groups of samples are near the bottom of the colour solid where the shape of a colour gamut tends to a point that represents black (*L**, *C** equal to zero). One possible explanation applicable to the former group of colours is that the actual colour sample is formed using a pigment that has not been used in the rest of the sample set. This could well be the case as the Munsell Atlas has been extended to higher Chroma colours as new pigments have become available.

The next step in characterisation was to investigate a polynomial optimisation. The median CIELAB Δ*E** value, for a quadratic function applied to both the Munsell and the Macbeth sample sets, was 2.9 and 3.2 respectively. There was also a marked decrease in the size of the maximum value of Δ*E**. Further results suggest that increasing the complexity of the functions does not gain any significant increase in accuracy. Note that a polynomial optimisation was expected to linearise the results automatically.

Despite the relatively small set of characterisation patches in the Macbeth ColorChecker, and a high neutral weighting, optimisation has given values of Δ*E** very close to those from Munsell characterisation. For a characterisation to be of broad application it must be tested using colour patches not included in the characterisation set. This was done by applying the characterisation derived from each sample set to the other sample set: Munsell-based characterisation appears the more robust. When applied to the larger Munsell set the median Δ*E** values are all superior, but results are worse than those obtained by applying each characterisation to its own generating colour set.

Theoretical Approach

To further investigate some of the variables described above it was thought useful to construct a computer model of the colour analysis system in a digital camera. An advantage of using a model is that the signal processing (curve shaping) and white point balancing issues are not present (unless they are deliberately factored into the model).

Camera Spectral Response

The R, G, B spectral responses of a number of cameras were available. These included single chip colour cameras; three-chip video cameras and monochrome cameras with external filters. The R, G, B image data for each colour sample were calculated using Illuminant D65 as the exposing illuminant. While this represents an unreal situation, because this illuminant is not realisable as a source, making the input and output illuminant the same minimises the effect of this potential variable.

Table 3. The results of applying a linear model to the Macbeth and Munsell samples using 10 cameras.

	Macbeth		Munsell	
	Median	Maximum	Median	Maximum
1	5.4	13.5	4.5	29.0
2	5.5	12.9	2.7	18.7
3	1.0	4.3	0.6	1.1
4	3.8	24.1	3.1	23.6
5	1.8	4.5	1.0	7.0
6	1.4	4.2	0.9	5.8
7	3.7	9.0	2.1	9.6
8	3.4	9.5	1.9	13.1
9	4.2	17.8	2.6	16.6
10	3.1	9.0	1.9	9.2

Table 3 shows the values of CIELAB ΔE^* obtained when the characterisation is calculated using the Macbeth ColorChecker and then applied first to that data to test its validity and then to the Munsell data-set. Values for both the median and the maximum colour difference are given. It is seen that the median values are similar ranging from 1.0 to 5.5 for the Macbeth and 0.6 to 4.5 for the Munsell charts. When applied to the alternative chart the ranges become 0.3 to 3.2 and 1.1 to 7.6 respectively. Thus, in the case of the Macbeth-based characterisation it is actually giving lower results when applied to the Munsell data set. It should be noted that one camera, No. 3, give a remarkable result when based on the Munsell data set. Camera 1 however, gives consistently poor results. The use of a quadratic regression, Table 8, considerably improves the overall results although the same pattern is still present in that Camera 3 is still very good, although the maximum colour difference for characterisation based on the Munsell data-set is higher. The equivalent ranges are now 0.7 to 4.1 for the Macbeth and 0.5 to 2.3 for the Munsell data sets respectively.

Table 4. The results of applying a quadratic model to the Macbeth and Munsell samples using 10 cameras.

	Macbeth		Munsell	
	Median	Maximum	Median	Maximum
1	4.1	10.7	2.3	11.7
2	2.9	4.4	1.9	15.3
3	0.7	2.6	0.5	4.9
4	2.4	20.5	2.3	21.5
5	1.1	4.1	0.8	5.5
6	1.1	3.0	0.7	4.6
7	2.8	8.4	1.5	18.3
8	1.8	10.1	1.5	11.4
9	2.8	18.8	2.0	14.2
10	2.6	7.7	1.5	8.2

White-point Correction

Application of both the linear and the quadratic regression to the characterisation procedure can lead to results where the tristimulus values of the white point are not correctly predicted. If such a characterisation were applied to an imaging system designed for visual display then this could be construed to be an undesirable feature and an effort might be made to correct it.

There are several references in the literature to methods that seek to constrain the white-point such that it is always 'correct'.[10] One such method has been applied in the model and the results show that, for some cameras, it leads to an improved overall median value, while in others it does not. On average, there is no change in the median value but the maximum value is lower by 0.5 CIELAB unit.

Subject Illumination

In the theoretical analysis presented so far, it has been assumed that the illumination on the colour test chart has a spectral power distribution similar to that of CIE Standard Illuminant D65. In practice, this is never going to be the case and so the model has been used to evaluate the effect of a number of different 'real' light sources. Results, in terms of the median of the CIELAB colour difference, together with the equivalent maximum value, are presented in Table 5 for a number of light sources.

It should be noted that the D65 simulator is a filtered tungsten source assembled for the practical work described in the earlier part of this paper. Its colorimetric match to Illuminant D65 is very good but it is not a spectral match and is hence metameric to Illuminant D65. The filtered tungsten source is a theoretical tungsten lamp with a Kodak Wratten 80B filter placed over it; a combination that might be used on a copy-stand. The D65 fluorescent lamp also has a spectral power distribution that is metameric to CIE Illuminant D65 and is representative of the lamp usually fitted in a viewing booth designed for daylight viewing. The three Fluorescent lamps, F2, F9 and F11, all have the same correlated colour temperature (approximately 4000 K) but represent three different spectral power distributions. They are drawn from a set of data recommended for use by the CIE. The data in Table 5, which are based on characterisation using the Macbeth ColorChecker, are for only two of the cameras, No. 3 and No. 7, and they show that there is some variation in the precision to be expected. This variation extends to 1.7 CIELAB units for Camera 3 and 2.8 units for Camera 7.

Table 5. The results of applying a linear characterisation model to the Macbeth samples using two different cameras and different subject illuminating sources.

	Camera 3	Camera 7
Illuminant	Median	Median
Illuminant D65	3.7	1.0
Electronic flash	3.3	1.3
D65 simulator	1.7	1.5
Filtered tungsten	3.8	1.2
Fluorescent D65	3.4	1.3
Fluorescent F2	2.8	2.5
Fluorescent F9	4.5	1.8
Fluorescent F11	2.5	2.8

Table 6. The results of applying a linear characterisation model to the Macbeth samples using two different cameras and different levels of subject illumination uniformity.

	Camera 3	Camera 7
Uniformity	Median	Median
0%	3.7	1.0
5%	3.8	1.3
10%	3.9	1.8
15%	4.0	1.9
20%	4.2	2.4
25%	4.7	3.4
30%	5.2	4.1

Table 7. The results of applying a linear characterisation model to the Macbeth samples using one camera and different infrared cut-off filters.

	Camera 7	
	Median	Median
No filter	6.2	21.3
+ ‘Hot’ filter	5.7	17.6
+ ‘Cut-off’ filter	3.7	9.0

Effective Uniformity of Illumination

The effective uniformity of illumination is the product of the real uniformity of the illumination of the test target, photometric properties of the objective and the spatial uniformity of the sensor. In order to make useful calculations it was assumed that the illumination in the corner of the Macbeth ColorChecker was less than that at the centre by a defined percentage and that the fall-off was linear with distance from the centre. From this value, a level of illumination for each patch could be calculated relative to unit value at the centre. The results of then performing the characterisation are given in Table 6, again for Camera 3 and Camera 7. It is seen that the camera that gives the best characterisation with totally uniform illumination, Camera 3, degrades more than that of Camera 7 which has a higher value when the chart is uniformly illuminated.

Infrared Cut-Off Filter

Table 7 gives some results using Camera 7 with no external infrared cut-off filter. This means that the long wavelength side of the red response is dictated by the red separation filter. Using a proprietary ‘hot filter’, attached to the lens improved the characterisation by only a small amount. Using a filter that gave a much sharper cut-off at 700 nm improved the result by a much greater amount both in terms of median and maximum values of colour difference.

Number of Colours

It could be inferred from the results described above that the greater number of colours leads to a ‘better’ characterisation. To investigate this the model based on the Munsell data-set was modified such that the 225 samples were placed in a random order and the top 100 values selected to perform the characterisation. This selection was repeated 100 times to give the corresponding 100 median values. The whole exercise was repeated selecting first 50 and then only 25 colours. The results show that the central tendency of the distribution of median values of colour difference is approximately constant and it is only the width of the distribution that changes. This supports the statistical fact that increasing the number of measurements available only lowers the uncertainty in those measurements but not their central tendency.

Conclusions from the Practical Experiments

The optimum characterisation matrix was found to be a polynomial in every case, the best result obtained giving a median CIELAB ΔE^* of 1.9 but with a maximum value of 6.1. This characterisation required a quadratic matrix, M, and the use of the 24 colour-patch Macbeth ColorChecker for characterisation, which was then applied to the same set of colours.

When applied to other sets of colours than those used for characterisation the optimum median CIELAB ΔE^* was 4.6 with a maximum of 17.5, and was obtained with half the Munsell set used for characterisation and the other half used as the test set of colours Once again the optimum characterisation required a quadratic matrix, m.

The characterisations proved less effective when applied to other colour sets than those used for characterisation.

Little advantage is gained by using a very large set of colour patches for characterisation Very nearly as good a performance can be achieved from characterisation using the more convenient Macbeth ColorChecker chart.

Conclusions from the Theoretical Model

Application of a computer model of the camera colour separation system shows that the results to be expected, expressed in terms of the median of CIE colour difference values, is very much camera dependent. This implies that the choice of separation filters is of paramount importance because the fundamental spectral responsivity of the light sensitive chip is not likely to vary significantly between cameras from different manufacturers. Indeed, some may source their CCD chips, for example, from the same manufacturer.

The uniformity of the subject illumination is a strong contributor to the characterisation process. The non-uniformity that is almost inevitably present in the camera-exposing situation must be factored out as part of the characterisation procedure. Failure to do this can give rise to a 2 – 3 ΔE^* increase in median colour difference.

The choice of light source does not represent such a significant variable but, in the real situation where comparison of the effects of different light sources in unlikely to be realistic, a source that is minimally metameric with Standard Illuminant D65 seems a good choice if CIE D65 colorimetry is required.

The issue concerning the choice of test target and the number of colours in that target is unresolved. The main criterion that should be adopted is to choose test colours that are similar to those likely to be measured. If a general colour-measuring instrument is required then this may not be a simple choice.

Acknowledgements

The practical aspects of this work were carried out as part of a LINK Project with funding from the Ministry of Agriculture, Fisheries and Food. The authors wish to acknowledge the constructive discussions held with other members of the project team. Dr. Pointer wishes to acknowledge the partial support of the National Physical Laboratory in the theoretical investigation into the parameters affecting the use of electronic cameras as colour measuring devices. The authors are also indebted to Dr Po-Chieh Hung, of the Konica Corporation, Japan, for providing some of the camera spectral responsivity data used in the theoretical analysis.

References

1. CIE Document 15.2, Colorimetry, CIE Central Bureau, Vienna, 1986.
2. Holst, G.C. CCD Arrays, Cameras and Displays, SPIE Optical Engineering Press, Washington, 1996.
3. Sproson, W.N. Colour Science in Television Display Systems, Adam Hilger, Bristol, 1983.
4. Hong, G., Luo, M.R. and Rhodes, P.A. A Study of Digital Camera Colorimetric Characterisation Based on Polynomial Modelling, Color Res. Appl. (2000), In press.
5. Thomson, M.G.A. and Westland, S. Colour Camera Calibration by Parametric Fitting of Sensor Responses, Color Res. Appl. (2000), In press.
6. Connolly, C., Leung, T.W.W. and Nobbs, J.H. Colour Measurement by Video Camera, J.Soc.Dyers Colourists, 111, 373 (1995).
7. Simpson, M.L. and Jansen, J.F. Imaging Colorimetry: A New Approach, Applied Optics, 30, 4666 (1991).
8. Spratlin, T.L. and Simpson, M.L. Color Measure-ments using a Colorimeter and a CCD Camera, Proc. SPIE Color Hard Copy and Graphic Arts, 1670, 375 (1992).
9. Wu, W., Allebach, J.P. and Analoui, M. Imaging Colorimetry Using a Digital Camera, J. Imaging Sci. Technol., 44, 267 (2000).
10. Finlayson, G.D. and Drew, M.S. Constrained Least-Squares Regression in Color Spaces, J. Electronic Imaging, 6, 484 (1997).
11. CGATS/ANSI IT8.7/2 Graphic Technology - Color Reflection Target for Input Scanner Calibration, 1993.
12. Hunt, R.W.G. Measuring Colour, 3rd Ed., Fountain Press, Kingston, 1998.
13. McCamy, C.S., Marcus, H. and Davidson, J.G., A Color Rendition Chart, J. Appl. Phot. Eng., 2, 95 (1976).
14. Scion Image, see www.scioncorp.com.
15. Hunt, R.W.G. The Reproduction of Colour in Photography, Printing & Television, 5th Ed., Fountain Press, Kingston, 1995.

Biography

Dr. Michael Pointer worked for many years in the Research Laboratory of Kodak Limited in England where he contributed to the development of colour appearance models and their application to photographic colour reproduction. The work to be presented in this paper was carried out in The Imaging Technology Research Group of the University of Westminster in Harrow as part of a government / industry LINK Scheme.