Digital Camera Color Calibration and Characterisation

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Abstract

A description and analysis of analytical methods to between a digital camera device color space and device independent color spaces under varying lighting conditions will be presented. This approach has been evaluated in the production of an art paintings catalogue.

Introduction

As part of the MARC project funded under the European Esprit III framework, a digital color camera was designed for the purpose of acquiring digital images of paintings to be later used in the production of art catalogues. The goal of the project was to provide a completely digital path between the painting on the wall to the print in the book. The image acquisition subsystem was to provide a color specification of the paintings in CIE Lab space under D50 illumination. Since this type of illumination was not available for photography, methods had to be evaluated to convert the image data to this type of illumination. This data was then taken and printed using calibrated separation techniques. This paper deals with the color calibration and characterisation of the acquisition system.

The camera utilised is based on the Kontron ProgRes 3012, which can take images up to 3072×2320 color pixels at 12 bit depths per color channel. For this project it was modified by adding a 2 dimensional stepper motor driven translation stage, which would enable it to cover a 60×60 mm image plane yielding a total of about 20000×20000 pixels.[1,2]

Since the spectral sensitivity of the color CCD was inalterable, the effect of the infrared cutoff filter in front of the camera on color accuracy was investigated. The theoretical response of the camera was calculated by multiplying a set of spectra derived from the NCS catalogue, the Kodak Q60, the Macbeth color checker and other charts with the camera spectral sensitivity, the transmission of the infrared filter and an illumination spectrum. The camera data was then converted by a matrix to CIE-XYZ values and compared to the theoretically exact XYZ values. The matrix was optimised to minimize the differences in Lab space. This was tried for several different infrared filters and the best one chosen. The results were different for daylight and tungsten type illumination. A thicker filter was required for tungsten, but since we did not want to exclude this type of lighting, a compromise had to be taken.

The color response of the camera prototype was tested on two reflectance color charts under 3200 K tungsten light and HMI lamps. The charts were a Macbeth color checker (24 colors) and a chart (MARC chart, 112 colors) specifically designed to contain colors used in paintings. The spectral reflectancy of both charts was measured and converted to Lab values under D50 illumination. In order to study the color accuracy of the camera, we used analytical (i.e. polynomial) type of mappings to convert the raw camera data to XYZ values. We chose analytical against 3D lookup table mappings for 3 reasons:

(1) Analytical mappings can have few parameters and thus work nicely on a limited set of calibration colors.
(2) They interpolate smoothly between the set of calibration colors and also have extrapolatory powers outside of the calibration gamut.
(3) They give an indication of the camera color accuracy, since the color errors can usually be made arbitrarily small on a given set of colors with the large number of parameters in 3D lookup table mappings.

We investigated linear (i.e. matrix), second and third order polynomial mappings with 12, 30 and 60 degrees of freedom, respectively. The higher order mappings generally do not scale linearly with brightness, i.e. doubling the camera RGB values don't lead to double XYZ values. Since we expected the camera to behave linearly, variants of the second and third order mappings were studied, which have linear properties in terms of brightness, although they do not behave linearly in the hue and chrominance plane. Due to this constraint their number of degrees of freedom was lower, i.e. 21 and 33, respectively.

We will show the statistics of CIE-Lab errors for all colors of the MARC chart under HMI illumination after optimising the set of parameters to obtain a minimal RMS E. This was done for all 5 mappings. The error sets were spaced apart.

The RMS E for the 12, 21, 30, 33 and 60 parameter sets were 4.4, 3.8, 3.6, 3.6 and 3.1 respectively. As is expected, the higher number of degrees of freedom lead to an increased fit accuracy. As a surprise came, that the number of colors, which had large errors decreased strongly with the higher order mappings, i.e. much more, than could be expected alone from the total performance in terms of RMS E's.

Even successful calibrations can fail miserably under a change of illumination. Some of the paintings for the catalogue had to be imaged in the gallery since they were to large to be transported to a studio. Even though it was generally attempted to keep the lighting as similar as possible extra lights had sometimes to be added to strengthen the illumination. Also stray sources of lighting, e.g. colorful carpets, the ageing of lamps, usage of different sets of polarizing filters etc. had to be compensated for.

The easiest way to account for illumination changes is a white balancing operation, where the camera red, green and blue values are each multiplied by different factors. In order to get a quantitative measure for the accuracy of this procedure we white balanced an image of the Macbeth chart under HMI illumination and optimised a matrix type of mapping from this. The white balance values were taken from the white patch of this chart. The resulting RMS E value were in this case 2.7. The errors from a white balanced Macbeth chart under 3200 K illumination corrected with the same matrix rise to 6.1. If a matrix is directly optimised for 3200 K illumination, the errors are much lower: E = 3.4. These results indicate, that a simple white to achieve the best color quality in the MARC project a different scheme was chosen. Two possibilities were tested:

(1) To image a MARC color chart beside each painting and perform a full 60 parameter color correction separately for each image.
(2) To image a Macbeth color chart beside each painting, perform a matrix correction separately for each image and then apply a post optimisation with 60 parameters, which is the same for all images. A full 60 parameter optimisation is not possible with limited set of colors on a Macbeth chart. This can be seen as a case, where the white balancing operation is replaced by a matrix "white balance".

In practice procedure (1) proved to be difficult, since the surface of the color chart was somewhat shiny and produced often specular reflections under otherwise optimal lamp positions. These reflections prohibited accurate color calibrations. For the final imaging run we opted the other method.

The following measurements quantify the results of this procedure.

(1) The white balance case:

(a) Optimisation with 60 parameters of a white balanced MARC chart under HMI: fs20 E = 3.1

(b) Treatment of white balanced MARC chart under 3200 K with the 60 parameter correction from (a): RMS E = 8.6

(2) The matrix white balance case:

(a) Optimisation with matrix of the MARC chart under HMI: RMS E = 4.4

(a') Post optimisation of image from (a) with 60 parameters: RMS E = 3.1

(b) Optimisation with matrix of the MARC chart under 3200 K: RMS E = 5.9

(b') Post optimisation of image from (b) with 60 parameter set from (a'): RMS E = 4.7

It is not surprising, that optimisations from images under HMI illumination work better than optimisations from 3200 K images as is evident from comparing cases (2a) and (2b), since the target values for all optimisations were calculated with D50 illumination from the spectral data of the chart. HMI illumination is much closer to a D50 spectrum, than to a 3200 K spectrum. Interesting is the severe degradation of color quality if a simple white balance operation is used to accomodate for the changes in lighting as comparison of the cases (1a) and (1b) show. It is obvious, that the 60 parameter optimisation depends strongly on the illumination spectrum.

A much better performance of the post optimisation process is obtained, if instead of a white balance a matrix operation is used to preprocess the image data as can be seen by comparing case (1b) to case (2b'). The drawback is, that this requires taking an image of a Macbeth chart beside the painting.

In practice, imaging charts alongside with paintings for color characterisation is somewhat awkward. Also care must be taken to avoid that additional errors are introduced due to lens vignetting especially at the border of images and spatially inhomogeneously colored lighting. On the other hand, color charts can be used to monitor the printing run.

It should be mentioned, that the attempt to calculate D50 image values from a 3200 K image is somewhat adventurous. This strong illumination change serves here only to illustrate the effects more clearly. In the painting acquisition runs only HMI lamps were used, although slight illumination changes during the run could not be ruled out completely. Furthermore the achieved color accuracy was reduced somewhat by the earlier mentioned imperfections of the MARC color chart.

The described approach was successfully used in the production of an art catalogue. Visual comparison of the catalogue images to the original paintings showed a strong improvement in color fidelity over non calibrated approaches. Further processing steps, e.g. color separation, could be performed without reference to the acquisition procedure and led to a very faithful reproduction of the paintings, once the characterisation of the printing press had been mastered. The effects of illumination differences could be effectively accounted for by a closed loop control with a color chart.

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References

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