Spectral Characterisation of COTS RGB Cameras Using a Linear Variable Edge Filter

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ABSTRACT

The spectral response function of a camera maps the relative sensitivity of the camera imaging system as a function of the wavelength of the light. The spectral response function of the colour channels of a commercial-off-the-shelf (COTS) Red/Green/Blue (RGB) camera is often unknown and not typically provided by the manufacturer of the camera. Knowledge of this response can be useful for a wide variety of applications such as simulating animal vision, colour correction and colour space transformations of the images captured by the camera. COTS cameras are widely used due to their low cost and ease of implementation. We investigate a method of using a Linear Variable Edge Filter (LVEF) and a low-cost spectrometer to characterise an RGB camera. This method has the advantage over previous methods in the simplicity and small number of measurements needed for spectral characterisation. Results are presented for three cameras: a consumer-level digital SLR and two point-and-shoot consumer grade cameras, one of them being an underwater camera.

Keywords: Camera Spectral Characterisation, Digital Photography, Linear Variable Edge Filter, Radiometric Calibration

1. INTRODUCTION

For a variety of computer-vision based applications, knowledge of the spectral response of the camera is often desirable, but for Commercial Off The Shelf (COTS) Red/Green/Blue (RGB) cameras this information is rarely available. COTS cameras are often an attractive choice due to their low cost, prevalence and ease of system implementation.

The spectral sensitivity of a camera is due to a combination of physical optics and software processing factors: the spectral response of the imaging sensor, the tricolour filters in front of the sensor and the on-board camera processing. However due to differences in materials, manufacturing, optics and back-end processing, different cameras can respond differently to a given array of incoming light.

The applications for which a known spectral response of imaging sensors is useful vary greatly. Research into animal vision[1] has found that knowing the spectral characteristics of the RGB camera allowed high resolution scenes to be captured and converted into an animal's colour space. Previously they had used a spectrophotometer which although high in spectral resolution lacked in spatial resolution. Along a similar vein knowing the camera's spectral characteristics allowed a camera image to be mapped accurately into the CIE (Commission internationale de l'éclairage) standard colorimetric observer,[2] which is designed to approximate human vision. The spectral response is also useful for colour processing, colour correction and consistency applications[3,4,5] as well as with the design of photography based experiment setups.[6] There is also a use in the display of products online and how they will appear on the customers computer; it is thought that the colour of a product is thought to be very important in a customer's decision to purchase an item. So modelling how it will look under different lighting conditions and colour spaces is important.[3] Colour scanners have also been characterised,[7] which is important with the translation of image data between colour spaces on different devices such as monitors and printers.

This paper outlines the use of a Linear Variable Edge Filter (LVEF)[8] to easily characterise the spectral response of several COTS cameras, including the derivation of the transmission properties of the LVEF and normalisation of the results to make the response curves invariant to the light source spectral distribution.

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2. PREVIOUS WORK

One of the issues with spectrally characterising trichomatic cameras is knowledge of the light intensity response characteristics. Vora *et al.*[10] used a method of photographing a target with different exposures for defining the linearity of photometric response. Grossberg and Nayar[11] developed a method using Principal Components Analysis (PCA) to derive constraints from the intensity response of a large number of cameras, which was then used to determine the response function for a new camera. It was found that many cameras exhibited a non-linear intensity response, but this could be easily corrected by evaluating a gamma correction curve.

An accurate method of chromatic characterisation is to use a monochromator to generate a narrowband light source which is imaged off a reflectance standard into a camera under test and a spectrophotometer.[12] Vora *et al.*[12] presented a processing technique using Wiener estimation methods to correct for errors due to the non-zero width of the spectral power distribution of the narrowband light source. The monochromator method is defined as the standard for the European Machine Vision Association (EMVA).[13] An alternative method for generating monochromatic light is through the use of a liquid crystal tunable filter in front of the camera which can tune into a specified narrow frequency (bandwidth = 10nm).[4] The disadvantage of the monochromator approach, despite the high resolution achieved, is that it requires costly hardware or needs strictly controlled acquisition conditions.[4]

A variation of the monochromator technique is seen in Mauer *et al.*[14] where 39 interference filters were used to characterise the spectral response of the RGB camera. The technique does not provide as high a resolution of characterisation as the monochromator technique, but did produce good results. This would be a slow process as at least 39 measurements need to be taken.

A quick method is seen in Finlayson *et al.*[15] who devised a quadratic programming technique to gain the sensitivity response by imaging a Macbeth colour chart* and gathered the spectral reflectance profiles of the lighting and Macbeth colour chart swatches. These measurements of the swatches from the camera and the spectral measurements impose a set of constraints which naturally form a series of linear inequalities which lends itself to a quadratic programming routine. The process could also be further simplified by using a pre-existing Macbeth colour chart reflectance library.[16]

The quadratic programming technique[1,16,5] works well, requiring only one picture of the colour chart for each illuminant type. There are however two issues with this technique: the first issue is that they assume that the lighting is identical between the photograph of the chart and the spectral measurements of the chart. This may not be the case if using a spectral library.[16] The second issue is that the color chart is made for photography applications, and so the colour panels are not evenly distributed in the spectral domain.[4]

The advantage of our method is the simplicity of the experimental setup and the small number of measurements needed for the characterisation. Our motivation in characterising COTS cameras is for the application of colour correction in underwater environments. Knowledge of the camera response allows spectral data of a higher dimensionality to be accurately down-sampled into the trichromatic domain of most COTS cameras. This will also help in allowing data of the same underwater area taken on different cameras to be chromatically comparable.

3. METHODOLOGY

Our approach requires a broad spectrum light source such as the sun or an incandescent light bulb, a Linear Variable Edge Filter (LVEF),[8] a dark box, a Spectralon reflection target, a spectrometer and the RGB camera under test. The light source is quite important; lighting sources such as fluorescent and Light Emitting Diode (LED) lights should be avoided due to their sharp spectral peaks and large troughs[1,17,18]

The LVEF is mounted on one side of the dark box and the camera under test on the other looking through the LVEF. On the outside of the box next to the LVEF, a Spectralon target is placed so as to reflect light from the light source through the LVEF into the camera. The dark box is quite important; this cuts out stray light which may reflect off the back side of the LVEF into the camera. The LVEF is very reflective on both sides, so stray light will greatly influence the results.

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*Xrite Photo ColorChecker Classic http://xritephoto.com/ph_product_overview.aspx?ID=1192

The spectrometer is mounted so as to measure the reflectance of the light source upon the Spectralon target. This gives us the spectral profile of the light before it passes through the LVEF. The spectrometer should acquire a spectra of the light at the same time as the RGB image is acquired. The spectrometer used was an Ocean Optics STS-VIS Micro-spectrometer with 100μm slit width, 6nm resolution (FWHM - Full width at half maximum) and a spectral range of: 350-800nm. The setup can be seen in Figure 1.

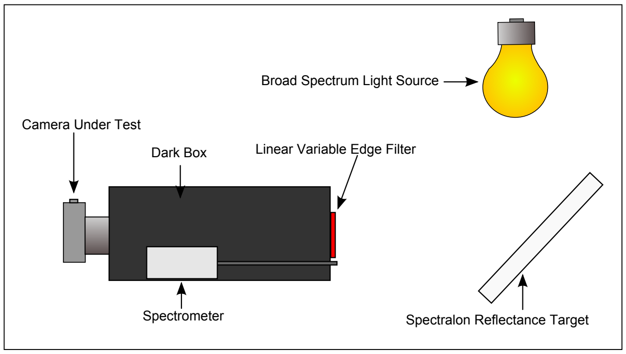


Figure 1. Camera characterisation experiment setup

To gain the unnormalised spectral response of the RGB camera, an image of the target is taken through the LVEF. Most point-and-shoot cameras are unable to save raw photographs so *Day light* white balance is the best to select. An exposure was chosen such that the image was not over exposed. Due to geometric lens effects, the signal around the outer edges of the image plane is attenuated (vignetting) where the fall off is proportional to the fourth power of the cosine off the off axis angle.[5] To minimise these effects we use only the central portion of the image.

The LVEF is a spatially varying bandpass optical filter. At one end it passes 380nm (near UV/Violet) and at the other end 745nm (near IR), then linear steps in frequency spatially in between, (see Figure 2).

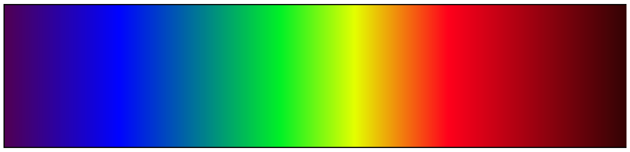


Figure 2. Linear Variable Edge Filter - pass band frequency changes along the horizontal spatial dimension

The transmission of the LVEF is non-linear across wavelengths and varies between 50-58% between 475nm and 745nm and drops down to 32% at 400nm. The transmission of the LVEF can be seen in Figure 3(a). The transmission was obtained by incrementally moving a spectrometer along the frequency axis of the LVEF. On the other side of the LVEF was a spectralon reflector, illuminated by incandescent photography lights. These lights were desirable because of their good distribution of energy across the visible spectrum, (see Figure 3(b) for the spectra of the reference light source). At each stop the peak of the transmission and frequency was measured, 12 locations were measured along the length of the LVEF.

To accompany the spectral sensitivity response of the camera system, the intensity response was also gathered. We found the consumer grade *point-and-shoot* cameras applied a gamma curve (non-linear response) to the received image. Whereas the SLR which was shooting in RAW exhibited a linear intensity response. To determine the intensity response we imaged a calibrated Spectralon 50% reflector over different shutter speeds.

For validating the camera model a variety of colour objects needed to be imaged with the RGB cameras and their reflectance measured with the spectrometer. We used 55 different paint sample swatches which varied chromatically across the visible spectrum. The paint sample swatches had the advantage over artificially created printed swatches in that they were made of well mixed paint pigments as opposed to four discrete inks (Cyan, Magenta, Yellow & Black - CMYK) in the case of digital printing. The spectrum of the illuminating light source was also measured (Figure 3(b)).

3.1 Processing

To acquire the unnormalised spectral response of the RGB camera a row vector was obtained from each of the chromatic channels of the acquired image. To reduce noise, the mean of the imaging sensor values perpendicular to the frequency axis was measured. For each channel the response of the imaging sensor colour filter was obtained with the limits of 380nm to 745nm due to the limits of the LVEF.

The LVEF inherently has some leakage or blurring at any point, whereby it will pass a peak frequency but with a Hann window[19] like shape passing neighbouring frequencies. The width of this window was found through the use of a red laser; the frequency width of the laser was measured without the LVEF and then measured through the LVEF. The window was found to have a width of approximately 17nm. To reconstruct the effect of frequency blurring we constructed a Hann window. The window is normalised such that the sum of the window is equal to 1, this is to maintain the power density of the spectra.

$$F_w = \frac{h_w}{\sum h_w} \qquad\qquad \sum F_w = 1 \tag{1}$$

where: F_w is the LVEF normalised Hann window, h_w is a Hann window of width 17.6nm.

The light received through the camera system is a combination of the light source, the LVEF transmission properties, the cameras' Bayer filter and the camera sensors' spectral sensitivities. We define the spectral sensitivity of the camera in the wavelength, λ, as $C(\lambda) = \beta(\lambda)\sigma(\lambda)$, where $\beta(\lambda)$ is the three channel Bayer filter spectral transmission properties and $\sigma(\lambda)$ is the transmission properties of the imaging sensor at wavelength λ. We can then write the spectrum of light received at each band b as:

$$S_b(\lambda) = C(\lambda)(F_w \cdot (F_t(\lambda)L(\lambda))) \tag{2}$$

where: $F_w(\lambda)$ is the smoothing window of the LVEF, $F_t(\lambda)$ is the transmission of LVEF. $L(\lambda)$ is the spectra of the light being reflected off the spectralon target into the LVEF. λ is the wavelength range of the LVEF.

We may also use our spectral response function to convert spectra into the camera's RGB colour space. The RGB response R_b to a certain spectra of light is the integral over all the K measured wavelengths of light of S_b for each band b (red, green & blue):

$$R_b = \sum^{K} S_b(\lambda) \tag{3}$$

3.2 Validation of Model

To validate the camera response model we utilise the quadratic programming method as seen in Pike.[1] This solves for $C(\lambda)$ in the camera model from Pike *et al.*:[1]

$$R_b = \sum^{K} \rho(\lambda)C(\lambda) \tag{4}$$

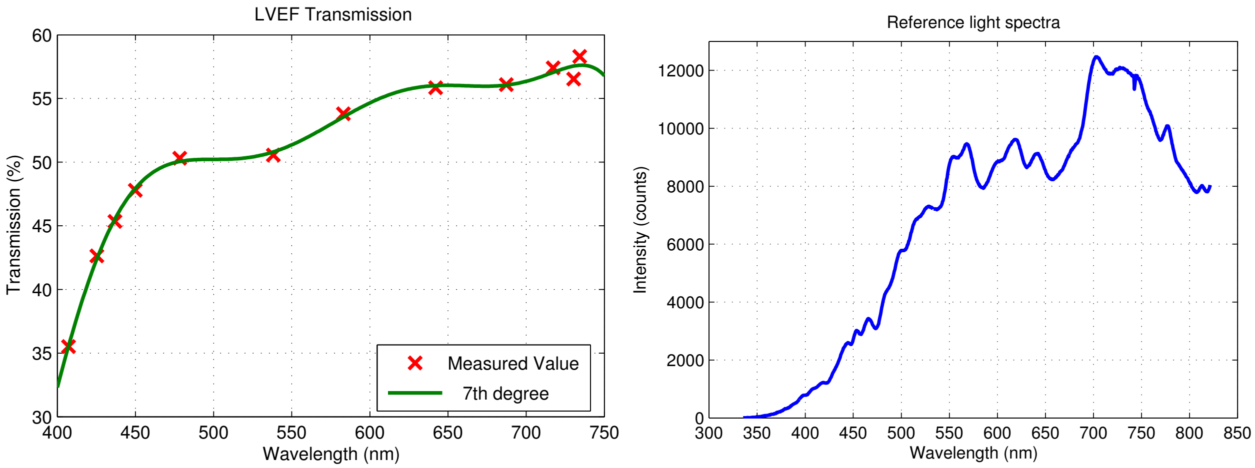
where $\rho(\lambda)$ is the radiance of the each of the colour swatches of the macbeth colour chart, which was measured with a spectrometer. $C(\lambda)$ was the camera model (Equation (2)) which refers to the spectral sensitivity for the bth RGB colour band, taking into account the transmission properties of the lens, colour filters and onboard processing. R_b was a RGB value gathered from each swatch from an image of the Macbeth colour chart taken by the camera under test.

To compare our LVEF method to the *Pike*[1] method, we used the validation data set consisting of 55 different colour swatches. The aim was to accurately reproduce the RGB value of these swatches from the measured spectral reflectance. The reconstructed RGB value from our LVEF model is derived from R_b using the equation in (4).

The chromatic accuracy was an important aim of this research, so to compare the performance of our LVEF method to the Pike method we used a Euclidean distance metric in a chrominance only colour-space. We chose the $YCbCr$ colour-space and negated the Y (luminance component).

4. RESULTS

In this section we present the results for the intensity response (section 4.1), the spectral response (section 4.2) for the three cameras under test. In section 4.3 we validate our model by comparing to the Pike method.[1]



(a) (b)

Figure 3. (a) Transmission of the Linear Variable Edge Filter. Note: 7th Degree refers to the fitting of a 7th degree polynomial to the measured points (shown in red). (b) Spectra of the light incident on the Spectralon reflectance target.

4.1 Intensity Response

Figure 4 illustrates intensity response for the *Nikon D5000* with the images taken in RAW mode; this shows the camera exhibited a linear intensity response. Whereas the intensity response of the *Canon Powershot A2000* and the *Olympus* μ*Tough 8000* are clearly nonlinear (Figure 5 & 6). The scale of the intensity response for the *Nikon* is greater than the other two cameras due to the *Nikon* capturing the photo in 16-bit resolution as opposed to the 8-bit resolution of the *Canon* and *Olympus*. The Red, Green and Blue channels are offset due to the colour of the lighting, as it had quite a yellow/red bias (Figure 3(b)). The intensity response curves (Figures 4-6) are show with the error bars showing the standard deviation of the measurements.

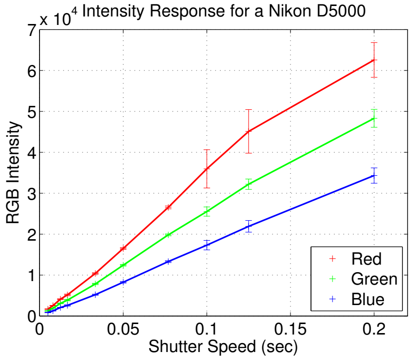


Figure 4. Intensity response of a Nikon D5000 DSLR

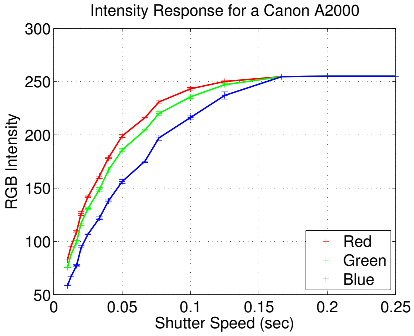


Figure 5. Intensity Response of a Canon Powershot A2000

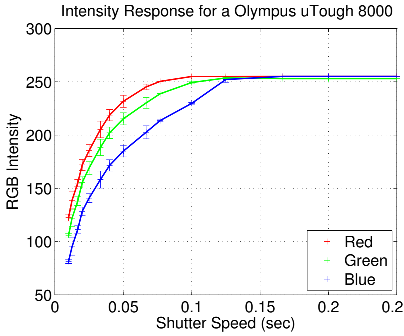
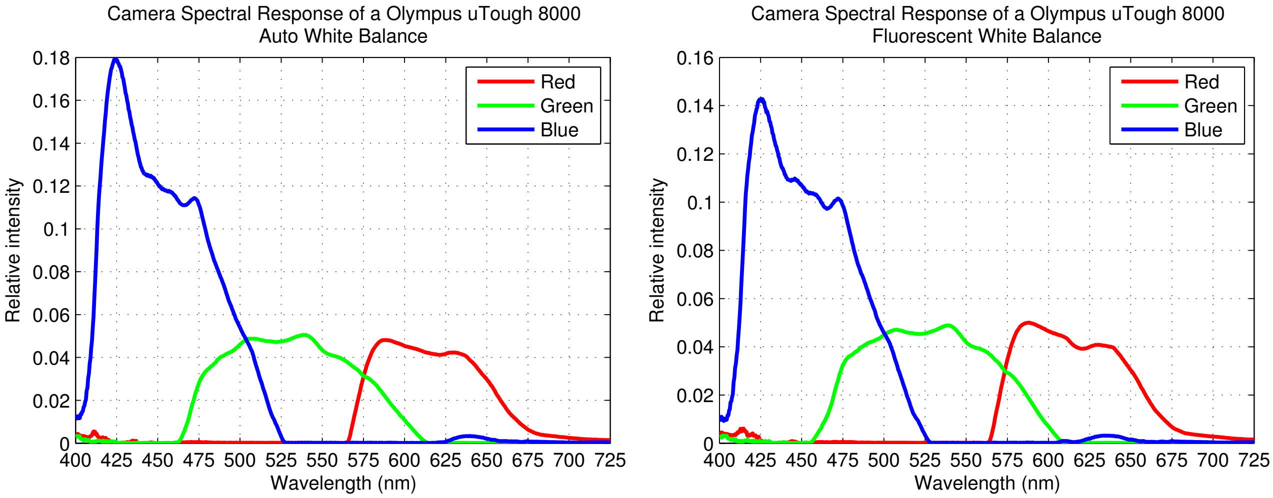


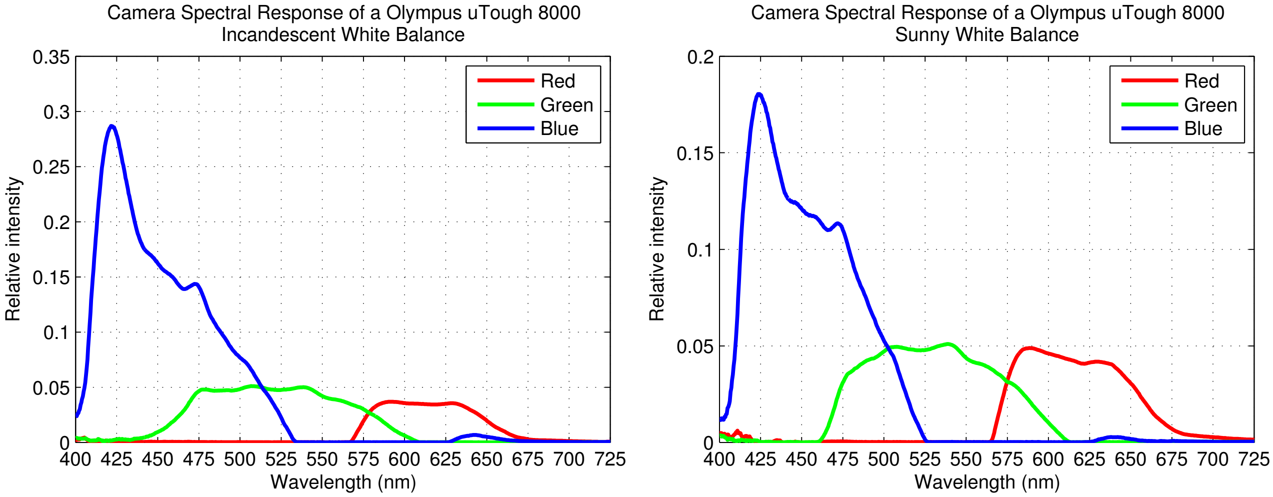
Figure 6. Intensity Response of an Olympus μTough 8000

4.2 Spectral Responses

The spectral response graph for the *Nikon D5000* is shown in Figure 4.2. The *Canon Powershot A2000* response is shown in Figure 4.2 showing the *Sunny* white balance response. The spectral response of the *Olympus* μ*Tough 8000* over four different white balances is shown in Figure 7. The vertical axis of the spectral responses are scaled such that the cross product of an imaged surface with the spectral response will result in an accurate reproduction in the camera's RGB space for a particular shutter speed. This shutter speed is what was used when generating the spectral response. Provided the nonlinearity of the camera is known, the spectral response may be scaled to accommodate different exposure levels.

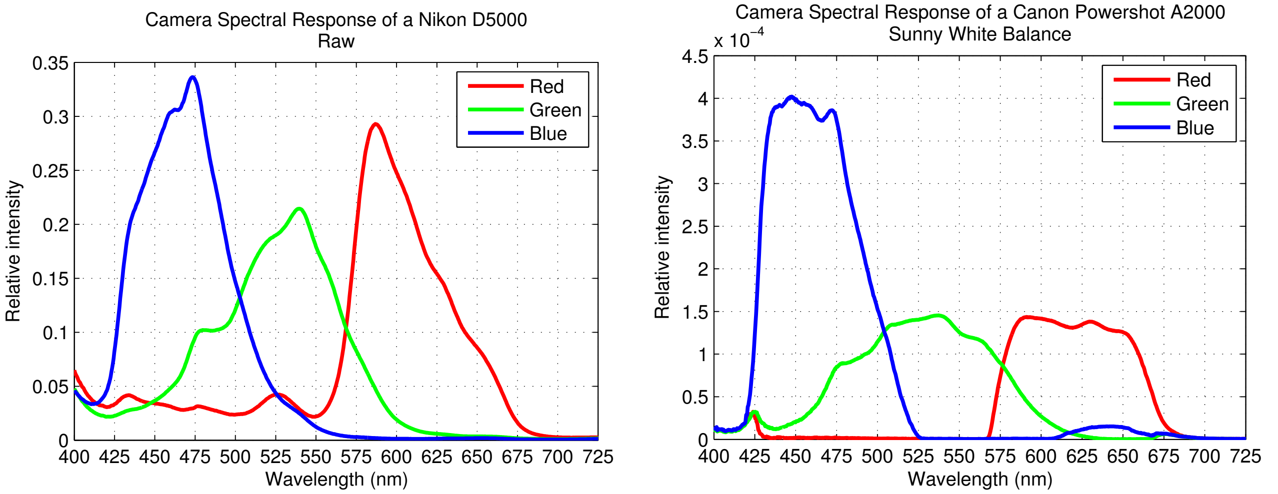


(a) Auto White Balance (b) Fluorescent White Balance



(c) Incandescent White Balance (d) Sunny White Balance

Figure 7. Spectral Response of Olympus μTough 8000



(a) Spectra response Curves for a Nikon D5000 DSLR (b) Spectra response Curves for a Canon PowerShot A2000

Figure 8. Spectral response functions for the Nikon and Canon cameras

4.3 Validating the Model

Using the quadratic fitting method from *Pike*[1] we were able to generate spectral responses for all the cameras under test. The spectral response for the *Nikon D5000* derived from the *Pike* method is shown in Figure 9. To compare the performance of our method we determine the Euclidean distance of the chrominance components in the YCbCr colour-space. Our LVEF method performance is shown in Figure 10(a) and the Pike method performance is show in Figure 10(b), with a table of the mean and standard deviation of the errors shown in Table 1. These results show our method is performing better than the *Pike* method. The RGB reconstruction is shown in Figure 11 this shows a visual example of the RGB reconstruction performance of the two methods.

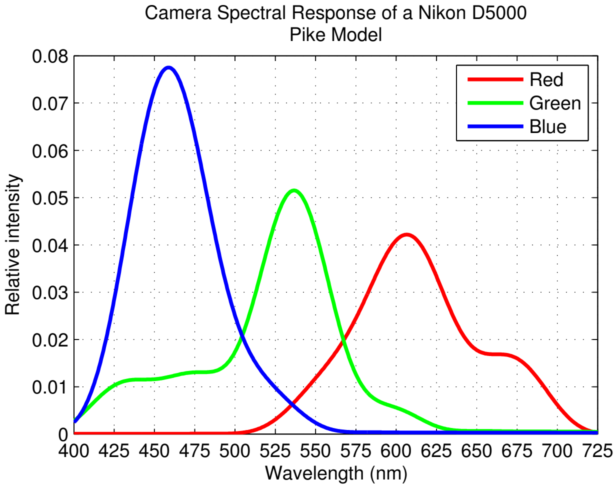
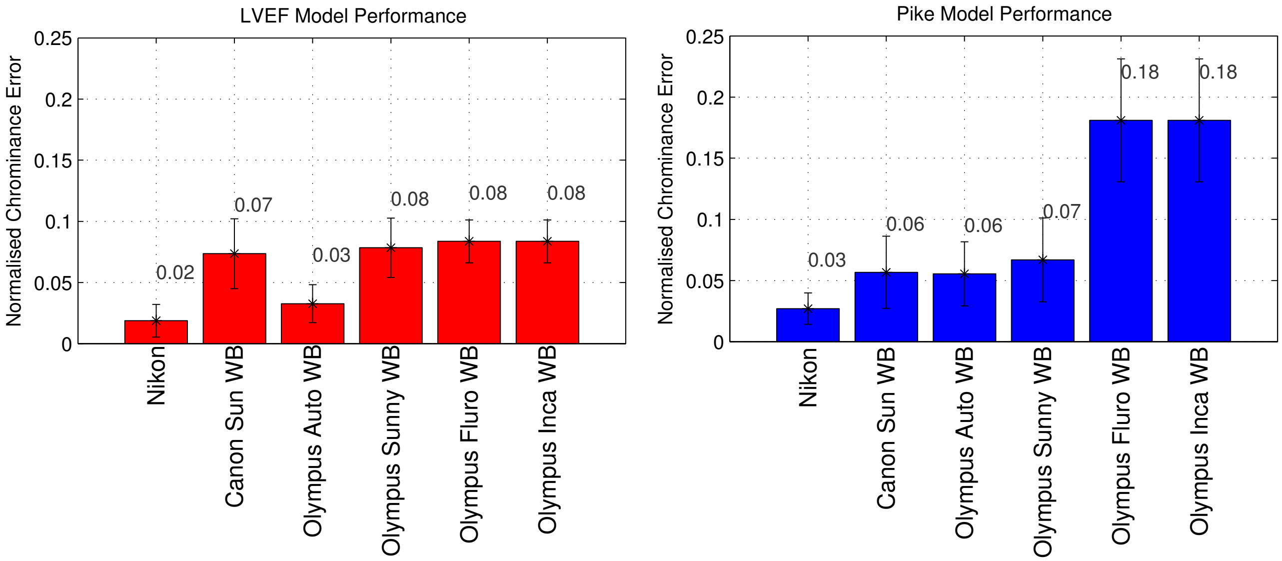


Figure 9. Spectral response curves generated using the *Pike* method[1]

Method	**Mean**	**Standard Deviation**
LVEF	0.06	0.0276
Pike	0.0967	0.0659

Table 1. Performance of the LVEF method vs. the Pike Method



(a) LVEF method error

(b) Pike method error

Figure 10. Chrominance RGB reproduction error for the LVEF and Pike methods for the different cameras and white balances. The error bars define the magnitude of the standard deviation. Note: Nikon error has been scaled from 16bit to 8bit for comparative purposes.

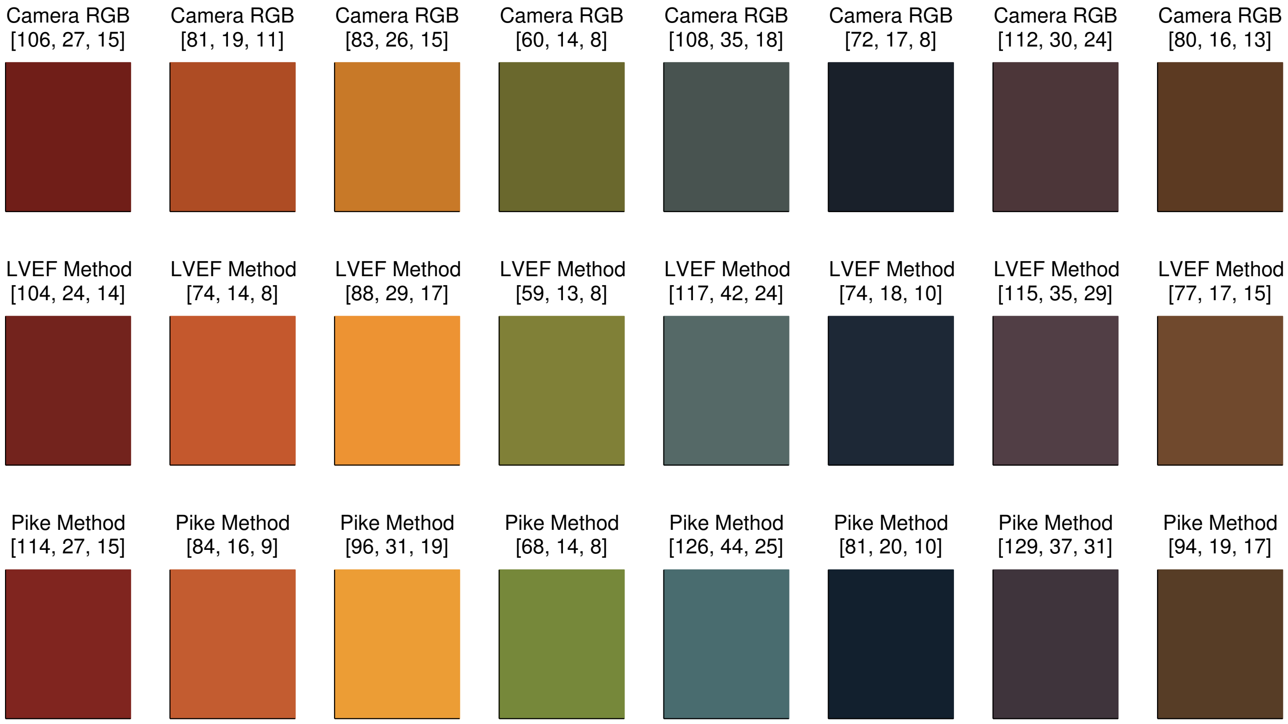


Figure 11. RGB reconstruction from spectral measurements of Colour Swatches. The top row is the swatch as seen by the camera, these are the truth measurements; the reconstruction process is attempting to create a RGB coordinate as close to what the camera would image. The second row is the RGB reconstruction using the model generated by the LVEF method and the 3rd is the RGB reconstruction using the model generated by the Pike method. Above each swatch is the RGB coordinate of the swatch.

5. DISCUSSION

The LVEF technique produced high spectral resolution results in a fast and low cost way. All the method required was a spectrometer reading of the light source, and a single photograph of the Spectralon reflector through the LVEF. The chromatic reproduction performance of our method was found to be slightly better compared to the quadratic fitting method presented in *Pike*[1]. Our method also had the advantage over the *Pike* method in that our results produced higher spectral resolution.

The limitation of our method was that it was unable to characterise the intensity response simultaneously with the spectral characterisation process. As most consumer grade cameras apply a non-linear gamma curve on the received image, knowledge of the intensity response is also required. This was however easy to acquire by imaging the same object under the same illumination but at different shutter speeds.

The other limitation of the LVEF method was that it treats the camera as a black box and does not reveal the additional processing or gamma correction which may be occurring. However as shown in the results from the *Olympus μTough 8000* (Figures 7) we were able to uncover some processing due to different white balances. We were also able to determine the gamma curve which is being applied using the intensity response method previously mentioned.

6. CONCLUSION

We have presented a new technique which provides a quick method of characterising the spectral response of three different COTS cameras. This differs from previous techniques which have only focused on high-end cameras and have disregarded the effect of on-board processing. Previous techniques have also required more than one measurement for spectral characterisation and have been costly or low in spectral resolution. We are able to produce high spectral resolution results in a simple, fast and low cost way which is able to characterise the spectral sensitivities of a COTS camera through the entire optics, sensor and on-board processing path.

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