Introduction: Color Theory

Human sight depends on light entering the eye and hitting a light detector on the retina. However, humans are only sensitive to light inside the range of wavelengths [380nm, 800nm] [1]. Digital cameras work similarly to the human eye as they detect intensities based on the amount of light that hits the detectors in the camera. Non-invasive imaging has advanced to from one panchromatic band or three-color bands covering the visible spectrum to many bands extending the near-infrared (NIR) (>800nm) and near-ultraviolet (NUV) bands (<380nm) [3].

Color can be broken down into hue, saturation, and lightness (or value). Hue is the pure color (like red, green, or blue) that makes up the dominant component of the color. Saturation is the purity of the color. Red is more saturated than pink. Lightness is the intensity of the reflectance of the color ranging from the minimum for pure black the maximum for pure white [1].

The color of an object depends on how the object reflects incident light, with respect to wavelength, over the visible region of the electromagnetic light spectrum. The color of a particular object can be predicted if its reflectance with respect to wavelength can be modeled. Humans are accustomed to using color as one of the ways to distinguish and identify materials and objects. [2].

In addition to reflecting color, the materials that make up objects in a scene reflect, scatter, absorb, and emit electromagnetic radiation. These reflections are characteristic of their molecular composition as well as their macroscopic scale and shape. Electromagnetic radiation read at the sensor of an imaging system is measured at many wavelengths and over a broad spectral band. The resulting spectrum can be used to identify materials and discern between different classes of material [3].

The Kubelka-Munk Pigment Model

Paint is a common material used to cover surfaces. Paint is made up of small colored particles suspended in a mostly transparent and colorless base. These small colored particles are called pigments [4].

The Kubelka-Munk Pigment model is a mathematical model used to describe the reflectance of opaque samples. The model examines the absorption and scattering occurring in a colored sample of fixed thickness. It is applied wavelength-by-wavelength...
through the electromagnetic spectrum. Four factors determine the reflectance of the sample at each wavelength. These include an absorption spectrum, a scattering spectrum, the sample thickness, and the reflectance spectrum of the substrate or backing. The Kubelka-Munk model assumes the illuminating light to be collected and the light penetrating the sample to be scattered. Light can be scattered in any direction, but the model considers two net fluxes in the upward and downward direction [2].

The Kubelka-Munk model presents some limitations. One limitation of the model is that it is based on the assumptions that paint is homogeneous and that pigments are uniformly sized spherical particles, which is not always the case. Another limitation is the model’s dependence on the combination of pigment and medium. Different pigment and medium combinations have different coefficients for scattering and absorbing light. Other necessary but limiting assumptions the model makes include that the substrate is planar and that paint is of uniform thickness [4].

**Hyperspectral Imaging**

RGB cameras divide the light spectrum into three overlapping image slices (red, green, and blue), which produces images similar to human vision. Hyperspectral images can process information across the electromagnetic spectrum. Hyperspectral imagers produce spatial and spectral representations, as they divide the spectrum into many more image slices (including UV and infrared light) [6, 7].

Spectral reflectance is the ratio of reflected energy to incident energy as a function of wavelength. For most materials, the reflectance changes at different wavelengths because energy at specific wavelengths is scattered/absorbed at different degrees [12]. Plotting the reflectance versus wavelength we obtain spectral reflectance curves. Spectral reflectance curves are different for different materials based on the wavelength ranges for which the material absorbs incident energy. The shape, strength, and position of a spectral reflectance curve can be used to identify materials [12].

**CCD**

CCD (Charge Coupled Device) converts photons into electrons. The electrons are stored in each pixel on the device. The pixels can hold a fixed number of electrons ranging between 35,000 to 500,000 depending on the model. During exposure, photons strike and converted to electrons, which are stored in pixel wells. The pixel value is converted from the corresponding number of electrons at that pixel, which is proportional to the number of photons that struck the pixel during the exposure. This determines how light or dark a pixel will be in the generated image. [13]

**Linearity**

CCD images are advantageous because of their linearity in response over a large range. The charge collected by CCD is linearly related to the output value for each pixel. The largest output number a CCD can have is set by the number of bits in its converter.
The output is always based on powers of two. The QSI Series has a 16-bit A/D converter and so $2^{16}$ values can be represented at each pixel (0-65,535). However, when the values get high (past saturation) the CCD becomes non-linear. Two types of saturation can occur: where the converter cannot output higher numbers, and where a pixel will leak into surrounding pixels. Therefore it is extremely important to limit the brightest pixel to around 50% of the full well depth. This value comes out to 25,500 for the QSI Series 683 [11].

**Noise, Defects, and Characterization**

Users of CCD imagers must calibrate images to deal with noise and defects. Calibration requires special kinds of exposures: Bias Frames, Dark Frames, and Flat Fields. Unlike in astronomy applications, processing for the spectral power curve of the light source must be done indoors [13]

**Bias Frames**

A Bias Frame is a zero-length (dark) exposure measuring the difference of noise added by the imager. This noise comes about when the CCD reads the image converts it into a digital image file [13]. Since the pixels are emptied before the image is read only a small amount of dark current builds up, and the rate of accumulation of this small amount of dark current varies in build up for each pixel [13].

![Example of a Master Bias Frame for QSI Series 683 (Average of 16 Frames)](image)

**Dark Current**

Dark frames are the buildup of dark current (caused by heat) from a CCD image. CCDs convert the energy from heat into electrons the same way they convert the photons. Dark current is accumulated on the CCD regardless of if it is being exposed to light. The rate
of dark current build up depends on temperature. Therefore, cooling the CCD reduces the
dark current [13].

While overall the dark current builds up at a constant rate, there are pixel to pixel
variations. Some pixels, called “hot pixels” build up dark current very fast. Hot pixels are
easily seen in the raw image as random bright dots placed [13].

Since the exposures for this type of application are very short (less than 30 seconds),
there is little dark current and very few “hot” pixels in the dark frames.

An example of a Dark Frame with a 6 minute exposure using QSI Series 500 [13]

**Flat Fields**

Flat fields are easily the most important calibration tool for CCD imager, and the most
difficult to do properly. Flat fields correct for any irregularities, which includes
vignetting, dust motes, and any pixel non-uniformity inherent in the camera. Pixels
respond slightly differently to light and all CCD cameras have a unique “signature”
caused by the pixel response to the light illuminating the CCD [13].

Flat fields depend on the linearity of the CCD camera and therefore require that the
exposure time be so that the pixel wells are filled to approximately half their full
capacity. With the QSI Series 683 average pixel values between 20,000 and 30,000 out of
a total of roughly 65,000 are appropriate. This requires experimentation with different
exposure times.
Example of Two Flat Field Images taken with QSI Series 683

Spectral Power Distribution

The Spectral power distribution is the power per unit area per unit wavelength of an illuminant. Given different lighting conditions images taken will appear different due to the spectral power distribution. To correct for this we use a spectralon reflectance target with known values to color correct the previously calibrated images. [10]

**Spectral Radiance (Spectral Power Distribution) SPD**

An example of two different Spectral Power Distributions for Daylight and White LED [10]

Practice

The QSI Series 683 is a thermo-electrically cooled CCD camera designed to produce high quality images with extremely wide dynamic range, excellent linearity and exceptionally low noise.

MaxIm LE CCD camera control software will be used with the QSI Series camera. MaxIm LE allows the user to have complete camera control, as well as filter wheel
control, automated sequences, image calibration and processing, focusing tools, and guide camera control.

**Connect/Cooler On**
After opening up MaxIm LE, connect to the QSI Universal and put the cooler on.

![Camera Control](image1)

**Focus**
While the temperature drops we can start focusing on the target.
First adjust the focus on the camera by turning the lens to the estimated distance away from the object.
Select the ‘Focus’ tab and Start Focus. Adjust until the image is as clear as possible.
Now wait for the camera to reach the desired temperature (-20.0).

**Exposure**
Test the exposure for different filters with the ‘Expose’ tab. Adjust the exposure time so that filter in the middle of the spectrum the best result.

Test exposure times at different filters to determine how long to expose flat field images. Brightest spots should have around 50% of full well depth.

**Setup Sequence**

![Setup Sequence](image2)

Select ‘Sequence’ tab. Select Options–>Setup Sequence. Adjust ‘Repeat’ to enable multiple exposures, as it is necessary to average many images for each filter, as well as for bias and dark frames.

Images will be saved to the path you set under options.
Do the flat field images first and then repeat Set up Sequence for the raw images.

**Processing**

Using Pixel Math tool, select the images and operations to be performed (Add, Multiply, Subtract, Divide).

The general formula for achieving dark, bias, and flat field calibrated images is:

$$IC = (IR-IB-ID) \times M / (IF-IB-ID)$$

where IC is the calibrated image, IR is the raw image, IB is the bias frame, ID is the Dark image, IF is the flat field image, and M is the Average pixel value of (IF-IB-ID).

Alternatively, the image processing can comfortably be done in ImageJ or MATLAB.

![Pixel Math Tool](image)

**Future Applications**

Different materials have different spectral reflectance characteristics. This can be used to identify materials without destructive testing. A challenge is to identify mixtures and combinations of materials, such as mixtures of inks on different types of paper. Future projects will involve gathering hyperspectral data, and then testing and extending existing techniques for identification. Once calibrated, transforming hyperspectral images into spectral reflectance curves can be done as illustrated in D.H. Foster’s MATLAB tutorials [5].

**Conclusion**

Before applying spectral reflectance characteristics to identifying materials, reliably calibrated hyperspectral data must be gathered and processed. First and foremost, it is necessary to develop an extensive understanding of high-powered CCD cameras and the different image calibration techniques available. The QSI thermo-electrically cooled
CCD camera was developed for astronomical imaging, however it can be used for other fairly new applications as a high-powered multispectral imaging system with good spatial resolution. There were guidelines for calibrating astronomical images, however many difficulties were faced calibrating images acquired indoor to account for the flat field calibration and spectral power curves of the light source(s). Having hardly any previous knowledge of the topics in this paper, the final research project took a turn from some of the applications in original proposal to understanding the theory and the physics of CCD cameras, noise, defects, characterization, image calibration, and hyperspectral imaging became a priority. This learning research project aimed at making progress towards establishing a streamlined standard practice for image acquisition, calibration, and processing to make hyperspectral applications possible, like applying the Kubelka-Munk Pigment model to identifying mixtures and combinations of materials in cultural heritage.

**Bibliography**


