Color and Multispectral Imaging with the CRISATEL Multispectral System

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Abstract

We present a first evaluation of the prototype multispectral camera developed in the framework of the IST-CRISATEL European project. This evaluation corresponds to the characterization of the filter transmittances, the CCD properties and the dark noise. We also show the importance of chromatic aberration correction for high resolution multispectral imaging systems.

Introduction

The increased interest in multi-spectral imaging over the last five years has unsurprisingly focused on certain fields where color fidelity is of the greatest importance. Prominent among these applications is that of imaging works of art, where an increasing demand for high-quality reproductions of artifacts has emerged alongside a traditional scientific interest in multi-spectral imaging as a means of measuring surface colors and its change with time.

Until now, the only high-resolution multi-spectral imaging system developed specifically to record the color of paintings was built in 1989–92 during the European VASARI project.[4] Although this system is still in use at the National Gallery, London, its major disadvantage is that it is a large fixed apparatus. Portable high-resolution cameras are now available, including the MARC camera developed in the eponymous European project,[2] but these produce three-band images rather than multi-spectral data.

A high-resolution multispectral color imaging system has been developed in this framework for the European project CRISATEL. This system includes a multispectral camera and a dedicated high power lighting system, both developed by LUMIERE TECHNOLOGY, Paris, France.

Major goals of the CRISATEL project are:

1. to digitally acquire high resolution multispectral images of art paintings (i.e. 12 000 x 30 000 pixels, ten channels in the visible spectrum, three in the near infrared),
2. to predict faithfully the appearance of a painting under different illuminants,
3. to provide high fidelity color reproduction,
4. to reconstruct at any pixel position the spectral reflectance of the painting area corresponding to that pixel,
5. to simulate the restoration process of varnish removal on a painting by compensating for the varnish spectral absorption to predict the underlying original colors.

A sister paper,[1] also in these proceedings, focuses on the hardware aspects of this multispectral color imaging system by describing the optical, mechanical and electronic technologies used for the camera and the lighting.

In this paper we provide a first evaluation of the multispectral camera. The paper is organized as follows. The next section summarizes the main characteristics of the camera. Afterwards, we characterize the interference filter spectral transmittances. The following two sections concern the electronic properties of the CCD array. We first characterize its linearity. Then we consider its noise properties. Finally, the problem of chromatic aberration and the need of precise optical registration among different channels are presented.

Multispectral Camera Description

We describe in this section the basic features of the CRISATEL multispectral acquisition system.

The CRISATEL multispectral camera is a digital camera based on a charge coupled device (CCD) with a 12 000 pixel linear array. This linear array is mounted vertically and precisely mechanically displaced by a step by step motor. The system is able to scan up to 30 000 horizontal positions. This means that images up to 12 000 by 30 000 pixels can be generated. The current camera is fitted with a system that automatically positions a set of 13 interference filters, ten filters covering the visible spectrum and the other three covering the near infrared. There is an extra position without filter allowing panchromatic acquisitions.

The linear CCD array is equipped with an electronic architecture allowing one, two or four parallel channels for the CCD readout operations. The current system uses two channels which process the pixels on the array occupying even or odd positions respectively. In each channel the raw signal coming from the CCD passes through an analog amplifier. Each amplifier has two control parameters, an offset and a gain. In our case, it is a set of two offsets and two gains which can be adjusted by a calibration procedure for each individual channel before a multispectral acquisition. The analog signal delivered by the amplifier for each pixel is then quantized into 12 bits by an analog to digital converter (ADC).

For a given scene and lighting, there remain two physical parameters which allow us also to control the amplitude of the signal: the aperture of the optical lens and the exposure time. Both factors can modify the number of incident photons trapped in each individual CCD cells. The aperture of our dedicated optical lens being not controlled electronically, is kept fixed during an acquisition. The exposure time can be automatically setup and changed from 1.3 ms to 200 ms by steps of 0.1 ms. Since the CCD readout speed is the limiting factor to the rate of acquisition, the minimum time of 1.3 ms could be reduced by using four parallel channels for the CCD readout. But in our case this value is already small enough and appropriate for applications to the scanning of paintings where having a high speed scanning system is not the most important issue.

The focus of the lens is precisely controlled by a stepper motor. Due to the remaining chromatic aberration of the lens, the focal length is not the same for the 13 channels resulting in images of slightly different scale. The CRISATEL multispectral camera provides a displacement system of the full camera body that can compensate these differences in scale for every spectral channel.

Filter Characterization

The filter transmittance of the 10 filters in the UV to Visible range were measured with a Hitachi U-4000 spectrophotometer at the Victoria and Albert museum in London (Fig. 1). The Hitachi double beam spectrophotometer consists of a scanning monochromator, a Spectralon coated integrating sphere, a Tungsten Halogen lamp and a light-tight sample compartment. The system was set up to scan the wavelength range 340-1500nm, using a photomultiplier at short wavelength (<850nm) with a slit-width of 1nm and a scanning speed of 300nm/min, and a PbS detector in the NIR (>850nm) with a slit-width of 10nm and a scanning speed of 750nm/min. First, a baseline calibration was performed by comparing the sample beam (with no filter in the beam) with the reference beam. The transmittance of each filter was then obtained by taking the ratio between the sample and the reference beam. Most of the filters have significant second order response beyond ~1100nm, which should not introduce a significant error, since the CCD quantum efficiency cuts off at ~1100nm.

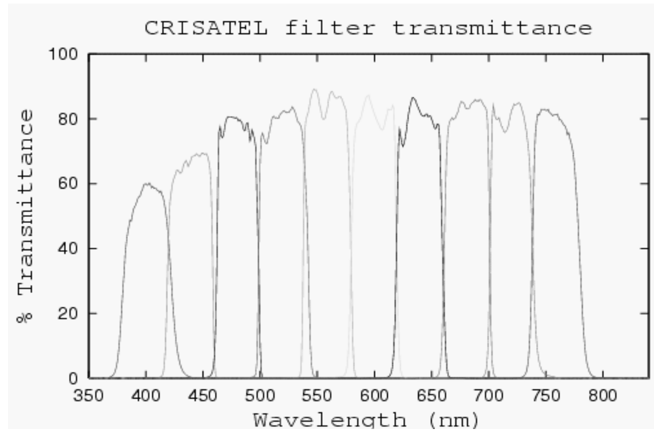

Figure 1. Transmittance of the 10 UV-VIS filters measured with the Hitachi spectrophotometer.

The transmittance of the above filters were also measured with a Monolight spectrophotometer at the National Gallery in London. The Monolight system consists of a scanning monochrometer, a stabilised Tungsten Halogen light source, a photomultiplier detector for 300-850nm, and a Si detector for 300-1100nm. Both the light source and the detector are connected with a optical fibre light guide and a collimated lens. The calibration procedure consists of a wavelength calibration with a He-Ne laser and a dark level measurement. The transmittance of the 10 filters obtained with the Monolight spectrometer were consistent with the Hitachi measurements within 2%. The transmittance of the 3 IR filters measured with the Si detector of the Monolight system (slit-width 0.45mm) is shown in Fig. 2.

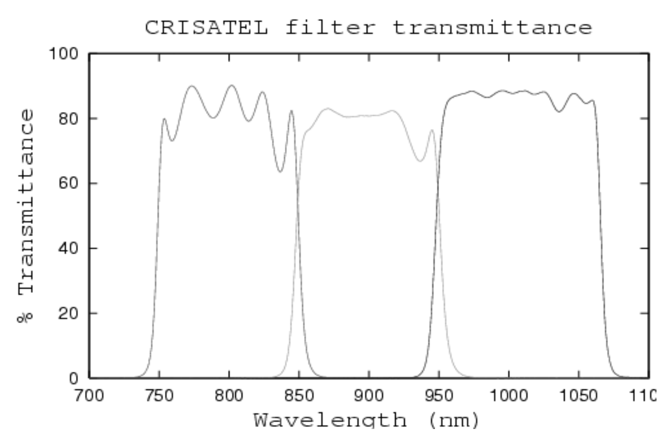

Figure 2. Transmittance of the 3 IR filters measured with the Monolight spectrophotometer

Since the transmittance of interference filters are known to depend on the angle of incidence, we have also measured the angular dependence of selected filters using the Monolight (e.g. Fig. 3). There is a 1.5nm shift to the blue at 5 degrees and a 4.5nm shift at 10 degrees with no distortion to the spectral shape. Since the maximum angle of incidence for the CRISATEL system is ~7 degrees, the maximum wavelength shift is only ~3nm.

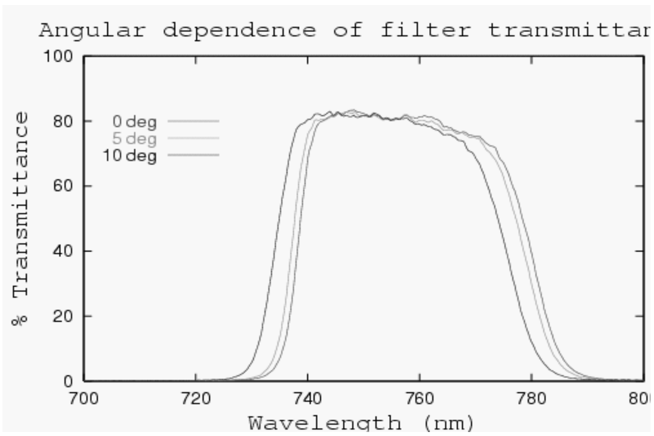

Figure 3. Angular dependence of filter transmittance.

CCD Linearity

To control the linearity of the CCD response, we use a calibrated white target under a CRISATEL lighting system equipped of HQI bulbs. All the camera parameters are kept constant except for the exposure time. The offset of each electronic amplifier is set to its minimum and the gain is kept at 0 db. The mean output signal corresponding to the white target should increase linearly with the exposure time. In figure 4 we show this test of linearity for three different filters.

We observe on these three channels a perfect linear response, up to a certain response level where the CCD starts to be saturated and reaches a plateau where the acquired images are overexposed. The transition between the linear behavior and the plateau is important to characterize in order to determine an optimal exposure time for which the CCD is not saturated and the images are not underexposed. When one channel sensitivity is too low as it is the case of the filter centered at 1000 nm in Figure 4, the output response needs to be magnified by increasing the amplifier gain.

We can compare the relative sensitivity of the 3 channels represented in Figure 4 by measuring their respective responses at a given exposure time where the 3 curves remain linear (e.g. at 20 ms). The result of this comparison between the 13 channels of the CRISATEL camera is shown in Figure 5. Channel 6 is the most sensitive. It corresponds to the filter centered at 600 nm. Channels 1, 9 and 10 are about 4 times less sensitive. They correspond to filters centered at 400 nm, 720 nm and 760 nm, respectively. Channels 11, 12 and 13 correspond to the three infrared filters centered at 800 nm, 900 nm, 1000 nm, respectively. Their larger bandwidth, 100 nm instead of 40 nm, explains the increase in sensibility of channels 11 and 12 compared to channel 10. Channel 13 is the less sensitive, about 20 time less than channel 6. It is due to a strong decrease of the spectral sensitivity of the linear array in that part of the infra-red.

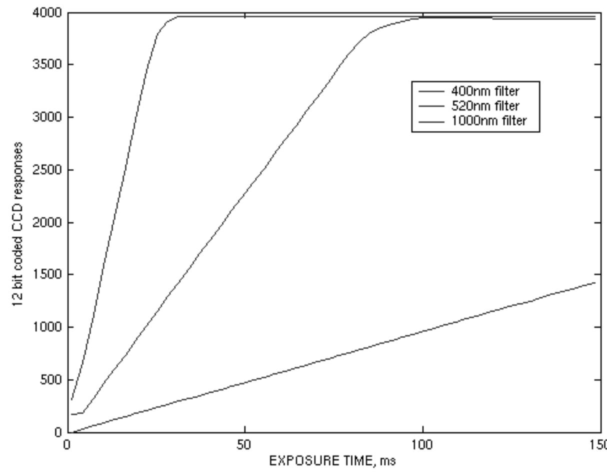

Figure 4. Curves showing the linear behavior of the CCD array for three different channels. Amplifier offset is fixed to its minimum level, amplifier gain is 0dB.

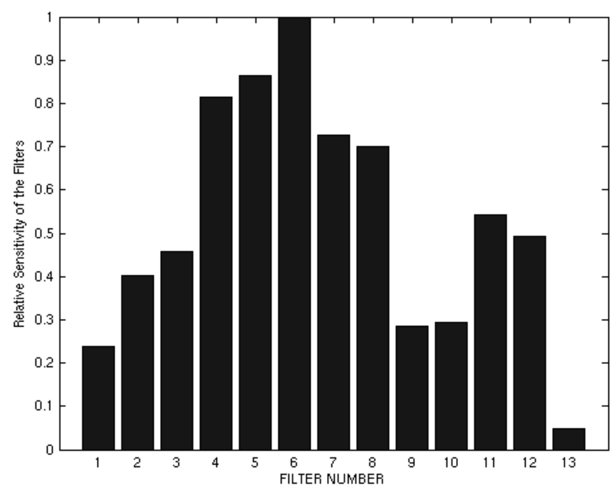

Figure 5. Relative channel sensitivity of the CRISATEL camera. Channels 1 to 10 correspond to the 10 filters in the visible spectral range, channels 11 to 13 to the three IR filters.

Dark Noise Characterization

One fundamental characteristic of a digital multispectral camera is its level of noise. In this section we present the results of a set of experiments performed to characterize the noise properties of the CRISATEL camera. This noise corresponds to spontaneous electrical charges inside the CCD created independently of the photon activity. It is often call dark current. In order to measure these dark signals we block the camera by using a cap and scanned "dark images". We have conducted all our experiments in a dark room in order to avoid any stray light.

Since we have a linear CCD array, we consider each line of a single large dark image as a population of samples of the corresponding CCD pixel and calculate on this line the mean, the variance and any other statistics corresponding to that CCD pixel. Then, the whole CCD array is summarized in one number by using the mean of all the pixels of a selected statistics. This mean is performed separately for even and odd pixels as their amplifiers are different. We recall that the output camera signal is 12 bits quantized in the range [0-4095]. The scales used in the various noise representations are then provided directly in units corresponding to that range.

We first present two sets of curves which relate the mean level of dark noise and its standard deviation with the exposure time. In Figure 6 we observe clearly that the mean value of the dark noise is linearly dependent on the exposure time. We also observe on Figure 6 that the amplifier gain changes the slope of the curve. All these observations agree with simple theoretical expectations. Since the mean dark noise is predictable it is then possible to correct it by applying a negative offset of the same amount on the output signal delivered by the amplifier. In Figure 7 we present the standard deviation corresponding to the same experiment as in Figure 6. We observe here that the standard deviation becomes constant after a given amount of exposure time and that constant value increases with the amplifier gain. This indicate to us that it is better to use a longer exposure time in the available range, when applicable, than to increase the amplifier gain, as far as the precision of the signal is concerned.

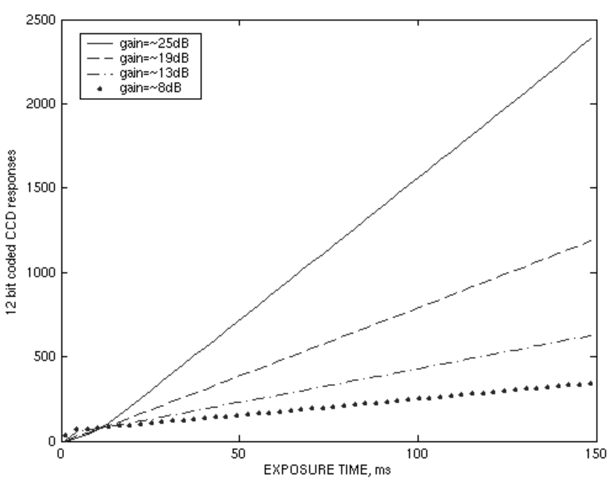

Figure 6. Mean value of the CCD dark noise. Each linear curve represents the dark noise mean value versus the exposure time for a fixed amplifier gain. The amplifier gain changes the slope of the lines.

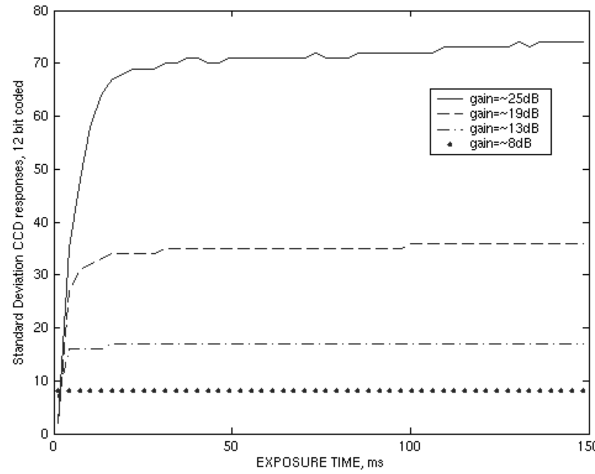

Figure 7. Standard deviation of the dark noise. Each curve represents the dark noise standard deviation versus the exposure time for a fixed amplifier gain. The standard deviation reaches a maximum which depends on the gain.

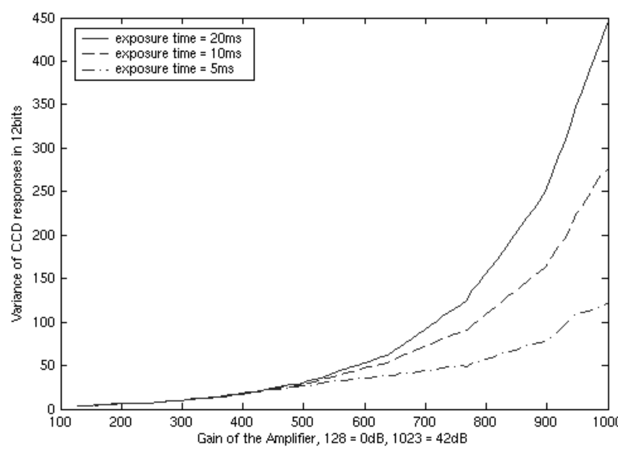

Figure 8. Standard deviation of the CCD dark noise. Each curve represents the dark noise standard deviation versus the amplifier gain obtained with a fixed exposure time. Gain is given in units accepted by the control system, 128 is 0 dB while 1023 is 42 dB.

We can further study the standard deviation of the CCD responses, in particular its dependency on the amplifier gain. In Figure 8 each curve represents the evolution of the standard deviation versus the amplifier gain obtained with a fixed exposure time. On the horizontal axis the gain is given in the units accepted by the control system, 128 corresponds to 0 dB while, 1023 to 42 dB. Three sets of experiments at an exposure time equal to 5 ms, 10 ms and 20 ms illustrate the effects of the gain on the dark noise in Figure 8. At gain = 250 (~ 8 dB) and exposure time 20 ms we obtain a standard deviation value of 8 which introduces an error of ~ 0.2 % in the 12 bits signal. At gain = 400 (~ 13 dB) the error is 18 (~ 0.45 %) and at gain = 750 (~ 29 dB) the error is 115 (~ 2.8 %).

These results confirm the previous ones. The exposure time does not affect the standard deviation, up to a certain amplifier gain value (~ 400 in our case). Dark noise can be considered as an offset that linearly depends on the exposure time. We can correct this offset in a post-processing stage or integrate part of this correction in the calibration procedure by the use of the electronic offset of the CCD amplifiers.

These results indicate also that it would be better to have a common gain for all the channels, when applicable, in order to have the same dark noise standard deviation. We cannot correct the error introduced by the noise standard deviation. Then, a common gain would provide a similar signal to noise ratio for all channels.

Chromatic Aberration

In this section we consider the problem of geometric differences between channels induced by chromatic aberration. The refractive index of a lens varies with wavelengths. Furthermore the interference filters used in our camera have different thickness. This makes the acquisition geometry of the channels slightly different. As a consequence, if the camera is fixed and the images focused individually for each channel, the resulting images will have not the same scale. A characteristic point of the scene may not be imaged in the same pixel in each channel. We illustrate this point by acquiring an image for two different channels of the simple test chart shown in Figure 9. It is composed of a large white band limited by two black bands. The chart was placed vertically and its size chosen such that its image covers the linear array.

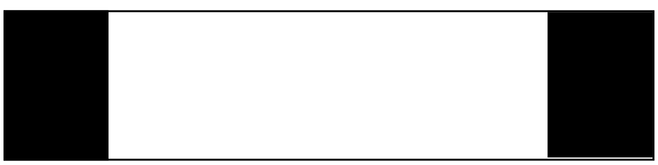

Figure 9.Test chart used to correct the chromatic aberration.

We chose one filter in the infrared area (centred at 1000 nm) and the other in the visible spectrum (centred at 680 nm). In the two images we simply note the pixel positions corresponding to the two black/white transitions as shown in Table 1.

Table 1. Pixel Distance between the black bands.

Filter	Pixel position => Distance
680BP40	10014-1606 => 8408
1000BP100	10041-1573 => 8468

The distance calculated in pixels differs by 60 pixels. This means that the acquired images need a posteriori inter-channel registration. To avoid this, the CRISATEL multispectral camera provides a displacement system that can compensate the differences in geometry for every spectral channel. The system mechanically displaces the whole camera along the optical axis. These displacements can be determined by a calibration process and incorporated in the control software providing the possibility of an fully automatic compensating system.

Conclusion and Future Work

One of the aims of the CRISATEL multispectral camera is to provide high fidelity color reproduction and spectral reflectance reconstruction. A first evaluation of this digital camera is presented in this article. We have characterized the filter transmittances, the CCD linear properties and the dark noise. We have also shown the importance of the chromatic aberration which should be corrected for high resolution multispectral imaging.

We are currently working on the implementation of an automatic calibration system along with the definition of protocols for image acquisition of art works.

The spectral reconstruction will be performed by the use of linear and non-linear methods that have already been developed by some of the authors. In particular we will apply a non-linear method based on Mixture Density Networks.[3] The spectral reconstruction approach for high fidelity color reproduction will be compared with direct regression techniques to reconstruct color.

Acknowledgments

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Biography

Alejandro Ribés received a computer science engineering degree from the *Universitat Jaume I*, Spain, and a DEA (one-year French postgraduate degree in research) from the *Université de Nice-Sophia Antipolis* specialized in image processing and artificial vision. He is currently preparing a Ph.D. in multispectral imaging at the *Ecole Nationale Superieure des Telecommunications* in Paris, since September 2000.