An imaging device for multispectral analysis in the visible range

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Abstract-The method of characterizing a tunable bench of filter in the visible range and the spectral responsivity of a CCD camera is described. The two instruments are joined to form an image spectroradiometer, the performances of which are estimated taking into account its ability in reconstructing the spectral radiance of the light. The criteria useful to compensate the effect of finite bandwidth of the tunable filter are presented showing the effectiveness of the correction in determining both the spectra and the colorimetric CIE Lxy coordinates of the analyzed coloured samples. The system presents the performance of a good colorimeter-spectroradiometer adding the ability of analyzing a wide surface with a good spatial resolution, contemporarily.

I. Introduction

The luminance can be defined as the luminous intensity per unity observed area; it represents the main stimulus received by retinal photoreceptors of the human eyes. Relative luminance differences on contiguous surfaces allow the perception of object details. Therefore, for close objects both luminance absolute values and differences should to be quantified well to evaluate the effectiveness of a lighting plant, in internal and external applications.

CCD luminance meters are usually employed in the Photometric Laboratory of the Padova University [1] both for analysis of light sources and for the study of the reflection characteristics of surfaces. An "Andor" scientific grade camera with a "Zeiss-Contax" 50 mm f/1.4 lens improves the performance of the Laboratory instrumentation, recently. The camera is equipped by a 1024x1024 CCD and is characterized by a sensibility up to 0.7 electrons per count of a 16 bit analog to digital converter. The CCD sensor can be cooled down to about -80°C to reduce the dark current and the noise. The camera linearity is better than 0.3% of the full scale and the uniformity of the CCD response is better than 0.8%. This device is more valuable than traditional luminance meter as it is composed by a high number of closely spaced small detectors (pixels) on a single chip. Each pixel can be associated with an element of the surface under measurement, therefore a CCD luminance meter allows to evaluate the luminance of many small portions of a surface ("point" luminance) for several directions of observation. It is of great interest in qualifying the luminance of a road surfaces allowing to the evaluation of its uniformity with just one measurement.

Analogous issues are present when dealing with colorimetric characteristic of wide surfaces and spectrometric measurements on paintings and frescos [2]. A device facing this problem was developed by the Photometric Department of the Italian metrological institute (Istituto Nazionale per la Ricerca Metrologica). It is the Mobile Imaging Radiometer (MIR), a transportable unity constituted by two main parts: a spectrometer with diffraction grating and a camera completed with a interference filters bench [3] [4]. The first equipment measures spectral reflectance factor with a great spectral resolution of a narrow stripe of surface, while the second one analyzes the checked area looking through interference filters.

To obtain a multispectral imaging of the observed scene the Photometric Laboratory in Padova decided to place the "Vari-Spec", a system of tunable filters, before the lens of the CCD camera. It is realized by liquid crystal filters activated by an electric signal. The declared bandwidth of each filter is 20 nm, the central wavelength can be selected with a resolution of 1 nm between 400 nm to 720 nm. The output light

is linearly polarized, it is not critical when working with randomly polarized light, taking into account that half the power is blocked by the filter.

The specifications of the CCD camera and the tunable filters suggest that the ensemble of the two systems could act as an image spectroradiometer with a good spatial and spectral resolution. The analysis of the performances of the two parts is here presented and used to quantify the quality of the realizable image spectroradiometer.

The characterization requires a stable light source with known spectral emission. It is the luminance integrating sphere standard available in the Laboratory, presenting a uniformity of 0.5% over its output window

Figure 1 Transmission coefficient of the tunable filters

and a short term stability equal to 0.5%. Its spectral radiance is measured by a spectroradiometer "Minolta" CS1000.

II. The tunable filter response
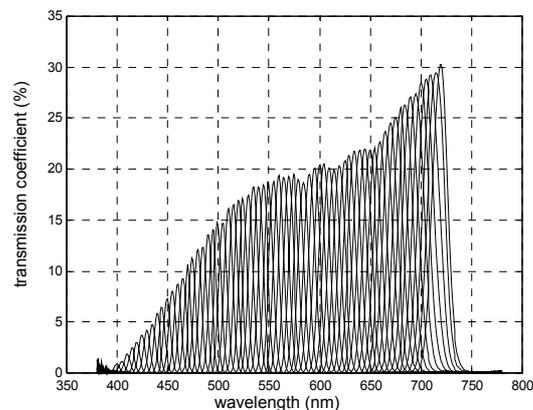
As the spectral power responsivity of each tunable filter could depend on its central wavelength, aiming at performing a correct multispectral analysis of an acquired image, a complete characterization of the tunable filter bench is required. It is obtained by measuring both the light entering each filter and the correspondent output, by the spectroradiometer CS1000. In order to verify the stability of the source, the measurements of its output and of the output of the filters were spaced out. Aiming at reducing the measurement time, only the filters the central wavelengths of which are spaced by 5 nm were analyzed; this resolution is considered acceptable also in LED colorimetry, where the measurements are particularly critical due to the reduced bandwidth of the source [5].

The transmission coefficient of the tunable filters is presented in Figure 1. The differences among the values obtained for the selected central wavelengths are apparent. Reconstructing the spectrum of the light framed by the camera requires the outputs of the filters have to be multiplied by adapted scaling coefficients. It is preferred to get them by normalizing to unity the area below each filter curve, rather than by normalizing the peak value. With this choice, when a light with a single wavelength is considered, the output of the filter bench conserves the total power associated to the input, but the filter spreads the power over its bandwidth. The total power is again kept when a source with a wideband spectrum is considered, even if dispersed over a wider band.

The finite bandwidth of the spectroradiometer (4.7±0.3 nm) causes a similar effect when it is used to characterize the filters: the peak of each filter is attenuated and the band is increased, apparently, but, the area under the detected curve of each filter is not modified, again. Therefore the scaling coefficients used to normalize the filter output are not affected by the spectroradiometer bandwidth. Conversely, the output of the spectroradiometer shows bandwidths of the filters wider than the real ones. Aiming at a more correct evaluation of the filter bandwidths, a Gaussian model of the filters was considered to estimate the error introduced by finite bandwidth of the spectroradiometer. This error is then subtracted from the measurement obtaining the result presented in Figure 2, where the upper curve represents the full-width at half-maximum (FWHM) derived from the measurement without the correction and the lower curve represents a more correct estimation of the FWHM. It can be noted the FWHM depends on the central wavelength and varies quite linearly from 4 nm to 19 nm moving from the minimal central wavelength (400 nm) to its maximum value (720 nm).

Several causes define the uncertainty on the characterization of the filters, the main identified ones are the linearity error of the spectroradiometer, its internal noise, the calibration of its wavelength scale [6] [7]. Other causes, as the repeatability of the filters and the stability of the light source, are of minor importance.

From the analysis of reflectance samples, the divergence from linearity of the spectroradiometer was estimated being within 1.5% quite uniformly in the visual range. This error is transferred directly to the transmission coefficient of the filters.

Errors in the calibration of the wavelength scale of the spectroradiometer result in an error in evaluating the shape of each filter. The effect of such an error in analyzing light sources using the tunable filters could present different entity depending on the source spectral emission, it could be important when narrow band source is studied, while it is usually negligible when broad band source is considered.

The measured relative variability of the spectra of the standard source includes both the variation of the source itself and the effect of the noise internal of the spectroradiometer. While for wavelength over 450 nm the dispersion is less than 0.2%, it increases for blue light and reaches the value of 1% at 380 nm. The flatness error of the spectroradiometer has no significant effect on the evaluation of the flatness of the filter bench as the filter transmission coefficients are obtained as ratio of measurements at the same wavelengths.

Figure 2 Full width at half maximum of the tunable filters: raw (upper line) corrected (lower line)

III. The CCD camera response

Knowing the spectral behaviour of the camera is of fundamental importance if it is used in spectrometric or colorimetric measurements. A characterization can be obtained by observing a monochromatic source (i.e. generated by a monochromator) by the camera object of the study and relating its output with the measure obtained by a calibrated detector (i.e. a calibrated photodiode or a spectroradiometer). The power spectral responsivity of the camera is the ratio of the output of the camera over the output of the detector [8]. The procedure can be hastened by using the tunable filters placed behind the camera lens.

The wideband light from the luminance standard source is observed by the camera after it passes through the tunable filters. The effect is similar to the one obtainable by the use of a monochromator, even if the light reaching the camera has a wider band, now. It implies a larger error and a related increased uncertainty on the spectral responsivity of the system.

At the same time measurements of the spectrum of the standard source by the spectroradiometer are collected so as to know the spectral radiance of the light. As the variation of the radiance of the source along the visual range is smooth, the error in estimating the actual distribution due to the finite bandwidth of the spectroradiometer is very small; its relative value can be estimated less than 10^{-4} at every wavelengths of the visual range [6] [7].

From the spectral radiance of the source and the characteristics of the filters, the light reaching the CCD camera can be evaluated. The ratio between the camera output, in counts, and the estimated input light can approximate the spectral responsivity of the CCD camera. The uncertainty on the knowledge of the CCD camera spectral responsivity is due to the uncertainties on the measurement of the source spectrum, on the knowledge of the tunable filters and on the noise and linearity error of the CCD camera.

The information on the spectrum presents uncertainties on the amplitude and the shape, depending on the absolute calibration of the spectroradiometer, on its internal noise, its flatness and its wavelength scale calibration. The error on the flatness can be corrected using its estimate obtained from the comparison between the theoretical radiance per unit wavelength of a black body approximated by an incandescent lamp and the spectrum measured by the spectroradiometer. After this correction, the relative uncertainty in the measurement of the luminance of illuminant A, equal to 2%, obtained from spectroradiometric measurements, is the main residual contribution. As for the characterization of the tunable filters, an error on the calibration of the wavelength scale of the spectroradiometer is transfer again on the knowledge of the CCD camera behaviour.
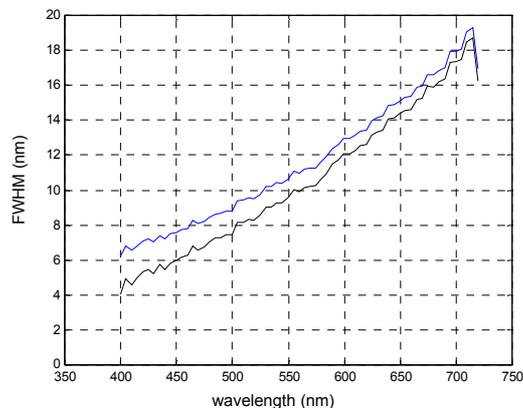
Figure 3 presents the behaviour of the spectral responsivity of the CCD camera with the adopted lens: its decay at the ends of the visual range is apparent, mainly at the shortest wavelength. Here the power of the light source used in the characterization is weak and the presence of noise both in the spectroradiometer and the CCD camera increases the uncertainty on the description of the system.

From the measurements of the responsivity of the CCD camera and of the characteristics of the filter, the output of the camera is calculated supposing a theoretical spectral radiance of the source close to the actual one. A new estimate of the CCD camera responsivity is obtained, again, as in the experimental conditions. The difference between the values of the two estimates of the CCD camera characteristic is an evaluation of the error due to the finite bandwidth of the filters. It is found within 2.5% of the maximum of the spectral responsivity.

Figure 3 Spectral responsivity of the CCD camera with the lens. normalized to its maximum

Aiming at building up a multi-luminance meter using the new camera available in the Laboratory, an ad hoc matching filter must be coupled with it. A high quality construction of this last, with a good adaptation to the luminous efficiency, $V(\lambda)$, according to CIE [9] [10], requires an accurate knowledge of the spectral response of the system composed by the CCD camera and the used lens. Thanks to the camera characterization, an ad-hoc filter can be designed and placed in front of the camera so as the overall system acts as a multi-luminance meter, provided its absolute calibration.
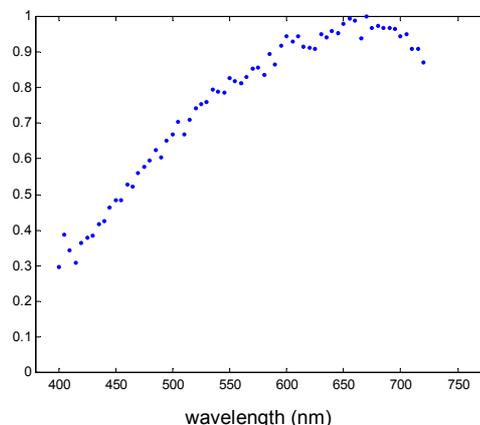
IV. Characteristics of the image spectroradiometer

The CCD camera together the tunable filters could act as a spectroradiometer with a FWHM of about 20 nm allowing the estimate of the spectral radiance of the source under test. Weighting the reconstructed spectra with the luminous efficiency allows to evaluate the luminance of the considered surface. The wide band of the filter can introduce significant error in the spectra measurement, the entity of which depending on the spectrum shape.

The responses of the system to light with different spectral distribution, white, blue, cyan, green, yellow, magenta and red, are considered. The inputs are the spectra of the light reflected by coloured samples lit by an incandescent source, the continuous lines in Figure 4(a) are their representation. They are supposed entering the system composed by the CCD camera and the tunable filters. The correspondent reconstructed spectra are represented by dots in Figure 4(a), while Figure 4(b) shows the error in reconstruction. Large error values are present for the magenta and red spectra at the centre of the visual range where fast variations happen. They are the consequences of the finite bandwidth of the tunable filters. High relative error values at the lowest wavelengths are due to a weak content of blue light in the considered source.

The system can be used also as a colorimeter to evaluate the colorimetric coordinates of the portion of the surfaces under analysis, according to the definition of the standard CIE colour spaces. A light spectrum can be associated to a point of a colour space by adequate mathematical transforms, the basic space is the CIE X,Y,Z. in which the coordinates are called tristimulus values [11] [12]. They are calculated from spectral data by a linear transformation according the following equation:

$$(1)\ \ X = \int_{380}^{780} L_{e,\lambda}\bar{x}(\lambda)d\lambda \qquad (2)\ \ Y = \int_{380}^{780} L_{e,\lambda}\bar{y}(\lambda)d\lambda \qquad (3)\ \ Z = \int_{380}^{780} L_{e,\lambda}\bar{z}(\lambda)d\lambda$$

where $L_{e,\lambda}$ is the spectral radiance of the light and $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are the CIE colour-matching functions.

The Y tristimulus values correlates are the luminance of the sample and the chromaticity properties can be synthesized by the coordinates, x e y derived from the tristimulus values according the following equations.

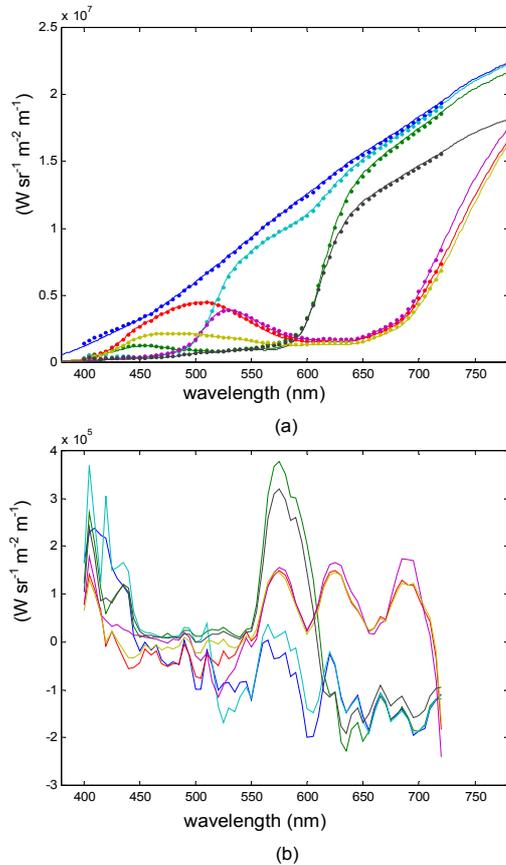$$(4) \qquad x = \frac{X}{X+Y+Z} \qquad (5)\ \ y = \frac{Y}{X+Y+Z}$$

(a)

(b)

Figure 4 Reconstruction of the spectral radiance of different colour samples (a) and error in the reconstruction (b)

From the reconstructed spectra supposed be acquired by the system, the estimates of the coordinates in the CIE-Lxy trichromatic space are derived, they are reported in Table 1, together with the relative error on the luminance evaluation and the absolute errors of the x and y coordinate. The largest luminance errors appear for the blue, magenta and red samples, they are due to the important errors in the reconstruction of their spectra, present at the centre of the visual range, where the weighting function $V(\lambda)$ has its maximum.

Models of the observed source spectra may allow to estimate the reconstructing error, which can be used to correct the first approximations of the measured spectral radiances. These last quantises are used as models and supposed being the input of the tunable filters and CCD camera, then the correspondent outputs of the system are calculated. The errors caused by the band pass of the filters and the camera are estimated as the difference between these outputs and inputs. The error estimates are subtracted from the first approximations of the spectral radiances, represented by dots in Figure 4(a), obtaining a better evaluation of the spectra. A reduction of the error by a factor larger than three appears in the central part of the visible range. Residual errors at the end of the range are due to a lack of knowledge of the spectrum beyond the central wavelength of the first and the last filters. As a consequence of the correction on the spectra, also the errors on the estimate of the CIE Lxy coordinate are reduced. Table 1 shows the new reconstructed values and differences from the coordinate of the input light. Now the luminance errors are less than 2% of the measured value and the errors on x and y are always less 0.003.

V. Discussion on the results

Both the MIR and the image spectroradiometer developed by the authors and discussed above aim at same goal of analyzing the luminance and the chromaticity of wide surfaces, even if they operate according different principles. The first system can measure the reflected spectra with a spectral resolution equal a 0.1 nm, but it can focus only narrow strip of the examined scene, their width ranges from 3 mm to 22 mm, depending on width of the observing window and on the distance from the analyzed surface. Therefore measuring a wide area with a good resolution requires a long time. Otherwise, it can capture a wider

	reconstructed value						reconstructed value after correction				
	L	δ_L	x	Δ_x	y	Δ_y	L	δ_L	x	Δ_x	y	Δ_y
colour	(cd m^{-2})	%	(-)	(-)	(-)	(-)	(cd m^{-2})	%	(-)	(-)	(-)	(-)
white	723	-0.8	0.444	-0.001	0.410	-0.001	729	0.1	0.445	0.000	0.411	0.000
blue	117	3.1	0.312	0.007	0.338	0.003	116	1.9	0.308	0.003	0.336	0.001
cyan	203	1.5	0.276	0.005	0.371	0.002	202	1.1	0.273	0.002	0.370	0.001
green	188	1.5	0.375	0.006	0.513	-0.005	187	1.2	0.371	0.002	0.517	-0.001
yellow	604	-0.7	0.511	-0.002	0.454	-0.002	609	0.1	0.513	0.000	0.456	0.000
magenta	184	4.4	0.550	-0.005	0.315	0.004	177	0.4	0.555	0.000	0.312	0.001
red	165	3.8	0.593	-0.008	0.350	0.003	160	0.4	0.600	0.001	0.348	0.001

Table 1 CIE-Lxy trichromatic coordinates of the light reflected by the coloured samples

surface but with a lower spectral resolution: in fact in this case the interference filters with a bandwidth of about 10 nm, placed in front of the camera lens, have the central wavelengths spaced by 50 nm between 350 nm and 800 nm [3]. The image spectroradiometer presented by the authors allows the measurement of the spectral radiance of a surface with a spectral resolution up to 1 nm between 400 nm to 720 nm, depending on the number of used tunable filters. Its spatial resolution depends on the distance between the system and the paint surface and from its observation angle. In fact the larger is the distance between the device and the object, the wider is the area corresponding to each pixel of the CCD matrix.

To quantify the reflection coefficient of surfaces, the MIR is equipped with a calibrated lighting system with a continuous spectrum and an automatic system to scan the surface under study without moving the spectrometer; this facility provide the possibility of fixing a reference point to grant the repeatability of the measurements. The image spectroradiometer here presented allows the measurement of the light emitted or reflected by a secondary source. The possibility of obtaining the reflection coefficient of surfaces is an issue which will be faced in the future developments.

V. Conclusions

The ensemble of the CCD camera and the tunable filter can act as a spectroradiometer, the performance of which are identified by characterizing of the spectral responsivity of the two elements separately. The method proposed provides the possibility of correcting undesired effect, in particular due to the finite bandwidth of the filter bench, partially. The results obtained after the correction are comparable with those obtainable by a good spectro-colorimeter. As collateral result, the performed analysis allows an accurate design of a filter to be placed in front to the CCD camera so as the system on the whole has a good adaptation to the luminous efficiency and can act as a multi-luminance meter.

Considering the obtainable performances, the system composed by the CCD camera, focusing lens and tunable filters can be considered an interesting tool for the analysis of luminance and chromaticity, and of their uniformity, over an extended surface, where methods and procedures using conventional luminance meters and chroma meters could be more difficult and time consuming.

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