A Portable Spectro-photo/radio-metric Camera with Spatial Filtering for VIS-NIR Imaging

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Abstract

This work proposes the design of a miniaturized spectro-photo/radio-metric camera with spatial filtering of the light for measuring the spectral reflectance factor and the spectral radiance of the objects of a scene.

Introduction

Trichromatic cameras, only in the case of a very accurate calibration, measure the color of objects illuminated by a particular light source and this quantity cannot be considered a measure of the spectral reflectance factor or of the radiance of a scene. Today, this limit is overcome by multispectral and hyperspectral scanners and big effort is dedicated to design new scanners and cameras, that, at the moment, for their size, are laboratory instruments, although transportable [1]. Multi-spectral and hyperspectral imaging are widely used in many fields (e.g. art conservation [2-5], bioimaging, remote sensing [6]), and several techniques have been proposed and realized over the time. Important effort has been made to find the minimum set of filters for the spectral reflectance factor reconstruction. Among these techniques, the use of Linearly Variable Filters (LVF) has been considered in publications [7-8] and patents [9-11]. This work proposes the design of a miniaturized spectro-photo/radio-metric camera, whose working principle makes no use of mathematical reconstruction model to return the spectral reflectance factor or the spectral radiance. This approach distinguishes the proposed instrument from the multispectral ones. This technique has two main characteristics: 1) a LVF on the image plane of the objective lens, translated in the direction orthogonal to optical axis of the camera, realizes the image spectral scanning and allows the measure of the spectral radiance of the objects of a scene and/or the spectral reflectance factor; 2) a relay lens transfers the image produced by the objective lens and filtered by the LVF to the image-matrix sensor; 3) once the LVF is removed, the same image-matrix sensor, used for measuring the spectral radiance of the objects of a scene, is used for image framing and focusing.

Spectro-photo/radio-metric camera

This work faces the design of a spectro-photo/radio-metric camera, that can be used in both portable and in-situ applications, although linked to a laptop for acquiring and processing the large amount of output data. The miniaturization is made possible by a suitable image spectral scanning scheme based on a LVF, i.e. an interference optical filter obtained by a thin-film wedge shaped coating with wavelength selective transmittance along one direction and uniform behavior in the perpendicular direction. The fundamental difference between a usual scanner and this camera is that in the scanner the whole apparatus is moved along a path as long as the scene, whereas in this project the camera body is still and the LVF inside of it is the only moving part. Its movement is obtained by a high precision piezo-positioner stage. This solution allows a compact design and easily portable instrument. The sketch of the whole spectro-photo/radio-metric camera is shown in Fig.1.

The objective lens of the camera focuses the image of a scene on a plane, that in Fig. 1 is called the 1st image plane. The objective lens is designed as an almost telecentric lens on the image side to have light rays crossing the image plane within a narrow angle. A LVF is positioned on the 1st image plane. A shift of the LVF orthogonal to the optical axis of the camera produces an image spectral filtering (Fig. 1 and 2) The LVF transmits a spectral light band centered on a wavelength λ, which depends on the filter position. The wavelength selection is in the shift direction of the LVF. A relay lens working with a 1:1 magnification ratio transports this filtered image on the 2nd image plane. An image-matrix sensor captures the filtered images produced on the 2nd image plane. Altogether, the relay lenses and the LVF work as a Wavelength Selective Optical System (WSOS). Any image strip orthogonal to the shift direction is selected at the wavelength λ, typical of the corresponding line on the LVF. The successive selections of the wavelengths are made through the LVF shifting. Step by step, the measurement of the spectral radiance of all the image strips is fully accomplished.

Advantages of WSOS are: i) the use of a standard relay lens; ii) a simple alignment of the optical components; iii) a simple arrangement of the moving LVF and of its motion supplier; iv) the LVF which does not alter significantly the optical aberrations budget.

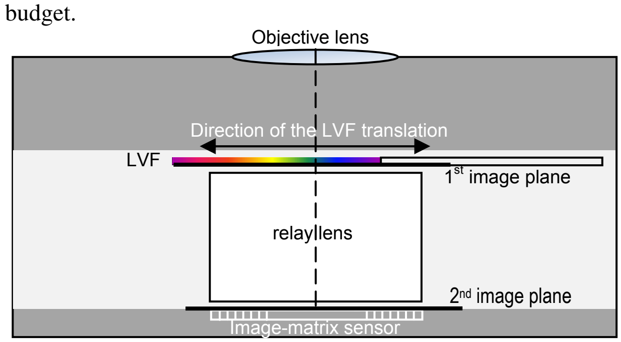

***Figure 1**. Cross sectional sketch of the spectro-photo/radio-metric camera. Each strip of the image on the 1st image plane is filtered by the LVF at a proper wavelength in order to return the spectral information. The filtered images are reproduced on the sensor by the relay lens. The whole spectrum is reconstructed strip by strip through LVF shifting.*

The sketch drawing of the WSOS is shown in the light gray square of Fig. 1. The WSOS consists of a moving LVF and a relay lens. The LVF is moved by a piezo positioner to scan along the direction of wavelength dispersion.

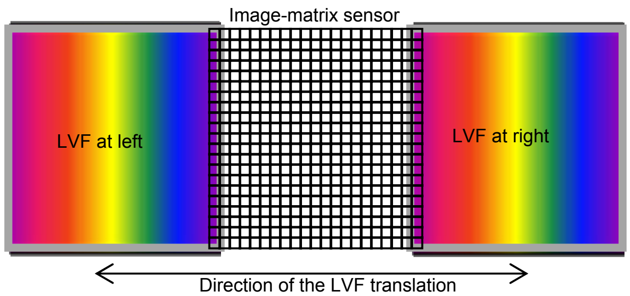

Figure 2. *Image-matrix sensor and LVF edge positions. Each column of the image sensor colliding on a LVF strip is filtered at a selected wavelength depending on the filter position.*

Optical components of the camera

The optical systems constituting the camera are substantially three, namely the objective lens, the relay lens and the LVF. The following considerations get into the details of the underlying lens design and of the LVF.

Objective lens

The objective lens (Fig. 3) focuses the image of a scene on the 1st image plane.

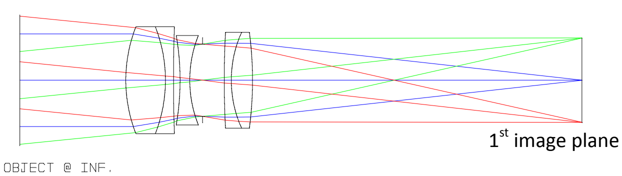

Figure 3. *Layout of the objective with on-axis and extreme off-axis ray-tracing.*

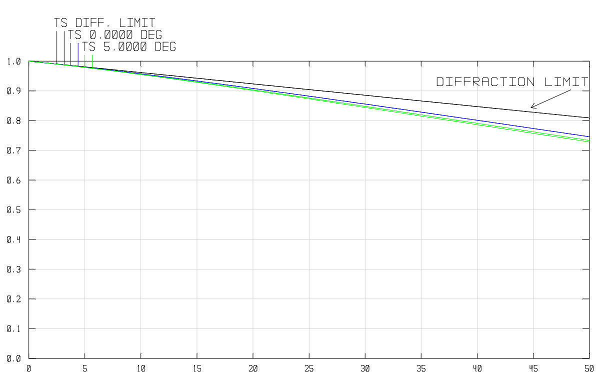

Figure 4. *On-axis and 5° off-axis polychromatic MTF of the objective up to the Nyquist frequency*

This objective must provide almost uniform illumination on this plane and this is achieved with low divergence of off-axis chief ray directions from the optical axis on their way to the image plane. Besides good correction of aberrations in the visible light, the lens must have extremely low distortion (< 0.1%) to accomplish pixel correspondence on the image. The choice of the working f-number (~5.2) is constrained 1) by relay-lens magnification, 2) by the allowable spot-size on the LVF coated side.

The objective chosen has five elements, with two external achromatic doublets, Heliar type triplet in crown-out arrangement [2], because this meets the above specifications satisfactorily; in fact, the objective is afocal in the object side, has a back focal length of 47 mm and a 20° full Angular Field of View (AFOV). The AFOV subtended on the 1st image plane is about 10° and is close to diffraction limit, because of its nearly symmetric layout. The illumination drop-off (relative to on-axis) at field edge is less than 1.5%.

The polychromatic Modulation Transfer Function (MTF) of the objective is shown in Fig. 4, where the diffraction-limit performance (black line) is very close to both the on and off-axis curves, even at the Nyquist frequency (50 cy/mm for a sensor matrix of square pixels, with a pixel size of 10 µm).

Relay lens

The relay lens is a symmetric system that leaves unaltered the image quality at the 2nd image plane on the image sensor (Fig.5).

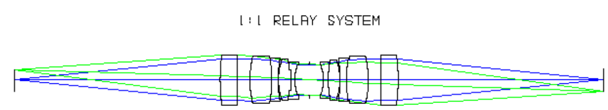

Figure 5. *Layout of the 1:1 relay system.*

Linearly variable filters

The multi-wavelength variable filter mentioned in the previous section is a narrow-band transmission filter whose peak wavelength is displaced over the surface of the filter itself, along one direction [12]. This non-uniform spatial performance can be obtained by an interference coating deposited on a glass substrate. The thin-film coating should have a variable thickness (Fig. 6) whose spatial variation depends on the required gradient of the peak wavelength. In this application the spatial gradient is about 100nm/mm. The other significant parameters of the filter are the operating wavelength range (400-1000nm) and the width of the transmission band (≤ 20nm). The required in-band (transmitted radiation) and out-band (rejected radiation) absolute values of transmittance should be respectively $T > 0.50$ and $T_{average} < 10^{-3}$.

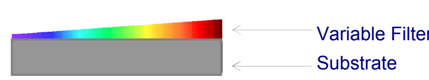

Figure 6. *Sketch of the variable transmission filter.*

A narrow-band transmission optical filter is in many cases obtained by an all-dielectric Fabry-Perot structure in which two reflecting multilayer stacks are separated by a spacer, the optical thickness of which is a multiple of the half-wave of the peak wavelength. The disadvantage of such a type of coating is the quite limited spectral range of operation, in fact the ratio between minimum and maximum operating wavelength is much lower than 2, because of the limited rejected radiation. Consequently, an additional filter would be required to block the out-band radiation in the range 400-1000nm. In this way the whole device will have a high number of layers and, for variable filters, the high number of variable thickness layers would increase the difficulties of manufacturing.

An alternative narrow-band transmission coating is the induced transmission filter. Here the reflection of a metal layer is avoided by matching its complex refractive index with the index of surrounding media (glass, air), at a single wavelength, through the addition of dielectric stacks on both sides. At that wavelength, a transmission peak will appear while the out-band radiation is reflected. The operating wavelength range is wider than in the previous case, while the maximum transmittance could be lower because of the metal absorption. For this reason, the metal layer should be very thin and a compromise on its thickness is needed to ensure a high out-band rejection.

The matching effect, and consequently the transmission peak, will be moved to different wavelengths, as the thickness of the dielectric stacks is changed. An example is shown in Fig. 7a), in which the performance of a 21-layer induced transmission filter is reported at several peak wavelengths. The metal layer is silver (70nm) surrounded by two stacks of dielectric materials whose thickness is spatially varied to obtain the reported displacement of the peak wavelength from 450nm to 950nm, over a predefined substrate dimension.

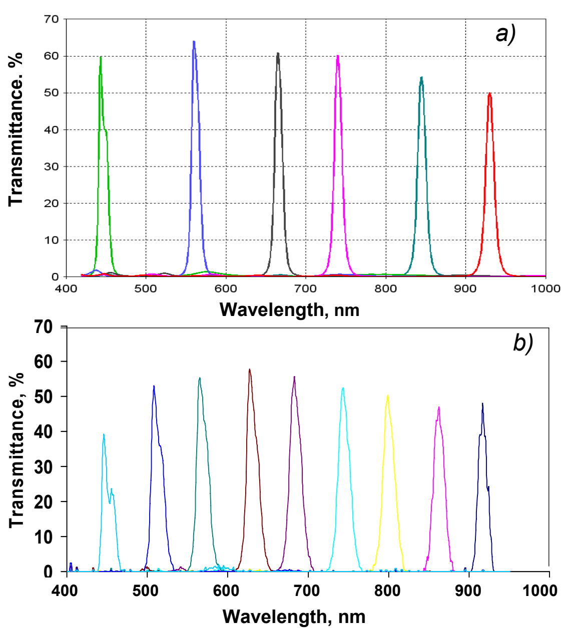

Figure.7. a) *Calculated transmittance of a variable metal-dielectric filter with 21 layers.* ***b)*** *measured transmittance of a variable metal-dielectric filter with 21 layers.*

A variable filter, according to the design of Fig. 7a), has been manufactured by radiofrequency sputtering using silicon oxide and tantalum oxide as dielectric materials. The linear profile of each layer thickness has been achieved by moving a properly designed mask inside the vacuum chamber during the thin film deposition [13]. The transmittance of the manufactured variable filter is shown in Fig. 7b), as measured along the wedge of the filter itself, by a dedicated set-up [14], over a dimension of few millimeters. The maximum obtained peak transmittance is about 60% and the width of the bandpass is lower than 20nm. Such kinds of metal-dielectric filters are not able to give a very narrow bandwidth (few nanometers), as all-dielectric Fabry-Perot filters, and their performance is highly sensitive to fluctuations of the metal thickness. In addition, the metal properties (complex refractive index) are fundamental for achieving an acceptable overall performance, for example silver is not adequate in the ultraviolet spectrum. However for such a type of coating, the total number of layers remains quite low and makes the fabrication of the variable filter easier.

Moreover, its sensitivity to the angle of incidence does not have a significant influence on the performance required for this application. Although LVF works best with incoming plane wavefronts, the beam convergence (half-angle of the converging cone) is acceptable of ±10° without significant spectral effects. As shown in Fig. 8 at 560nm, the transmission band for a convergent beam of semi-angle 10° has a wavelength shift of 1 nm and a reduction on the peak transmittance of about 1%, the width of the bandpass is almost unchanged. In this project, the considered convergence semi-angle is approximately 5.5°, with no significant reduction of the filter transmission. The same effect will be present at the other peak wavelengths.

Fig. 9 gives a sketch of the spectral transmittance of the LVF for a slit equal to the pixel size. Computation gives a bandpass far below 20nm. The 20nm bandpass is very frequent in industrial spectrophotometers, anyway the spectral resolution can be improved by a deconvolution technique [15], specific for colorimetric analysis.

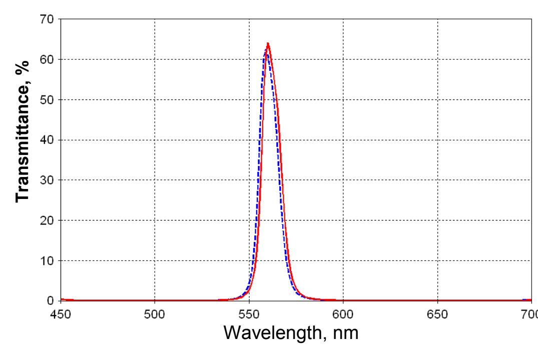

Figure 8. *Calculated transmittance of a metal-dielectric filter centered at 560nm, illuminated at normal incidence (solid red curve) and with a convergent beam of semi-angle 10° (dashed blue curve).*

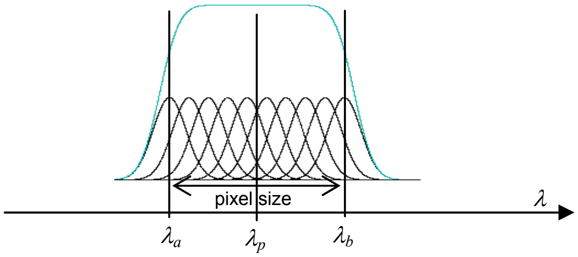

Figure 9. *Spectral Transmittance of the LVF associated to a slit as large as a pixel.* λ_p *is the central wavelength of the band,* λ_a *and* λ_b *the boundary wavelengths. This bandpass does not consider the effect of the relay lens.*

Spectra and image reconstruction

Figure 2 shows the plane of the image-matrix sensor with the LVF positioned in the two end positions. The LVF shifts, step by step from left to right, and filters the light that activates the pixels of each matrix column at the wavelength associated with the superimposed column of the filter itself. Any captured image is constituted by pixel columns, filtered at different wavelengths, and is the record of the corresponding raw radiances at the same wavelengths. The collection of all the captured images contains the raw radiance spectra of all the pixels of the scene. The raw radiance spectrum of any pixel is obtained by an ordered selection of the matrix elements of the captured images. These raw spectral data, decreased by the dark current and multiplied by a proper calibration factor, are transformed into correct radiance units.

The radiance spectra related to a standard reference white surface covering all the scene, measured in the same geometry of vision and illumination of the measured image, allow the measurement of the spectral reflectance factor of all the pixels of the scene.

The wavelength gradient of the LVF and the number of captured images defines the scanning step of the spectra.

The scanning step and the bandpass function of the LVF define the quality of the spectral output.

The trichromatic image of the scene is obtained from these spectral data by a colorimetric computation for each pixel.

Conclusions

This project is in progress and all parts of the considered spectrophotometric camera require optimization. Currently, the solutions here presented are considered and compared with others possible system configurations. About the filter performance the advantages offered by the all-dielectric structure, in terms of bandwidth and maximum transmission, are under evaluation.

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Author Biography

Andrea Della Patria received the degree in physics from the University of Salento, Lecce, Italy in 2000 and is a PhD student in Science and Technology of Innovative Materials at University of Parma, Parma, Italy. He is currently working as a Researcher with the National Institute of Optics, Arnesano. His research activities have focused on the design of optical devices for the diagnostics of artworks and spectrophotometry and colorimetry for the characterization of natural dyes.

Fernando Fermi received the degree in Physics in 1971 at the University of Parma, Italy, and is Associated Professor of General Physics at the same university. Research has been on the photoluminescence properties of semiconductors and insulators. Now the research activity is devoted to optical applied spectroscopy and colorimetry. In particular: color characterization of phosphors, electroluminescent displays, industrial sorting and packaging, instrumentation for imaging spectroscopy and its application on the tile industry.

Claudio Oleari became "Dottore in Fisica" in 1969 with full marks. In 1981 he was qualified Associated Professor in Theoretical Physics. Today he is: 1) regular teacher in Parma University of Colorimetry and

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Angela Piegari graduated in Physics in 1977 and has been working for 30 years in the field of optical thin-film coatings at ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development). Head of the Optical Coating Laboratory since 1994. She collaborated with many European Institutes in the frame of European projects and acted as evaluators of both National and European research proposals. Member of various technical committees, author of more than 100 papers in the field of thin-film optics.

Anna Krasilnikova Sytchkova, graduated in Physics from M. Lomonosov Moscow State University, received there a PhD in Mathematical Physics on analysis and synthesis of waveguiding structures in fiber optics. She worked as a researcher and taught physics and mathematics at the University of Moscow till 2000. Since 1997 she has been involved in research activities in the field of thin film optics at ENEA, at University "La Sapienza" of Rome and at University of l'Aquila. Now she is with ENEA Optical Coatings Group and her scientific interests are focused on thin film-characterization techniques and material research for thin film applications.