A compact spectral camera for VIS-NIR imaging

Andrea Della Patria[1], Claudio Oleari[2], Fernando Fermi[2], Angela Piegari[3], Anna Sytchkova[3]

[1] *National Institute of Optics (CNR - INO) U.O.S. di Lecce, Arnesano, Italy*
[2] *Parma University, Physics Department, Parma, Italy*
[3] *ENEA – Optical Coatings Laboratory, Rome, Italy*

Abstract

This paper describes the design of a spectro-photo/radio-metric camera, that can be used in both portable and in-situ applications, whose compactness is made possible by a suitable image spectral scanning scheme based on a Linearly Variable Filter (LVF). Such filter is able to operate continuously from 400 nm to 2500 nm, allowing the hyper-spectral imaging from visible to near infrared.
In traditional scanners the whole apparatus is moved along a path as long as the scene, whereas in this instrument the camera body is still and the LVF it is the only moving part. This solution allows a compact design and an easily portable instrument.

Introduction

Many fields take advantage of multispectral and hyper-spectral imaging (e.g. art conservation, bio-imaging, remote sensing), and several techniques have been proposed over the time [1-6]. In particular, the color of objects measured by multispectral cameras and hyper-spectral scanners is lacking the limits of trichromatic cameras because it is calculated from the spectral reflectance factor; however, it must be pointed out that such types of scanners and cameras are frequently only laboratory instruments, due to their size [1].
In some of instruments the spectral attribute is implemented through a set of filters, with efforts either to find the minimum number of filters needed for the spectral reflectance factor reconstruction or to employ tunable filters. Within this context, the use of Linearly Variable Filters (LVF) has been considered in publications [7-8] and patents [9-11]. Here is proposed the design of a miniaturized spectrometer for the measurement of the spectral radiance of the objects of a scene and/or the spectral reflectance factor, combining measurement accuracy with small dimensions of the whole instrument. The reproduction of the image of the observed scene will result from the measurement of the spectral reflectance factor.

The camera

The spectro-photo/radio-metric camera can operate either linked to a laptop or in a standalone mode, because is equipped with a rechargeable battery that supplies a CPU and a physical memory used for the scanning process for the acquisition. The miniaturization is made possible by a suitable image spectral scanning based on a LVF.
The LVF is an interference narrow-band transmission filter, obtained by a thin-film wedge shaped coating with wavelength selective transmittance along one direction. The camera body is still while the LVF translates. Its movement is supplied by a piezo-positioner stage with high accuracy and precision. The instrument layout is shown in Figure 1.

The objective lens of the camera focuses the image of a scene on a plane, named the 1st image plane.

The lens is approximately telecentric image side, so as to have rays crossing the image plane within a narrow solid angle. The LVF on the 1st image plane transmits a spectral light band centered on the wavelength λ, which is continuously variable along a direction on the filter whereas remains constant orthogonally. The wavelength is changed on the image by shifting the LVF along the line where the transmission peak wavelength changes, as in Figure 2. Image strips orthogonal to the shift direction are selected at the wavelength λ, for a particular position of the LVF. A relay lens, working with a 1:1 magnification ratio, transports the filtered images on the 2nd image plane, where are captured by an image-matrix sensor. Subsequent wavelength selections are effected through the displacement of the LVF. So, by iterating this procedure the measurement of the spectral radiance of all the image strips is fully accomplished. This method conveniently allows: a) the use of a standard relay lens; b) a simple alignment of the optical components; c) a simple arrangement of the moving LVF and of its motion supplier; d) the use of a LVF that does not affect significantly the optical aberration budget.

A piezo positioner translates the LVF along the direction of wavelength selection.

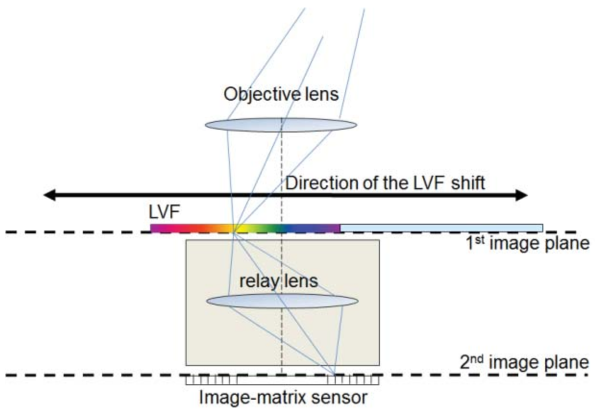

Figure 1 Cross sectional sketch of the proposed camera. Each strip of the image on the 1st image plane is filtered by the LVF. The filtered images are reproduced on the sensor by the relay lens. The whole spectrum is reconstructed strip by strip as the LVF moves.

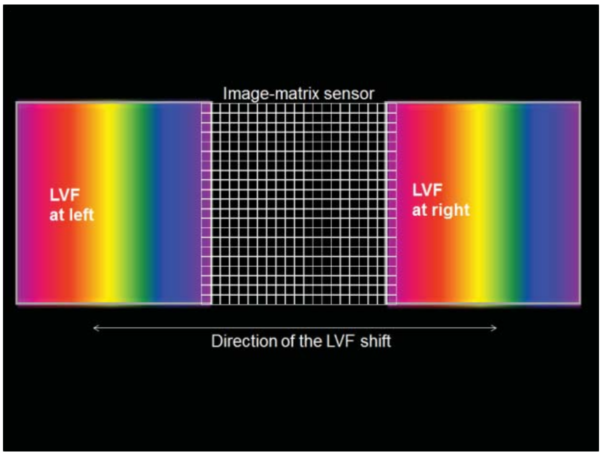

Figure 2 The image-matrix sensor and the two outermost positions of the LVF. Each column of the image sensor colliding on a LVF strip is filtered at a selected wavelength depending on the filter position.

Optical elements

The camera consists of three optical elements, namely an objective lens, a relay lens and a LVF.

Objective and relay lenses

The objective lens creates an image of a scene on the 1st image plane, where it has to provide almost uniform. This is achieved with almost parallel, to the optical axis, off-axis chief ray directions. Besides good correction of aberrations in the visible light, the lens must be well corrected for distortion (< 0.1%), to accomplish pixel correspondence on the image.

The selected objective has five elements, with two external achromatic doublets, Heliar type triplet in crown-out arrangement [2]. It is afocal in the object side, with a back focal length of 47 mm and 20° full Angular Field of View (AFOV). The latter is subtended on the 1st image plane and is approximately 10°, close to diffraction limit due to the nearly symmetric layout. The illumination reduction (relative to on-axis) at field edge is less than 1.5% and if in the case of reflectance factor measurement is unimportant, it is corrected by calibration in the case of radiance measurement.

The symmetry of the layout of the relay lens leaves unaltered the image quality at the 2nd image plane on the image sensor (Figure 3).

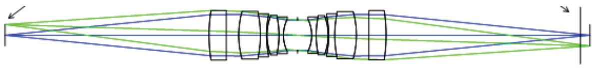

Figure 3 Layout of the symmetrical relay system

Linearly Variable Filter

The multi-wavelength linearly variable filter (LVF) is a narrow-band transmission filter with peak wavelength displaced over the surface of the filter itself, along one direction [12]. It is made with a variable thickness interference coating, whose spatial profile depends on the required gradient of the peak wavelength. Here the overall filter length is few millimeters, whereas the spatial gradient is of the order of 100 ÷ 200 nm/mm.

It can work in the wavelength range 400-2500 nm, with transmission bandpass of nearly 20 nm. The required in-band (transmitted radiation) and out-band (rejected radiation) absolute values of transmittance should be respectively $T > 0.50$ and $T_{avg} < 10^{-3}$.

The operating wavelength range will be divided in two parts, 400-1000 nm and 1000-2500 nm, because two different matrix sensors will be necessary to cover the whole spectrum.

Two induced transmission narrow-band filters will be used in these wavelength ranges. Such filters, containing metal and dielectric materials, have a wider rejection range with respect to classical all-dielectric Fabry-Perot filters. An induced transmission filter is made of a stack of metal and dielectric layers and the reflection of the metal layer is suppressed by matching its complex refractive index with the index of surrounding media (glass, air), at a single wavelength, by adding dielectric stacks on its sides. At that wavelength, a transmission peak will appear while the out-band radiation is reflected. The metal layer must be very thin in order to avoid absorption, but a compromise on the value of its thickness is needed to ensure a high out-band rejection, that is higher for greater thickness. The matching effect, and consequently the transmission peak, will shift to different wavelengths, as the thickness of the dielectric stacks is changed. Figure 4 reports the performance of an induced transmission filter at several transmission windows. The metal layer is silver (60-70 nm) surrounded by two stacks of dielectric materials whose thickness is spatially varied to obtain the reported displacement of the peak wavelength from 450 nm to 2500 nm, over a predefined substrate dimension.

Following the profile of Figure 4, a 21-layer variable filter has been manufactured by radiofrequency sputtering using silicon oxide and tantalum oxide as dielectrics.

Wedged thickness profile has been achieved by moving a properly designed mask inside the vacuum chamber during the thin film deposition [13-14]. The maximum obtained peak transmittance is about 60% and the width of the bandpass is narrower than 20 nm. Induced transmission filters give bandwidths broader than all-dielectric counterparts; moreover, their performance is highly sensitive to variations of the metal thickness. However for such a type of coating, the total number of layers remains quite low and makes the fabrication of the variable filter easier. Although the LVF performance was calculated with incoming plane wavefronts, the beam convergence of 10° cone semi-angle was demonstrated not to introduce significant spectral effects. For this instrument the cone semi-angle is approximately 5.5°, so no significant reduction of the filter transmission is expected.

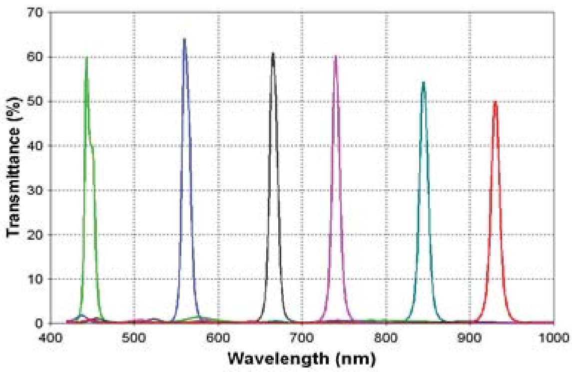

Figure 4 Calculated transmittance of a variable metal-dielectric filter with 21 layers in the visible

Figure 5 is a sketch of the spectral transmittance of the LVF for a slit as wide as the pixel size. The 20 nm bandpass is very frequent in industrial spectrophotometers; however, spectral resolution can be improved by a deconvolution technique [15], specific for colorimetric analysis.

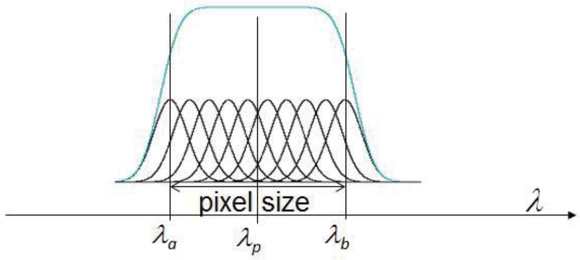

Figure 5 Spectral transmittance of the LVF associated to a slit as large as a pixel. λ_p is the center wavelength, λ_p and λ_p the boundary wavelengths.

Figure 6 shows a view of the LVF as designed for this instrument, with an uncoated area useful for alignment procedures.

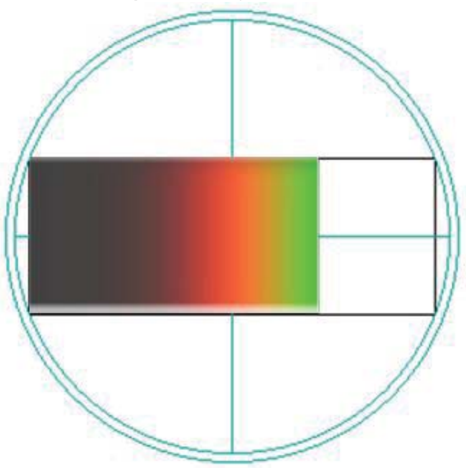

Figure 6 The LVF (8.8 x 6.6 mm^2) is deposited on a 1 inch disk of optical glass. A central strip lager than 8.8 mm, is partly covered with the filter an partly uncovered for framing and for correct setting of the exposure time.

Image reconstruction

From Figure 2 it can be seen that the LVF travels step by step from left to right, while filtering 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 relative 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.

Camera

The use of interline transfer CCD cameras avoids the use of mechanical shutters. With these sensors, each column of pixels is associated with an adjacent column of equal elements. After the exposition process, the charges accumulated in the photosensitive elements are instantly transferred into the vertical registers (before being transferred, line by line, in the horizontal register to read the output signal of the CCD). The shift of the charges from the pixels to the vertical register reading takes about 1µs.

This prototype comes with a 2/3" image sensor. The matrix is 1600x1200 (1.9 MP). The pixels are square with a size of 5.5 µm.

Conclusions

All parts of the proposed spectrophotometric camera have been optimized [16]. Currently, the construction of a first prototype is in progress with all the optical parts moving for an optimal optical arrangement. This compact instrument, even if designed for application to cultural heritage, will be suitable for all applications in which the hyper-spectral imaging is useful. Furthermore, compactness makes it suitable for remote sensing and in-situ measurements.

References

[1] G. Antonioli, F. Fermi, C. Oleari, R. Reverberi. "*Spectro-photometric Scanner for Imaging of Paintings and Other Works of Art*", *CGIV 2004: The Second European Conference on Colour Graphics, Imaging and Vision*, Aachen, pg 219-224 (2004).

[2] Saunders, D., Cupitt, J. "*Image processing at the National Gallery: The VASARI Project*", *National Gallery technical bulletin*, 1 4:72 (1993)

[3] Ribés A.**,** Brettel H., Schmitt F., Liang H., Cupitt J., Saunders D. "*Color and Spectral Imaging with the Crisatel Acquisition System*", proceedings of *PICS'03 The Digital Photography Conference*, pp. 215-219. Rochester, USA (2003)

[4] F. H. Imai, R. S. Berns. "*Spectral estimation of artist oil paints using multi-filter trichromatic imaging*". *9th Congress of the International Color Association*, Proc. of SPIE Vol. 4421 pg. 50-53 (2002)

[5] C. Fischer, J. Kakoulli. "*Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications*". *Reviews in Conservation*, 7, pg 3-16 (2006).

[6] Alexander F.H. Goetz. "*Measuring the Earth from Above: 30 years (and Counting) of Hyperspectral Imaging".* photonics.com: 06/01/2011.
http://www.photonics.com/Article.aspx?AID=47298

[7] M. Hauta-Kasari, K. Miyazawa, S. Toyooka, J. Parkkinen, and T. Jaaskelainen. "*Spectral Vision System based on Rewritable Broad Band Color Filters*", proceedings, *International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives*, MICR'99, Chiba, Japan, October 21-22, pg 155-158 (1999)

[8] K. Miyazawa, M. Hauta-Kasari, and S. Toyooka. "*Rewritable Broadband Color Filters for Spectral Image Analysis*", *Optical Review*, Vol. 8, No. 2, March / April 2001, pp. 112-119

[9] Chengye Mao, Slidell, L. "*Focal plane scanner with reciprocating spatial window"*, United States Patent number 6,166,373, Dec. 26, 2000.

[10] Lewis Neil E, *Haber Kenneth S.* "*Hybrid imaging spectrometer*", World Intellectual Property Organization, Pub. Number WO 02/077587 A2, 03.10.202. / United States Patent number US 2008/0130001 A1, Jun. 5, 2008.

[11] W. J. Smith. "*Modern Lens Design: a resource manual*", (McGraw-Hill, 1992)

[12] D. Morelli. "*Interference Filter Handbook*", (OCLI-JDSU, California, 2006), pg 195-200.

[13] A. Piegari, A. Krasilnikova Sytchkova, J. Bulir. "*Variable transmission filters for spectrometry*", from Space 2. Fabrication process. *Appl. Opt.* Vol 47, C151-C156, pg 13 (2008).

[14] A. Krasilnikova, A. Piegari, M. Dami, L. Abel, F. Lemarquis, M. Lequime. "*Spatially resolved spectroscopy for non-uniform thin film coatings: comparison of two dedicated set-up*", *SPIE Proc. Optical Fabrication, Testing and Metrology*, Vol 5965, pg 573-580 (2005).

[15] C. Oleari. "*Deconvolution of Spectral Data for Colorimetry by Second Order Local Power Expansion*", *Color Research and Application*, 35, pg 334-342 (2010).
[16] A. Della Patria., F. Fermi, C. Oleari, A. Piegari, A. Sytchkova. "*A portable Spectro-photo/radio-metric Camera with Spatial Filtering for VIS-NIR Imaging*", *19th CIC, IS&T: Society for Imaging Science and Technology.* San Jose California Nov. 7-11, 2011. Springfield USA, 285-289, 2011. HSI2012 55