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Detection of a One-Way Mirror Transmittance Byline Spectrometry

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ABSTRACT: The paper describes a system for light spectrum detection of an one-way mirror transmittance by line spectrometry. The system is composed of a focusing lens, a dispersion device and a monochromaticcamera. The focusing lens system determines the Region Of Interest (ROI), consistingof a slight rectangular area that can be considered as a linear array of adjacent cells,and sent the light emitted by the region to the entrance slit of the dispersion device. The light rays emerging from the dispersion device hit the area sensor of the camera,that produces an image composed by the spectra of the elementary cells of the ROI. The paper reports a processing procedure for transforming raw data produced bythe camera into transmittance or reflectance data. The system allows to measurespectra in the range 380-780nm, with spectral resolution of about 5nm.The spatialresolution, that is the dimension of the cells of the ROI, can be set by the imaginglens. The paper describes also an application realized to determine the spectraltransmittance of transparent or semi-reflective mirrors and plates.

KEYWORDS: Cognitive Radio, Spectrum Sensing, Efficient Communication, System Security.

I.INTRODUCTION

We set up a system for performing spectral measurements of the light emitted, reflected or transmitted by an object, which can provide useful information for the research in many application. To achieve this purpose, we used cheap optical components and common hardware and software already used in a previous research [2]. This choice allowed us to quickly set up our measurement system. It allows to simultaneously detect the density spectrum of the light emitted from different points reflecting on the object to be examined. For example, the system was used to evaluate the influence of semi-transparent mirrors, on the quality of the images acquired by placing a camera behind the mirror [3].
Regarding the use of the system in general [6], it is recalled that the quality of the light emitted from a point source is characterized by the spectral density function$S$, which defines the energy radiated at different wavelengths λ; in the case the source is an extended object, a single function S may not be sufficient to characterize the emission and it is necessary to determine the spectral densities relating to elementary areas $\Delta A = \Delta x \times \Delta y$ located on the object surface. In this case, assuming that the object is flat and considering a reference system$\Omega(x, y)$, coplanar to the object, we have a function of three variables$S(x, y; \lambda)$, that can be determined with an instrument able to measure the spatial position of $\Delta A$and its corresponding emission spectrum.

The$S(x, y; \lambda)$ function can be determined by means of line inspections: this means to obtain the $S(x; \lambda)$ function for all the ΔA located on a line with $y = constant$, and then obtain the spectra related to other lines by varying the value of the $y$coordinate (see figure 1).
This kind of examination is simplified when it takes just a line spectrometer, that provides simultaneous spectra emitted from points along a line and produces a B-scan image, as shown in figure 1; the inspection of the entire object is made as subsequently translations along the $y - axis$ of the spectrograph.

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In general, it is possible to use a discrete approximation of $S(x, y; \lambda)$, performing a quantization of the variables in an appropriate manner: in fact we perform measurements only at the discrete spatial coordinates x_i, y_j, with increments $\Delta x$and Δy, and we take only the spectral samples at the discrete wavelength values λ_k with increments$\Delta\lambda$.

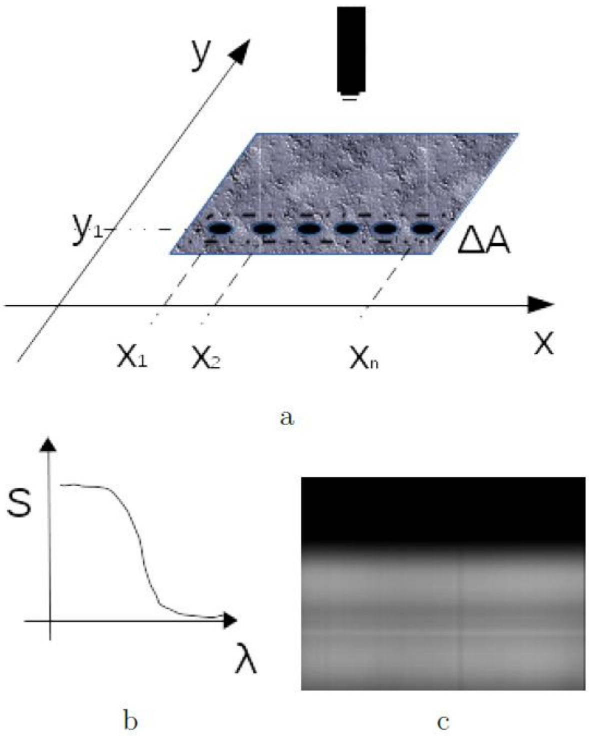

Fig. 1 Line spectrometry of a two-dimensional object: a) inspection plane, b) single spectrum and c) B-scan image

II.MEASUEMENT METHOD

The system realized has the structure shown in figure 2.

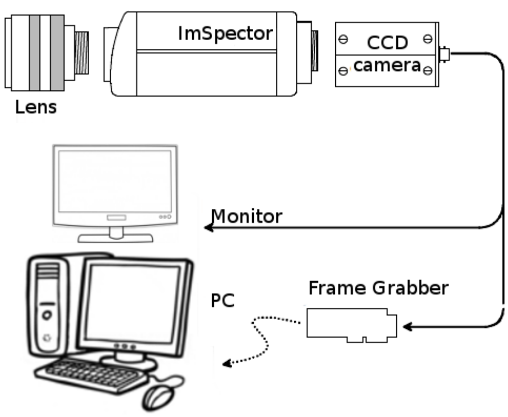

Fig. 2 Structure of the spectrometry system for images

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It consists of:

- a lens, framing the object to be examined
- a dispersion optics, which produces the spectral image $S(x;\lambda)$;
- a monochrome camera, which generates the video signal determined by $S(x;\lambda)$;
- a frame grabber, which gets the corresponding data matrix $S(x_i;\lambda_k)$;
- a computer, which stores and processes data.

The dispersion optics is a line spectrograph, that produces a spectral color image [8]: if the image is formed on the sensor area of a monochrome camera, it is possible to get the gray levels output image, whose axes identify respectively one spatial coordinate and the wavelength of the spectra. The combination line spectrograph - camera is therefore a line spectrometer, that produces a spectral image relative to a thin strip of the scanned object. In the developed system this optics is constituted by a spectrograph ImSpector V8 [4]. This device makes use of a dispersion element PGP (Prism Grating Prism) [1], consisting of a pair of prisms and a holographic transmission grating; these components disperse each collimated beam of light incident on the prism input so that an output beam is produced in which the shorter wavelengths are diverted to the bottom compared to the central wavelength and the longer ones are diverted to the top (see figure 3).

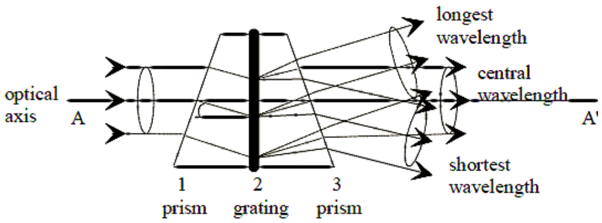

Fig. 3 Light dispersion in ImSpector

The input light passes through a slit placed in the front focal plane of a lens triplet, which produces a collimated beam which enters the PGP; the second lens triplet projects all the rays with the same wavelength at a point on the back focal plane, thus producing the entire spectrum of the input light (see figure 4).

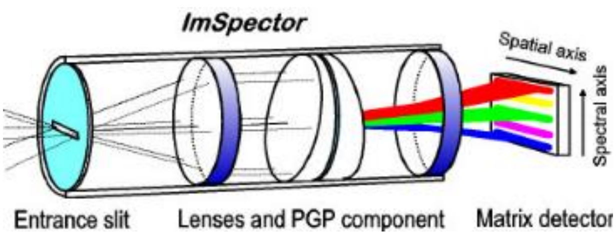

Fig. 4 Collimation and focusing of light in ImSpector

The ImSpector spectrograph can accept a C-mount objective, which have a sufficient MTF (Modulation Transfer Function) and a suitable spectral transmission, and which do not introduce vignetting. The lens focal length and the size of the entrance slit both define the size of the selected ΔA. If the slit has dimension$h \times w$ (where h is the height and w is the width), ΔA has dimension $M \times (h \times w)$, where M is the magnification factor. According to the geometrical optics we have:

$$M = \frac{S_1}{f} \tag{1}$$

where s_1 is the distance between the object and the frontal focal point of the lens and f is the focal length. Table 1 reports the view angle Θ (for a $2/3"$ sensor), the magnification M and the width $W = Mw$ of the examined area, in a function of the focal length f of the objective. The distance of the shooting area from the spectrograph is $s_1 = 1\ m$, the slit width is $w = 8.8\ mm$.

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f	Θ	M	W
8	58°	125	1.11
12.5	39°	80	0.70
16	31°	62.5	0.55
24	20°	41.7	0.35
35	13°	28.6	0.23
50	10°	20	0.18

Tab. 1 View angle (*degrees*), magnification and width (*meters*) in function of objective focal length (*mm*)

Table 2 reports the characteristics of the spectrograph.

Spectral band and dispersion	$380 - 780\,nm \pm 5\,nm$
Spectral resolution with a 80 μm slit	$5\,nm$
Output image	$8.8\,nm \times 6.6\,mm\ 2/3''$
Spatial resolution	*15 lp/mm*
Numerical aperture	*0.18 (F/2.8)*
Height of the slit	$50\,\mu m$
Effective width of the slit	$8.8\,mm$
Total efficiency	$> 50\%$
Connecting optical and camera	C-mount

Tab. 2 Characteristics of the V8 ImSpector spectrograph

ImSpector is designed for the use of cameras with $2/3$" ($6.6 \times 8.8\,mm$) sensor, the camera should be selected so that its performances are in accordance with those of the spectrograph.
In our application we used a CS8310BC camera, produced by Toshiba Teli Corporation.
This camera is equipped with a CCD 2/3" sensor, generates an analog video output and can be set for manual or automatic gain. Table 3 reports the characteristics of the camera; figure 5 shows the camera spectral response.

Image sensor	Interline CCD (Charge-Coupled Device) active pixels: 752 (H) x 582 (V) pixel size: $11.6\,\mu m \times 11.2\,\mu$ m active area: $8.8\,mm\,(H) \times\ 6.6\,mm(V)$
Spatial resolution	H 560 TV lines, V 575 TV line
Standard sensivity	100 lx (at f4, 3200 K, GAIN = FIX, Gamma = 1.0) Minimum 0.5 lx (at f1.4, Gain = max., Gamma = 0.45)
Video output	VS (Video + SYNC) 1.0 Vp-p/75 Ω
Objective mount	C-mount

Tab. 3 Characteristics of the CS8310BC Teli camera

The video signal produced by the camera is digitized using a Matrox Meteor card, able to acquire video signals with the CVBS, Y/C NTSC/PAL and RS-170/CCIR standards. The card is plugged in the 32-bit PCI bus and it is supported by the Software Driver MIL (Matrox Imaging Library[3], for Microsoft Windows.
The user interface of the software (see figure 6) includes several drop-down menu and buttons for selecting and controlling various functions for the acquisition, analysis and storing images.

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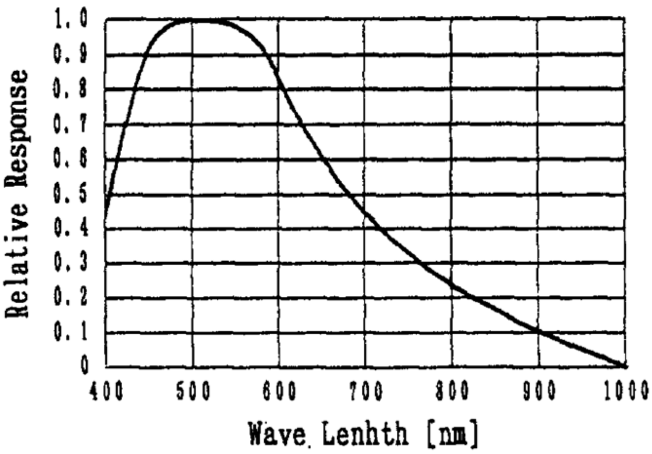

Fig. 5 Spectral response of the CS8310BC camera

The raw data produced by the camera are $L(i,j)$ luminance values, where i and j are row and column indexes respectively. Each column profile $L(j)$ corresponds to the spectral values in function ofλ; therefore to obtain the spectrum value it is necessary to perform the transformation of j in λ and to correct the exposure for the measured artifacts.
Therefore two types of calibration are performed, valid for all the acquisitions made without changing lens setting and object illumination.
In order to correctly measure the wavelengths of the spectrum it is necessary to perform a calibration procedure, using sources that produce known spectra.

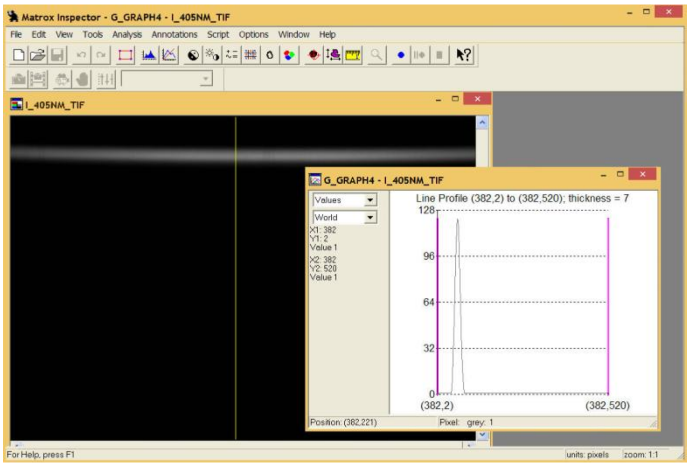

Fig. 6 User interface for image acquisition and processing

To calibrate the system we used interference filters with certified response, produced by Spindler & Hoyer *(currently QiOptic Photonics*, https://www.qioptiq-shop.com) [5]: the filter was placed in front of the slit of the spectrograph, without using an objectives, and it was illuminated by a halogen lamp. The spectral image was obtained and then we got the column profile. Figure 7 shows obtained results.

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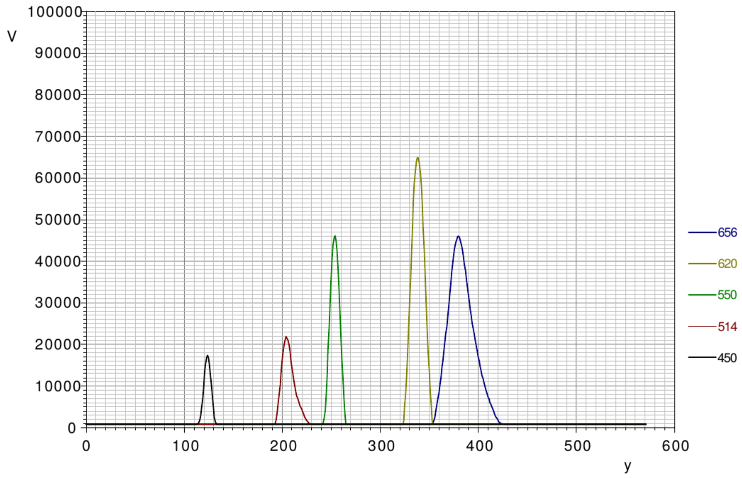

Fig. 7 Columns profile of the interference filters used for the spectral calibration

We have then determined the maximum value of each plot, and formed the corresponding y_i coordinate, obtaining the set of the y_i values. Being y_i known values, constituted by the peak values of the curves, we performed the linear regression of y in function of λ, obtaining in this way the calibration of the column index of the spectral matrix.
Table 4 shows the wavelength of the peak of each filter examined relative to the corresponding coordinate; it moreover reports the correspondence of each filter with a spectral line of emission of an element or a type of laser. The result of the linear regression is:

$$\lambda = 0.8018 \cdot y + 349.5411 \quad (2)$$

with:

- Adjusted R-Squared = 0.9992
- Correlation Coefficient = 0.9997
- Model Selection Criterion = 6.664

λ_{max} , nm	spectral line	y_i
450	C_S	124
514	Argon Laser	204
550	C_S	254
620	Rb	338
656	C_S	380

Tab. 4 Characteristic of the interference filter used during the spectral calibration

Figure 8 shows the measures and the regression line.

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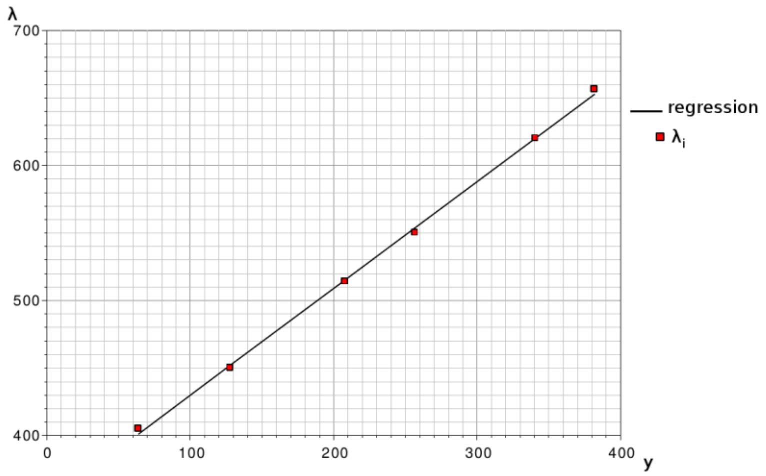

Fig. 8 Linear regression of the data produced by the interference filters.

The obtained scale with the regression is extended on the $349 - 807\ nm$ interval, with an excursion of $456\ nm$ and a resolution of $0.8\ nm$. The nominal spectrograph range is $380 - 780\ nm$, with an excursion of $400\ nm$, for a sensor of $2/3"$ located at $17.53\ mm$ from the output slit.
The elements constituting the image spectrograph have responses dependent on the wavelength of the light. When the light $I(\lambda)$enters the objective, the output of the sensor is (see Figure 9):

$$O = I(\lambda) \times [T_O(\lambda) \times T_S(\lambda) \times S_S(\lambda) \quad (3)$$

where

- $T_O(\lambda)$is the objective transfer function
- $T_S(\lambda)$is the spectrograph transfer function
- $S_S(\lambda)$is the sensor response

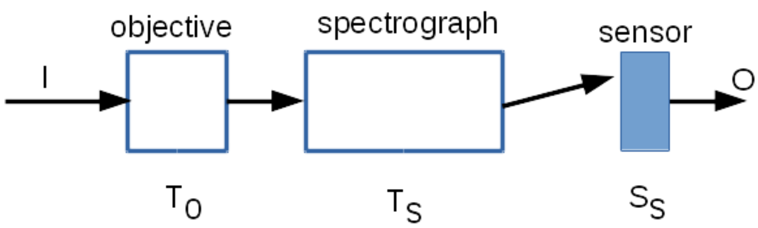

Fig. 9 Components of the spectrometer with response dependent on the wavelength

Equation 3 shows the wavelength dependance of this system. It can be erased considering the output O_o obtained using a white light as calibrating light, characterized by $I_O(\lambda)$ spectrum.
We have:

$$O_O = I_O(\lambda) \times [T_O(\lambda) \times T_S(\lambda) \times S_S(\lambda) \quad (4)$$

Dividing 3 by equation 4 we:

$$\frac{O}{O_O} = \frac{I}{I_O} \quad (5)$$

Equation 5 defines the reflectance $R(\lambda)$of an object spotted by a white reference light. Moreover, equation 5 defines the transmittance $T(\lambda)$ of a filter that is traversed by the reference light.
The light sensor has a non-zero output when it is not illuminated: this noise component (called dark current) can be eliminated by subtracting from the measured signal the signal obtained by obscuring the sensor.
In order to obtain a fine measure of the spectral image M it is necessary to calculate:

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$$M = \frac{O - N}{W} \tag{6}$$

where:

- O is the raw sensor output
- N is the dark spectrum
- W is the spectrum generated by white calibration light

The equation 6 correct the gain of the system too.

III.MEASUEMENT APPLICATION

We have used the described equipment to calculate the transfer function of an one-way mirror.The one-way mirror has the objective to hide the equipment used during the data acquisition to exploit the face as a major indicator of individuals well-being by tracing traits of physical and expressive status. In accordance to a semeiotics viewpoint, face signs will be mapped to measures and computational descriptors, automatically assessed. SEMEOTICONS will design and construct an innovative multi-sensory system integrated into a hardware platform having the exterior aspect of a mirror: the so-called Wize Mirror. This will easily fit into users home or other sites of their daily life (e.g. fitness and nutritional centres, pharmacies, schools and so on).

The equipment used in SEMEOTICONS project consist of a set of cameras working at different wavelengths. It is important to know the transfer function in order to understand if it is possible to elaborate the data acquired by the equipment and eventually to restore the original data.
The figure 10 shows the installation used to measure the transfer function of the one-way mirror.

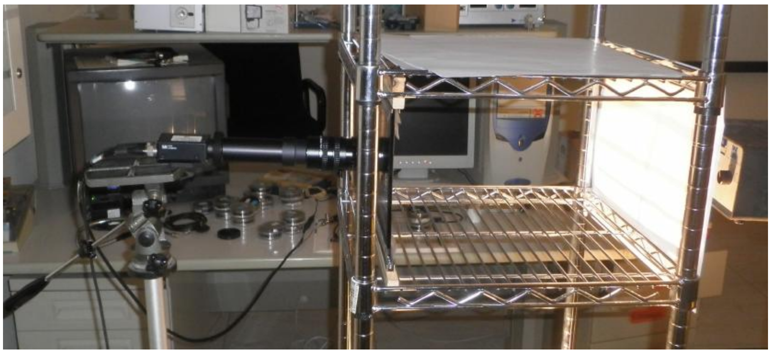

Fig. 10 System used during the measurements

In order to calculate the transfer function we recorded the spectrum of the direct light and the spectrum of the light filtered by the one-way mirror. The figure 11 compares the direct spectrum and the filtered spectrum. Obviously the filtered spectrum has a minor amplitude.

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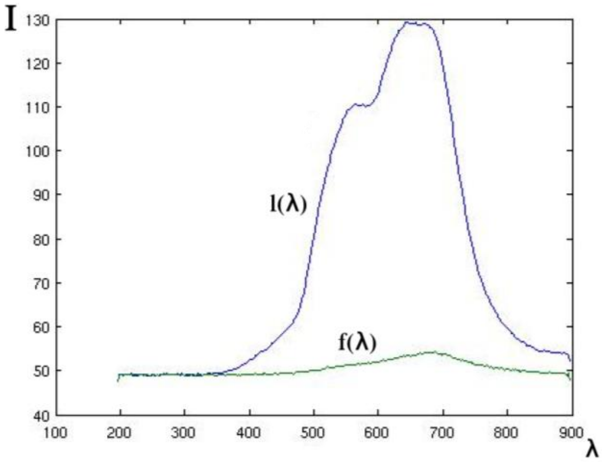

Fig. 11 The figure shows the spectrum of the source light $l(\lambda)$ and the spectrum of the filtered source light $f(\lambda)$

The transfer function $\frac{l(\lambda)}{f(\lambda)}$is shown in the figure 12.The evaluation has been calculated using equation 7.

$$100 - \frac{\int_I \ f(\lambda)d\lambda}{\int_I \ l(\lambda)d\lambda} \cdot 100 \quad (7)$$

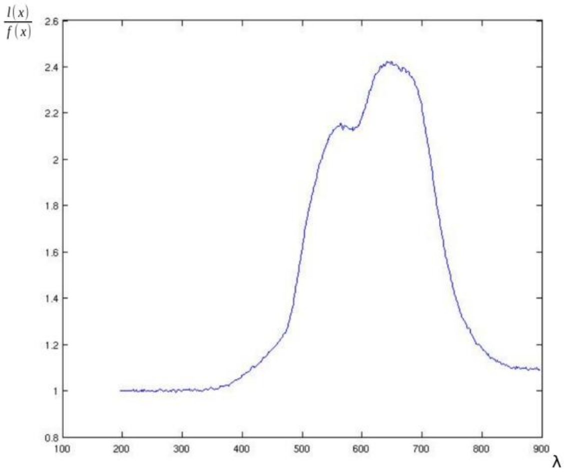

Fig. 12 The figure shows the spectrum of the source light and the spectrum of the filtered source light

The attenuation is 33% in the interval $200 \leq I \leq 900$ and 47% in the interval $400 \leq I \leq 750$.

IV. RESULT AND DISCUSSION

To test the response of the system two types of measurements were performed, in transmission and in reflection. For both types of measurements a Lafayette PA 1508 light source has been used, consisting in a reflector and a 150 W halogen linear lamp. A Javelin TV 12,5 -75, F 1.8 objective was mounted on the spectrograph.

In this series of measures spectral images have been obtained by interposing color glass band filters, produced by Spindler & Hoyer, between the light source and the spectrograph.

To obtain the response of the filters the next basic steps have been followed. Initially we obtained the spectral image produced by the light source, without interposing filters and adjusting the lens aperture for maximum undistorted signal (see Figure 13).

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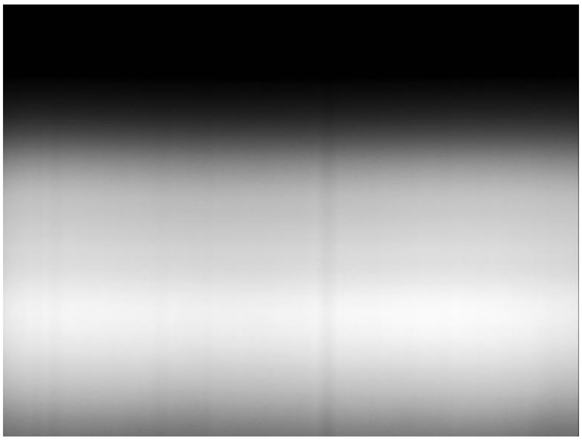

Fig. 13 Spectral image produced by the white reference light source

We calculate the column profile $W(y)$. It is computed considering the column average of the 768 column values and it represent the spectrum of the reference white light. $W(y)$ is shown in figure 14.

Then we plugged the camera in order to calculate the dark current. By computing the column average of the acquired image we obtain the $B(y)$ dark current reference function. The output image generated by this experiment has each pixel value close to zero.

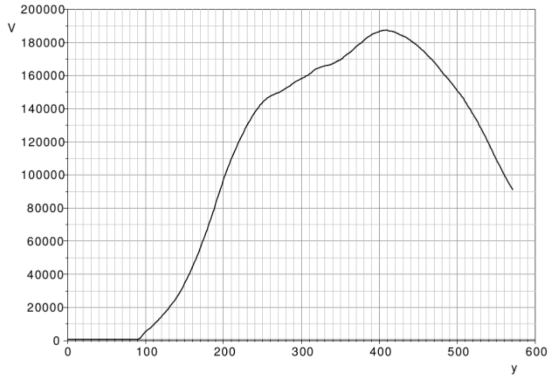

Fig. 14 Spectral image produced by the white reference light source

Then we have computed the spectral image for each filter (figure 15 is an example) and we have computed its profile (figure 16 is an example).

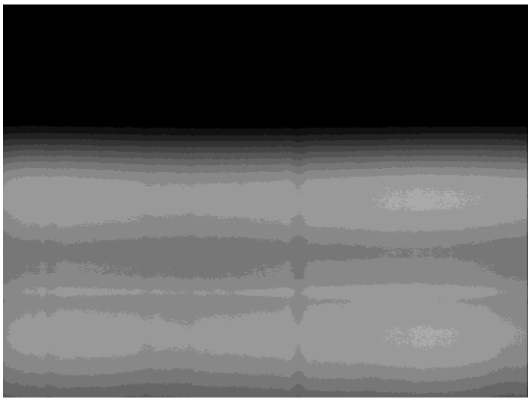

Fig. 15 Sample image obtained by the color glass GG10

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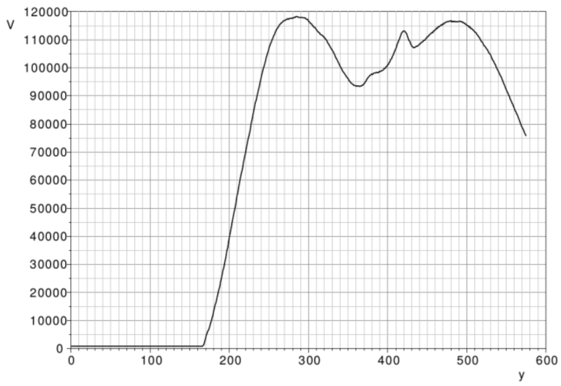

Fig. 16 Profile obtained by the color glass GG10

According to previous equation, we calculated the profile ratio:

$$M_y = \frac{O(y) - B(y)}{W(y)} \quad (8)$$

by the equation 2 we computed the transmittance function of the filter (that is defined in figure 17).

The examined filter responses follow, they describes the filter spectrum. The filters of the groups 1-3 are band pass filter, the filters of the group 4 are high pass filters.

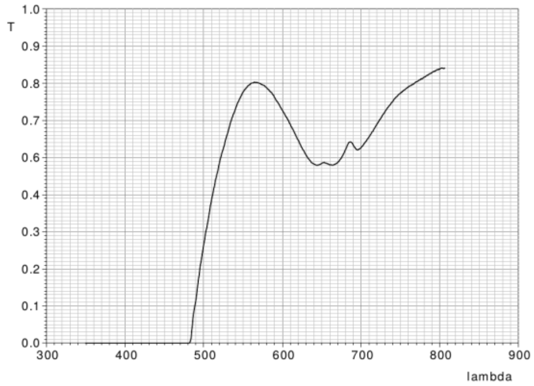

Fig. 17 Transmission curve of the color glass GG10

We performed the image acquisition tuning the numerical aperture and the gain according to reference white settings. We use these settings for all filters except to UG1 filter: in this case we set the gain G to auto in order to obtain a significant signal.

During this experiment we calculates the spectral image of a ceramic tile illuminated by the reference white light [9]. The tile is composed of 12 bars of different colors (see figure 18). We refers to the bars with a label from 1 (one indicates the leftmost, the red one) to 12 (twelve indicates the rightmost, the black one). The bars 4 and 6 have the same green color, the bars 9 and 11 have the same gray color. The width of each bar is about 1 cm.

The tile was aligned with the sensor columns, figure 19 shows tile spectral image of the ΔAareas, with $y = y_1$the sample spectrum.

The sample spectrum has a band structure because each bar reflects an homogeneous light according to its color. Figure 20 show the profile $O(x)$.

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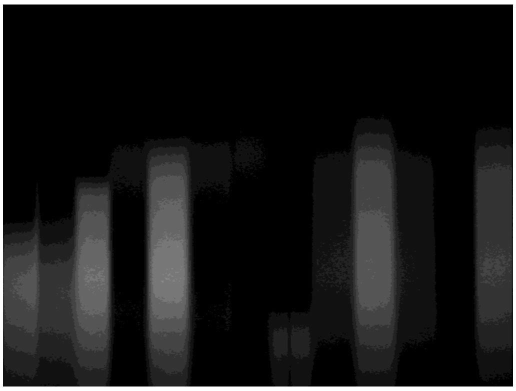

Fig. 19 Spectral image of the tile

The image is composed of 768 columns. The first 714 columns are referred to the 12 bars, the last 54 ones are referred to the background. According with this result, each band has the following width:

$$\Delta x = \frac{714}{12} \cong 60 \tag{9}$$

The spotted field has a widthw $= \frac{768}{714} \cdot 12 = 129.1\ cm$. The effective width of the slit is $w_s = 8.8\ mm$, the optical magnification that the acquiring objective introduces is m $= \frac{129.1}{8.8} = 14.7$. The magnification factor is the same for the height ($h_s = 50\ \mu m$), consequently the spectrograph receives the lightfrom a thin strip of the object, parallel to the entrance slit and with dimensions: $h = 0.73\ mm$ and $w = 129.1\ mm$.

Each column of the image spectral then defines the spectrum of the reflected light from an elementary area of the object, with dimensions $H = 0.73\ mm$ and W $= \frac{129.1}{767} = 0.17\ mm$.

Image spectral profiles were obtained relative to each column of 12 bands; each profile has been averaged over 15 columns, centered on each band. The vectors $O(y)$ were corrected using the vector $W(y)$ relative to the reference white, thus obtaining the vectors $M(y)$; operating the transformation defined by the equation $\lambda = 0.8018 \times y + 349.5411$.

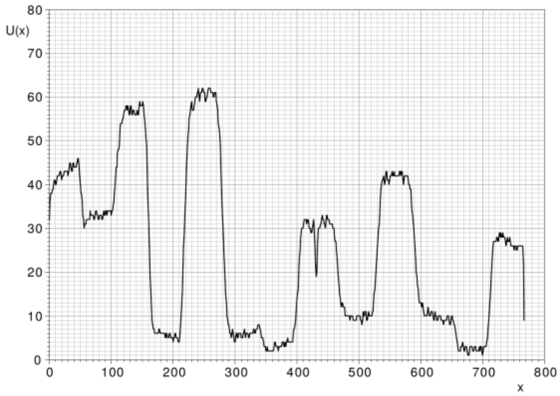

Fig. 20 $O(x)$ profile of figure 18

Figures 21 and 22 represent the calculated spectrum for each bar.

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V.CONCLUSION

The described system is able to simultaneously measure the spectra of light emitted by 768 elementary areas aligned, placed on the surface of an extended object. The dimensions of the areas are determined by the the magnification of the optical lens used to take pictures and the size of the entrance slit of the spectrograph: by opportunely choosing the shooting distance and lens focal extended objects can be examined with the spatial resolution required.

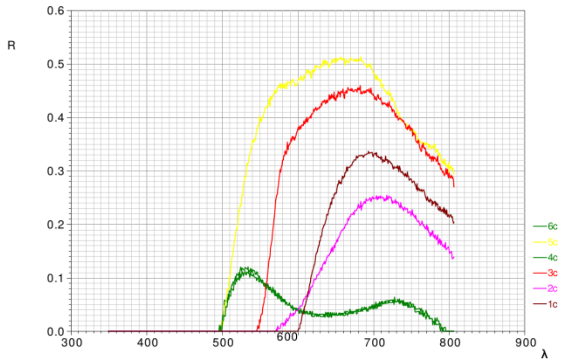

Fig. 21 Reflectance of the bars 1-6

The system can therefore be used for effectively measuring the spectrum emitted from a light source, the spectrum of light reflected from an object, or the light transmitted from a transparent material. The current version of the system makes use of an analog camera and a video card capable of capturing images without compression, defined by the raw data; it is of course possible to use other types of cameras, both analog and digital, according to the work requirements. For processing the acquired data, we made use of standard application programs: since the processing procedure is well defined, it is possible to easily develop its own application able to perform measurements without a need for interaction and able of running on any support.

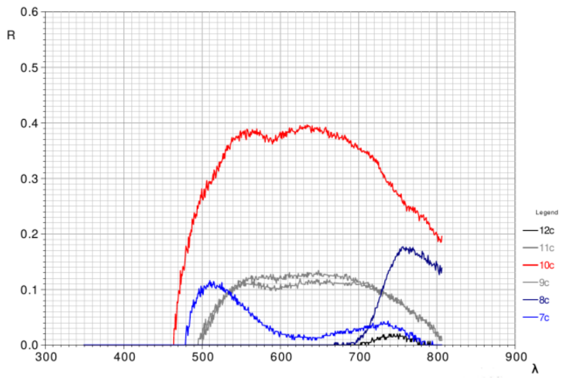

Fig. 22 Reflectance of the bars 7-12

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