MSc in Photonics

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Master in Photonics

MASTER THESIS WORK

DEVELOPMENT OF A SPECTRAL GONIOMETRIC IMAGING SYSTEM BASED ON LEDS

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Development of a spectral goniometric imaging system based on LEDs

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Abstract. The use of goniochromatic pigments, which have a different luminous and color appearance depending on the illumination and observation angles, is rapidly increasing in a wide range of industries. To respond to the companies needs in relation to the control of manufacturing processes and finished products quality controls, some commercial goniospectrophotometers have been developed. They allow performing spectral color measurements using several geometries. In this work a new spectral goniometric imaging system based on LEDs is presented, which allows performing such measurements but with a high spatial resolution as an image sensor is used. It includes 19 groups of LEDs with wavelengths ranging from 368 to 748 nm, as a light source, and a visible and ultraviolet enhanced sensitivity CCD camera. As a first stage, spectral and colorimetric comparisons at standardized geometries have been made between the proposed system and the commercial goniospectrophotometers BYK-mac® and X-Rite MA98®. The results of the measurements on three samples with solid, metallic and pearlescent pigments, showed the usefulness of the system.

Keywords: goniochromatic pigments, goniometric system, multispectral imaging system, light-emitting diodes, spectral reflectance, colour differences.

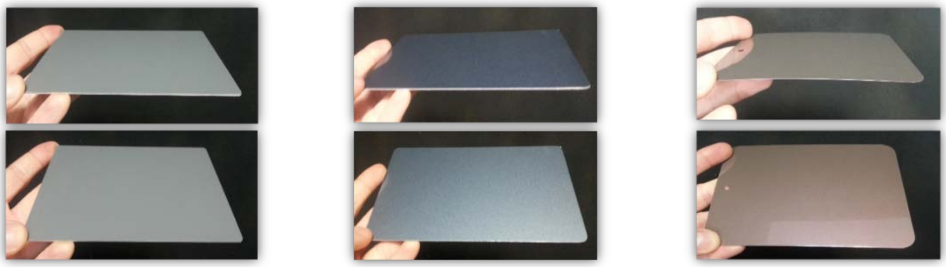
1. Introduction

In recent decades, many industries have included goniochromatic pigments (Figure 1) in their products, such as cosmetics, printing inks, and car paintings. Such pigments, contrary to what happens with standard or solid pigments, have the property of varying the luminous and colour appearance as a function of the incidence and observation angles [1]. Goniochromatic pigments are mainly divided into two categories: metallic and pearlescent pigments [2] (Figure 2). The first ones often show major changes in luminance, while the latter cause changes in hue and chroma. Because of their special and directional features, these pigments cannot be characterized by means of standard spectrophotometers, which only analyse small areas of the sample using specific standard illumination/observation geometry.
As a result of this industrial interest, some companies have launched goniospectrophotometers to measure colorimetric, or even spectral, features of samples with goniochromatic pigments. These systems include a spectrophotometer and a goniometric system which allow characterizing the samples under analysis using different geometries, i. e. several angles of illumination and observation. Examples of these systems are the BYK-mac® and X-Rite MA98®. Similarly to conventional spectrophotometers, these devices include a photodiode and integrate the light coming from a small area of the sample. Therefore, they are unable to differentiate

chromatic and photometric characteristics across the sample surface and only provide averaged luminance and chromatic values.

Figure 1. Some products which use goniochromatic pigments.

Several researchers have demonstrated the usefulness of multispectral imaging systems [3] [4] [5] for the spectral and chromatic characterization of objects with a high spatial resolution. This makes them suitable for the analysis of non-homogeneous samples. They consist of a digital camera together with a spectral sampling system enabling to acquire images of the scene through several spectral bands. The spectral sampling technique might consist of a line scanning spectrograph located in front of the camera to diffract the light into the wavelengths [6] although often wheels with narrow-band or tunable filters based for instance on liquid crystal devices (LCD) can be used instead [7] [8]. To acquire spectral data all the aforementioned approaches require a white light source with a wide spectral emission.
However, the current development and availability of the light emitting diodes (LED) provide new solutions for setting up multispectral imaging systems. LEDs have a narrow spectral emission enabling customized combinations of wavelengths speedily and in switching synchrony with the imaging sensors [9]. However, to our knowledge none of the developed multispectral imaging systems include a goniometer allowing different illumination/observation angles.
The goniometric spectral imaging system presented in this report, which is based on LEDs, allows obtaining spectral and colorimetric measurements of samples with goniochromatic pigments with several geometries. In addition, it also allows the detailed analysis of different parts of the sample due to its high spatial resolution. The aim of this master thesis was performing a preliminary validation of this system, demonstrating its usefulness in performing spectral and colorimetric measurements under different geometries and comparing the results with those obtained using other commercial devices.



(a) (b) (c)
Figure 2. Samples used in this study: (a) solid, (b) metallic, (c) pearlescent.

2. Experimental setup

2.1. Components of the system

The proposed system consists of a set of narrow colour LEDs with peaks from 368 nm to 748 nm, a collimating lens, two motorized rotation stages, a digital camera and specific developed software to command all these elements (Figure 3). A linear actuator (ZLW-0630-02-B-60-L-1000; IGUS, Germany) holds and moves a LED board with 19 different groups of LEDs from manufacturers Philips and Roithner which are centred sequentially in front of the collimating lens (UV-VIS #67-228; EDMUND OPTICS, USA). Every group of LEDs is made of 3, 4 or 5 units depending on the luminance of every unit. The spectral emission and characteristics of every LED group are shown in Figure 4 and Table 1.

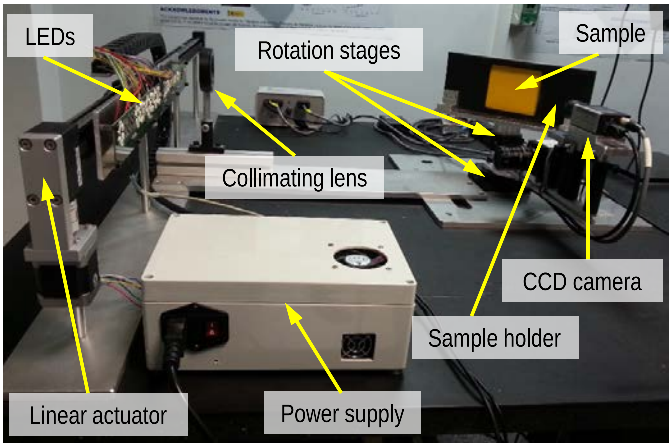


Figure 3. Experimental setup.

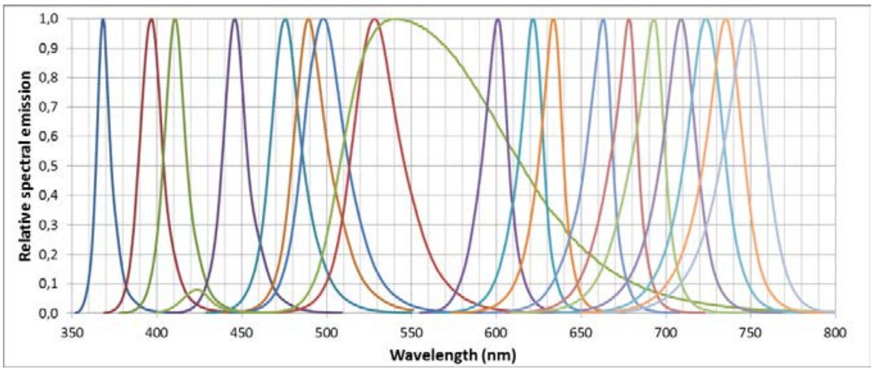


Figure 4. LEDs emission spectra.

To setup the system, we followed the standards ASTM E2194-09 [10], ASTM E2539-08 [11] and DIN 6175-2 [12] which depict the geometries of illumination and observation angles to be used when dealing with goniochromatic pigments, and the aperture of the optic system that collects the reflected light for the measurements. The angle of illumination, i. e. the angle between the light beam and the sample surface, is controlled by the rotation stage where the sample holder is located (8MR151-30; STANDA, Lithuania). The second motorized stage (8MR191-30-28; STANDA, Lithuania) has an arm where the camera is placed, and its movement allows controlling the observation angle, i. e. the angle between the sample surface and the camera. The distance between the lens of the camera and the sample was adjusted so that its entrance pupil subtended less than 4º from the centre of the sample as recommended by the standard.

Table 1. Peak wavelength (λ_p) and Full Width at Half Maximum values (nm) corresponding to LEDs of the system.

LED	λ_p (nm)	FWHM	**LED**	λ_p (nm)	FWHM	**LED**	λ_p (nm)	FWHM
1	368,0	10,0	**8**	528,0	37,0	**15**	693,0	21,5
2	396,5	14,0	**9**	542,0	107,5	**16**	709,0	23,0
3	410,5	14,0	**10**	601,0	16,5	**17**	723,5	25,5
4	446,0	15,0	**11**	621,5	15,5	**18**	735,5	25,0
5	475,5	20,0	**12**	633,5	15,5	**19**	748,0	28,0
6	489,5	23,0	**13**	663,0	17,0			
7	498,0	26,0	**14**	678,0	17,5			

The camera is a monochromatic visible CCD camera (CM-140GE-UV; JAI, Japan) with enhanced sensitivity in the ultraviolet (200 nm – 1.000 nm), 10-bit depth and 1392x1040 pixels. To avoid blurred images for the different wavelengths a central channel is focused and the objective aperture is reduced as maximum as possible (avoiding too low digital levels) to enlarge the depth of focus.
To command the elements of the setup a customized software was developed using MATLAB®. The Graphical User Interface (GUI) of the programme is shown in Figure 5.

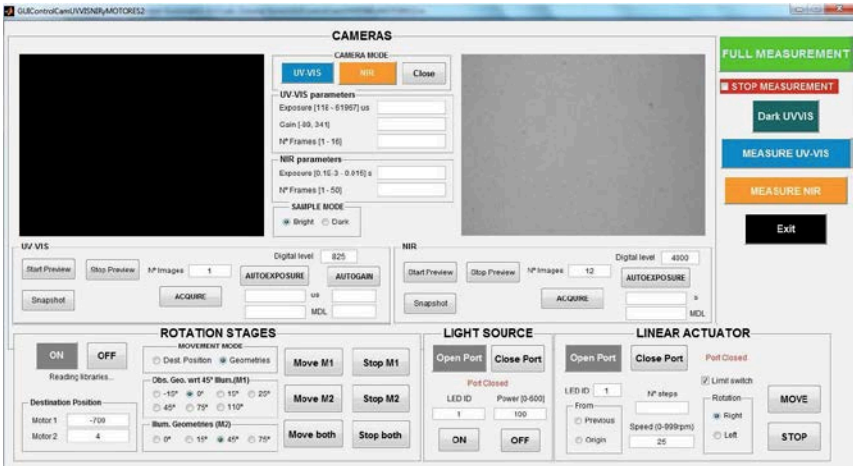


Figure 5. Graphical User Interface (GUI) developed to command the setup.

For each geometry, the developed system and GUI allowed lighting the sample sequentially along all wavelengths, thus obtaining spectral images of the samples.
The geometries chosen were those recommended by the standard DIN 6175-2 (Figure 6): 45ºx:-60º, 45ºx:-30º, 45ºx:-20º, 45ºx:0º, 45ºx:30º and 45ºx:65º (Illuminationºx:Observationº angles).
Autoexposure and autogain algorithms were programmed to properly adjust the exposure time and the gain of the CCD camera to obtain acceptable images with digital levels within the dynamic range for every geometry.

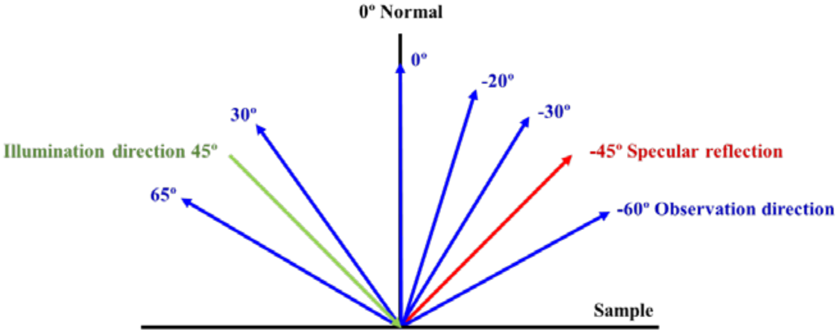
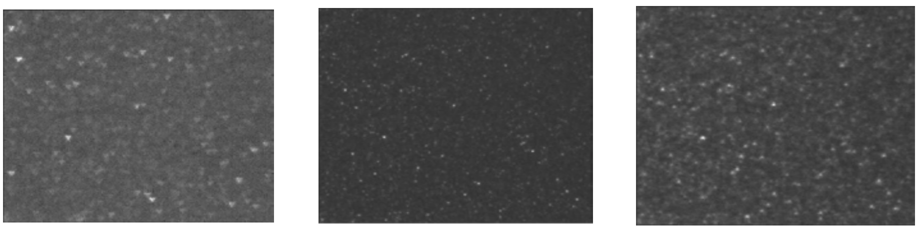


Figure 6. Measurement geometries: 45ºx:-60º, 45ºx:-30º, 45ºx:-20º, 45ºx:0º, 45ºx:30º and 45ºx:65º.

Figure 7 shows several images at different wavelengths and geometries for a specific sample taken with the developed setup.



(a) (b) (c)

Figure 7. Images obtained for the pearlescent sample at geometry 45ºx0º: (a) LED3, λ_p =410,5 nm, (b) LED10, λ_p =601 nm, (c) LED15 λ_p =693 nm.

2.2. Stability of the LED emission, linearity of the CCD response and repeatability of the measurements

As the measurements to be done imply lighting on and off every group of LEDs several times, an analysis of stability of their emission was done by means of images of a calibrated reference white (BN-R98-SQ10C; GIGAHERTZ OPTIK, Germany) with a geometry 45ºx:0º (illumination/observation angle). Several images were captured every 6 seconds during 1 minute for each LED group and the differences among them were computed in terms of mean digital level. A number of 10 images was found to provide differences under 1% in 14 of the 19 wavelengths (only LED 2 exceeded 5%). Therefore, 10 images were subsequently acquired for each geometry and wavelength in order to reduce temporal noise [13] and to ensure good stability of the results over time.

Similarly, the linearity of the response of the CCD camera was checked by taking images for different values of exposure time ranging from 120 μs to 60.120 μs. The results demonstrated an absolutely linear dependence between exposure time and mean digital level (correlation coefficient r = 0,999994).

Finally, the repeatability of the measurements, in terms of digital levels of the images, was also tested. In this context, acquisitions of the calibrated reference white were taken for two different LEDs, each one belonging to a different manufacturer: Philips (LED 8) and Roithner (LED 14). Acquisitions were done with the white reference sample remaining in the sample holder and removing it and putting it again. The variation of the digital level was analysed comparing digital levels pixel by pixel (and then computing the mean), and averaging digital levels of the whole image first and then comparing the means. The results, summarized in Table 2, showed that the two LEDs considered had a similar behaviour. Moreover, differences in digital level never exceeded 2,80% even in the pixel by pixel comparison and when removing and putting again the white reference sample in the holder.

Table 2. Repeatability of the measurements in terms of digital levels.

Differences in Digital Level	Pixel by pixel		Whole value	
	LED 8	LED 14	LED 8	LED 14
Sample remaining in the holder	2,16%	1,66%	0,66%	0,47%
Removing and putting it again	2,77%	2,80%	1,45%	2,28%

3. Image acquisition and colour analysis

With the purpose of comparing colorimetric features measured with our spectral goniometric imaging system and those measured with commercial goniospectrophotometers (BYK-mac® and X-Rite MA98®), three different samples, each one belonging to a different group of pigments, were analyzed: one solid, one metallic and one pearlescent.

For each sample and geometry a 4-dimension matrix (1392x1040x10x19) was created with the measurements taken: the first two dimensions corresponded to digital level values of each pixel of the raw image, the third dimension to the 10 repeated raw images, and the last dimension to the 19 wavelengths used to light the samples.

Acquisitions of the calibrated reference white were also needed for every geometry and wavelength to posteriorly compute the reflectance values. For the same reason, acquisitions were done to know the effect of the CCD camera dark current. Accordingly, dark current images were obtained with all LEDs switched off, and also placing the cap on the objective lens of the camera.

The following formula was applied to obtain the spectral reflectance of the sample at each pixel of the image:

$$r(i,j) = c \cdot \frac{DL_I(i,j) - DL_{DC}(i,j)}{DL_W(i,j) - DL_{DC}(i,j)} \quad (1)$$

where $r(i,j)$ is the reflectance at the pixel (i,j) for a specific wavelength, $DL_I(i,j)$, $DL_W(i,j)$ and $DL_{DC}(i,j)$ are the digital levels of the raw image, the reference white and the dark current images, respectively, and c is the reflectance value of the calibrated reference white given by the manufacturer.
A central area of the image of 400 x 400 pixels was considered in all calculations, which corresponded to an area of approximately 23 x 23 mm on the sample similar to that measured by the goniospectrophotometers BYK-mac® and X-Rite MA98®.
Even the system provided values from 368 nm to 748 nm, calculations with interpolated reflectance data between 400 nm and 700 nm every 10 nm were carried out by means of a Spline interpolation. This was done because posterior colour calculations are always computed within this range and using this step.
While the BYK-mac® goniospectrophotometer only measures colorimetric values, the X-Rite MA98® provides spectral reflectances of the sample under analysis. To compare the spectral curves obtained with the developed spectral imaging system and those measured with the X-Rite MA98®, two helpful spectral metrics were used: the Root Mean Square Error (RMSE) [14] [15] and the Goodness of Fit Coefficient (GFC) [16] [17], which are defined as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left[r_m(\lambda_j) - r_e(\lambda_j)\right]^2} \tag{2}$$

$$GFC = \frac{\sum_{j=1}^{n}\left[r_m(\lambda_j)\cdot r_e(\lambda_j)\right]}{\sqrt{\sum_{j=1}^{n}\left[r_m(\lambda_j)\right]^2 \cdot \sum_{j=1}^{n}\left[r_e(\lambda_j)\right]^2}} \tag{3}$$

where n is the number of wavelengths, and $r_m(\lambda_j)$ and $r_e(\lambda_j)$ are the reflectances measured with our system and with one of the commercial spectrophotometers.
An RMSE value of 0 means a perfect spectral match. The GFC ranges from 0 to 1. GFC values above 0,995 are considered colorimetrically accurate [16], above 0,999 mean a good spectral fit, and above 0,9999 are linked to an excellent spectral fit.
In order to compare the colorimetric values measured with both commercial goniospectrophotometers and with our system, the CIELAB colour coordinates (L*, a* and b*) were computed. L* is the lightness of a colour and its scale goes from 0 (black) to 100 (white). The chromaticity of a colour is codified by a* (degree of red vs green), and b* (degree of yellow vs blue). These parameters are computed as follows:

$$L^* = 116 \cdot f\left(\frac{Y}{Y_W}\right) - 16 \tag{4}$$

$$a^* = 500\left[f\left(\frac{X}{X_W}\right) - f\left(\frac{Y}{Y_W}\right)\right] \tag{5}$$

$$b^* = 200\left[f\left(\frac{Y}{Y_W}\right) - f\left(\frac{Z}{Z_W}\right)\right] \tag{6}$$

where

$$f\left(\frac{\Phi}{\Phi_W}\right) = \left(\frac{\Phi}{\Phi_W}\right)^{1/3} \qquad if \quad \frac{\Phi}{\Phi_W} > 0{,}008856 \tag{7}$$

$$f\left(\frac{\Phi}{\Phi_W}\right) = 7{,}787\left(\frac{\Phi}{\Phi_W}\right) + \frac{16}{116} \qquad if \quad \frac{\Phi}{\Phi_W} \leq 0{,}008856 \tag{8}$$

The X, Y, Z, X_W, Y_W and Z_W are the tristimulus values of the sample and the reference white in the (CIE-1931 color space, respectively [18].
Results were computed using the standard daylight illuminant D65 (DIN 5033-7) [19] and the 10º standard observer (DIN 5033-2) [20].
From the L*, a* and b* coordinates it is also common to compute the Chroma value (C^*):

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (9)$$

The CIELAB colour space is very useful since it allows computing colour differences between samples by means of the colour difference formula CIE 1976 (Nassau 1997):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (10)$$

Colour differences below 1 unit are considered not perceptible. Regarding typically used industrial tolerances, ΔE until 3 can be considered small, between 3 and 6 moderate, and above 6 large colour differences.

4. Results and discussion

Figure 8 shows a comparison of the spectral reflectance curves for the three samples considered (solid, metallic and pearlescent) obtained at different geometries, with the developed system and the X-Rite MA98®. Table 3 shows the values of metrics used to compare spectral differences, i. e. RMSE and GFC values, when all geometries are considered. As it can be seen, the GFC values for the samples are above 0,999 and accordingly can be considered good spectral fits.

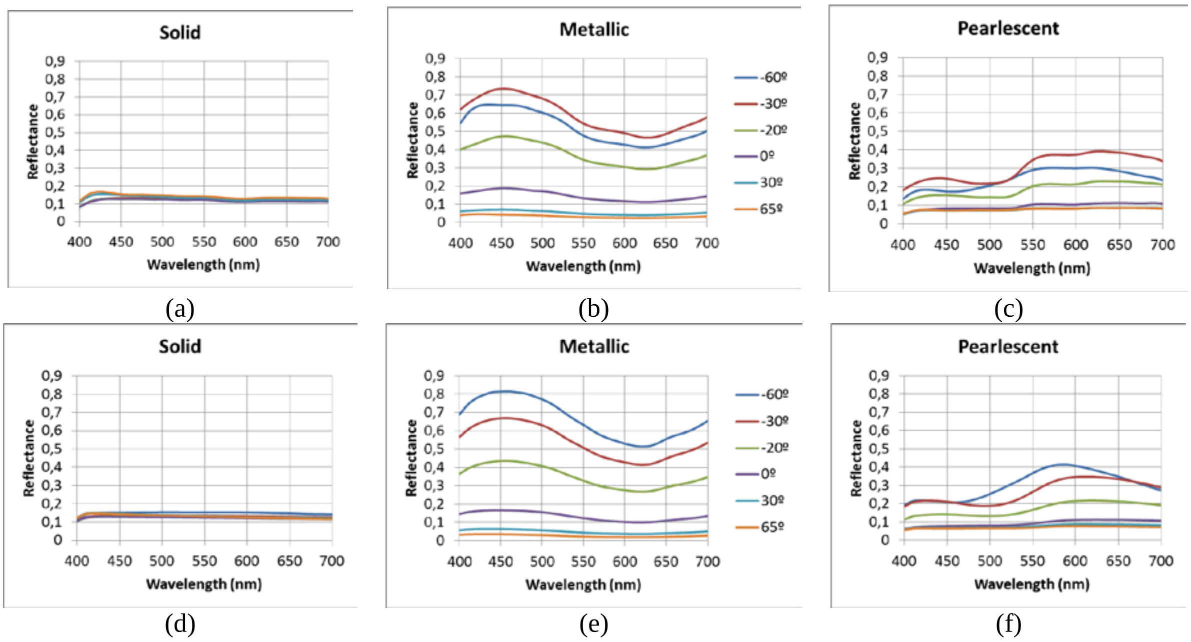


Figure 8. Spectral reflectance of the three samples for different geometries, obtained with the developed system: (a) solid, (b) metallic, (c) pearlescent; and obtained with the X-Rite MA98® system: (d) solid, (e) metallic, (f) pearlescent. Geometries: *45ºx:angle*, where *angle* is the value shown on the graphs.

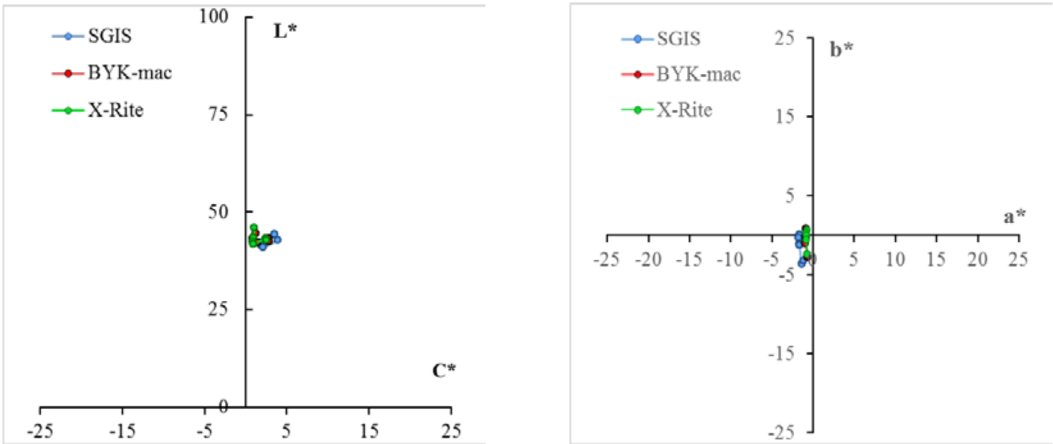
Table 3. RMSE and GFC when the reflectance spectra given by the spectral goniometric imaging system and the X-Rite MA98® spectrogoniophotometer are compared.

	RMSE			GFC		
	Solid	Metallic	Pearlescent	Solid	Metallic	Pearlescent
45ºx:-60º	0,0265	0,1689	0,0957	0,9995	0,9998	0,9982
45ºx:-30º	0,0060	0,0923	0,0714	0,9998	0,9995	0,9994
45ºx:-20º	0,0073	0,0590	0,0294	0,9997	0,9995	0,9997
45ºx:0º	0,0057	0,0380	0,0091	0,9995	0,9995	0,9996
45ºx:30º	0,0035	0,0068	0,0019	0,9998	0,9994	0,9997
45ºx:65º	0,0109	0,0071	0,0094	0,9998	0,9992	0,9997

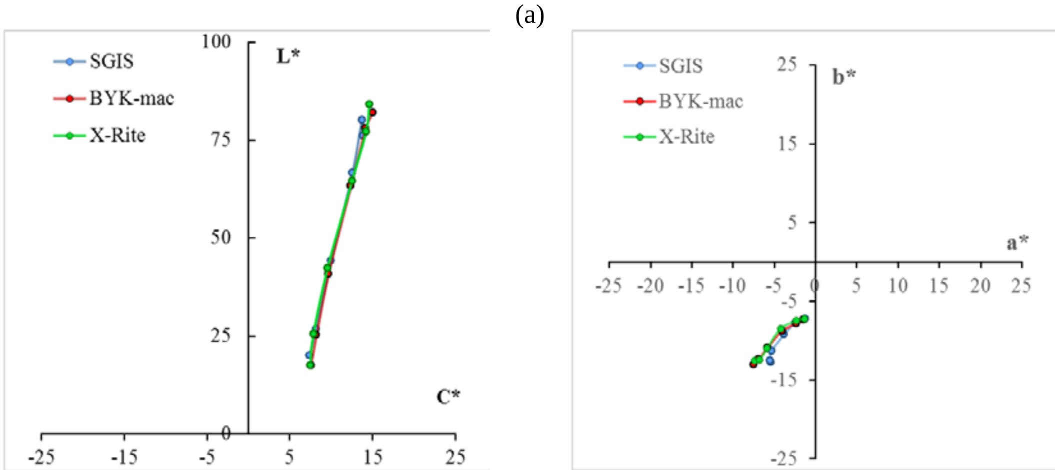
Figure 9 depicts the colorimetric features of the three samples measured with the spectral goniometric imaging system and the commercial goniospectrophotometers BYK-mac® and X-

Rite MA98®. The results obtained by each device are represented by six points joined with a solid colour line, corresponding to the 6 different geometries.

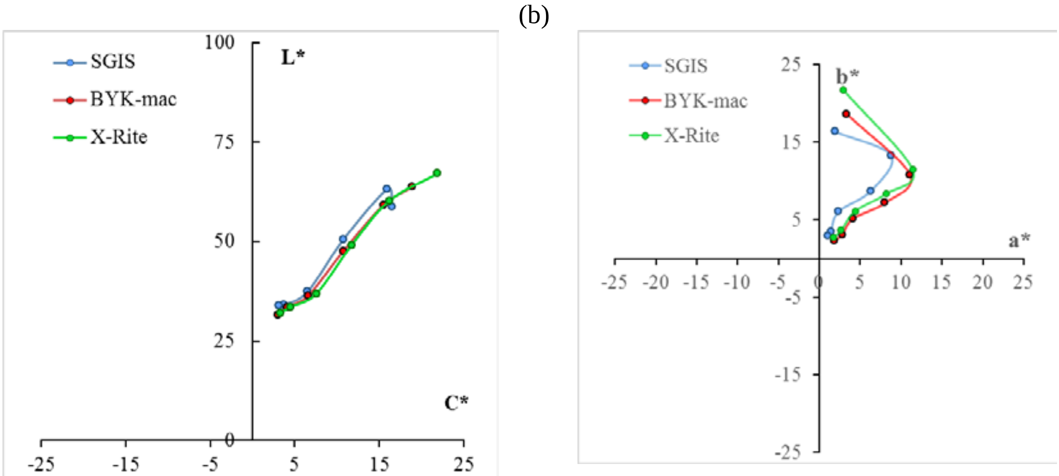
The solid sample gave rise to the lowest variations in lightness (*L**) and chroma (*C**) for al geometries and devices. This was expected because its chromatic appearance does not vary significantly for different viewing angles. However, when samples with goniochromatic pigments are taken into consideration, a different colour appearance is observed when the angle is changed. The metallic sample experienced variations in both, lightness and chroma, but *L** changed much more than *C**. On the contrary, the pearlescent sample suffered lower changes in *L** and larger changes in *C**. As it can be seen in the plots, this behaviour was found using the three devices.



(a)



(b)



(c)

Figure 9. CIELAB diagrams of the solid (a), metallic (b) and pearlescent samples (c) for the three devices tested (SGIS: spectral goniometric imaging system).

In Table 4 the colour differences (ΔE) between the outputs of our spectral goniometric imaging system and those of the BYK-mac® and X-Rite MA98® are summarized.
As it can be seen the best results in terms of colour differences are achieved with the solid sample. The metallic and pearlescent samples were linked to slightly larger colour differences although in general they were below 6, which is generally considered acceptable for industrial purposes. However, for the geometry 45ºx:-60º, which is close to the specular reflexion angle, ΔE exceeded this value. It is worth noting that differences between both commercial devices were also larger in this specific geometry, with values above 3 and 4 in case of metallic and pearlescent samples, respectively.

Table 4. CIELAB colour differences (ΔE) when comparing the goniospectral imaging system and the commercial devices for the 3 samples.

Sample	ΔE	45ºx:-60º	45ºx:-30º	45ºx:-20º	45ºx:-60º	45ºx:-30º	45ºx:-20º
Solid	BYK-mac	2,48	1,33	1,59	1,36	1,24	2,01
	X-Rite	3,93	1,65	1,77	1,39	1,49	1,72
Metallic	BYK-mac	6,24	2,43	3,37	3,37	1,60	2,61
	X-Rite	8,19	3,22	2,12	2,12	1,29	2,63
Pearlescent	BYK-mac	5,61	5,21	3,67	2,21	1,51	2,51
	X-Rite	9,95	4,28	2,42	2,10	1,39	2,12

5. Conclusions

A spectral goniometric imaging system based on LEDs has been presented in this study. Spectral and colorimetric measurements have been made on three samples, one solid and two with goniochromatic pigments: one metallic and one pearlescent. The spectral reflectance curves were obtained for six standardized geometries of illumination and observation: 45ºx:-60º, 45ºx:-30º, 45ºx:-20º, 45ºx:0º, 45ºx:30º and 45ºx:65º, and were compared with those measured in the same conditions with two commercial goniospectrophotometers: the BYK-mac® and X-Rite MA98®.
Spectral metrics to analyse differences between curves (RMSE and GFC) as well as colour coordinates in the CIELAB space (L*a*b*) and colour differences (ΔE) were used to study the performance of the new developed system in comparison with the commercial devices. The results obtained suggest the feasibility of the system to perform both spectral and colour measurements as similar results were obtained.
Future work will be focused on extending the measurements in the near-infrared range, as well as on developing software routines to get texture descriptors as sparkle, graininess and mottling.

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