High spatial resolution imaging colorimeter and gloss-meter for measurements of small parts

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Abstract

A high spatial resolution imaging colorimeter and gloss-meter is presented. The combination of a high quality imaging colorimeter with an off axis imaging optics and a highly stabilized RGB LED source allows color and gloss measurements of small parts with high accuracy. The characteristics of the system with some experimental results on black coated and printed papers are presented.

Introduction

Surface quality inspection has become important in a variety of fields such as the metal, plastic, paper and printing industries. Optical measurement methods, in particular, are widely used for surface quality inspection since the optical measurements do not destroy the measurement objects [1]. Two commonly used parameters for surface appearance evaluation are surface color and gloss. Conventional gloss-meters and colorimeters can provide such information averaged on a small spot on the surface of a flat object. Nevertheless, these instruments are not capable to measure very small pieces and do not provide any information on the sample microstructure that generally plays a key role in the aspect of the object. The purpose of this paper is to present a new instrument capable to measure color and gloss of small pieces with high spatial resolution and high accuracy.

The gloss is strictly speaking the ratio of the reflectance ratio of the measurement with a C source in very specific geometric conditions to the measurement in the same conditions on a black flat glass mirror [2]. In the literature, different methods have been proposed to make gloss imaging but very few fulfill exactly the standards. The simplest setup includes a collimated beam illumination coupled to an imaging camera at the specular position [3]. Combination of linear collimated light source and line-scan camera improves the evenness of focus [4]. Diffractive optical element based gloss-meters have also been introduced [5]. This type of instrument works even on curved surfaces but requires a scanning to make imaging with medium spatial resolution.

Imaging colorimetry has been used for many years and various applications. To obtain color accuracy in all conditions, there is no other solution than making a system that closely matches the CIE curves at any wavelength [6]. It is why sensors with imbedded colors filters cannot be used for this purpose. One practical solution is to use monochrome sensors and to match their spectral response to CIE curves adjusting the transmittance of the color filters to each sensor [6]. For imaging of non-emissive objects it is needed to illuminate and the control of the color and stability of the light source are potentially additional sources of errors. In the present paper, we introduce an instrument capable to measure the color and gloss of $3x3cm^2$ surfaces with high spatial resolution and excellent accuracy. The key points of the system are presented first. Then several examples of applications are reported.

Experimental details

General description:

A schematic diagram of the system is presented in figure 1. It is composed of an off-axis imaging objective associated with a high resolution ELDIM UMaster video colorimeter, a computer control LED based illumination and a mechanical setup for easy control of small samples. The sample is illuminated at several geometric configurations and observed at 25° in specular configuration. It is mounted on a horizontal sample holder that can be shift back for easy replacement. Vertical movement of the illumination and detection allow manual adjustment of the focus. All the components are included in a box to get rid of the external parasitic light.

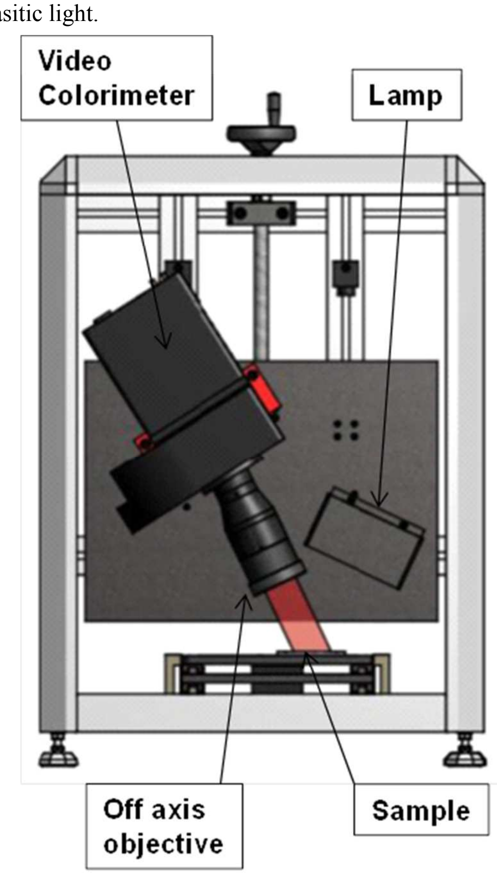

***Figure 1**. Schematic diagram of the VGC100 system*

Imaging colorimeter

Imaging polarimeter UMaster is based on a Peltier cooled CCD sensor with true 16-bit analog digital converter. UMaster includes a set of five color filters designed specifically for each CCD sensor. These filters are manufactured as a combination of different color glasses that work in absorbance. Advantages are very good accuracy because of the adaptation of the design to each CCD sensor and an excellent durability. All the objectives are telecentric on the sensor side to ensure the same transmittance of the filters in the entire field of view of the system. In addition this configuration ensures that collection efficiency is independent of the distance to the object [7].

Off axis imaging optics

For the present measurement system, the objective is also telecentric on the object side to ensure the light collection on the entire field of view (cf. figure 2). In addition the imaging optics is slightly tilted in order to obtain a well-focused image in the entire field of view for a collection angle of 25°. An intermediate iris is used to fix the collection aperture that is the same for all the point on the object surface (~4° in the present configuration).

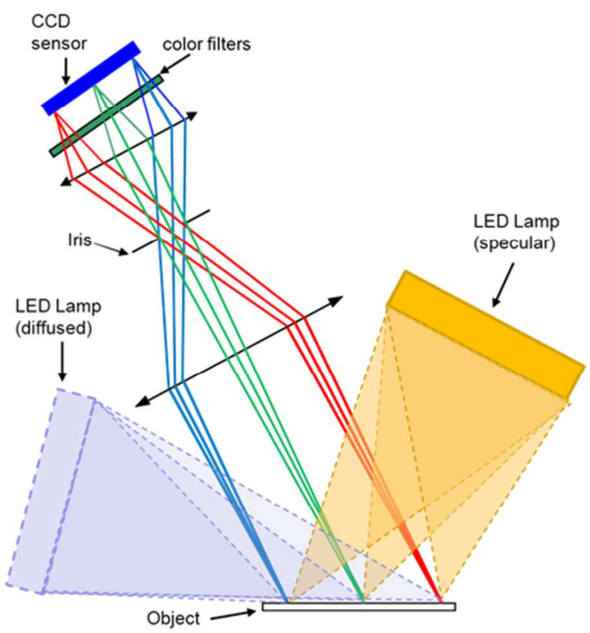

***Figure 2**. Schematic diagram of the off axis imaging objective and large aperture illumination in specular of diffused configuration*

Illumination lamp

The LED illumination is realized with RGB LEDs regularly positioned on a dedicated IC that can be controlled with a USB connection. Additional RGB photodiodes and temperature sensors allow a good stabilization of the emission. The source emission is calibrated in an absolute way using a reference spectrophotometer [8]. The independent control of the R, G, and B channels allows adjustment of the color of the illumination within the RGB triangle (cf. figure 3). Two light source configurations are available for gloss or color measurements.

For gloss measurements, the LED source is included in an integration sphere whose exit is used as punctual source with the same telecentric optic to obtain a collimated beam illumination in specular configuration. The illumination aperture is maintained constant all over the field of view and much smaller than the collection aperture (~1°).

For color measurements, a flat diffusor on top of the LED IC increases the homogeneity of the source. The maximum luminance for white state is around 1400cd/m^2. Two positions are possible for the source, one in specular configuration and one in backscattered configuration (cf. figure 2).

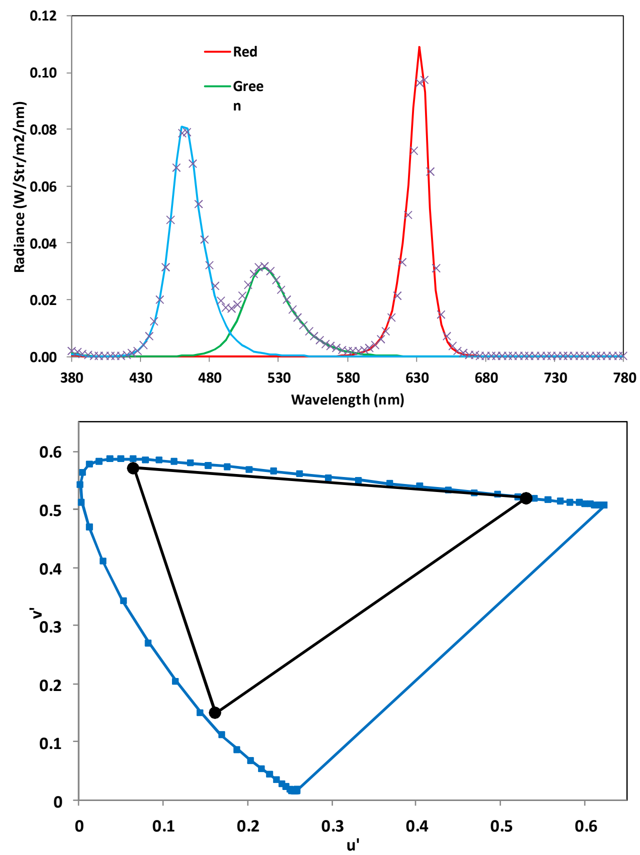

***Figure 3**. Emission spectra of the R, G and B LEDs of the LEDLamp and corresponding gamut*

Two characteristics are important for the illumination source; the stability of the source versus time must be very good not only in terms of luminance but also in terms of chromaticity; in addition the homogeneity of the source in terms of chromaticity must be good also. The homogeneity in terms of luminance is not mandatory since the lack of homogeneity of the illumination on the sample surface can be calibrated using a reference sample or a black glass. The stability is ensure by regulating the temperature of the source with different temperature sensors directly on the integrated circuit and by using one RGB sensor to adapt in real time the flux of the three types of LEDs. We have measured the stability of the chromaticity of the source using a SR3 spectrophotometer. The standard deviation on x and y color coordinates for a D65 illuminant are around ± 0.00016 for x and ±0.00006 for y for a time of 1 hour.

The homogeneity in terms of chromaticity is not good if the same working conditions are applied to each LED as shown in figure 4.a. The chromaticity variation is due to the dispersion of the emissive characteristics of the different LEDs on the integrated circuit. To improve the homogeneity it is necessary to measure the emissive properties of each LED and to apply calibration coefficients to each LED to match the same target for red, green and blue emission. This procedure generally applied to LED displays improves strongly the homogeneity of the chromaticity of the source as shown in figure 4.b.

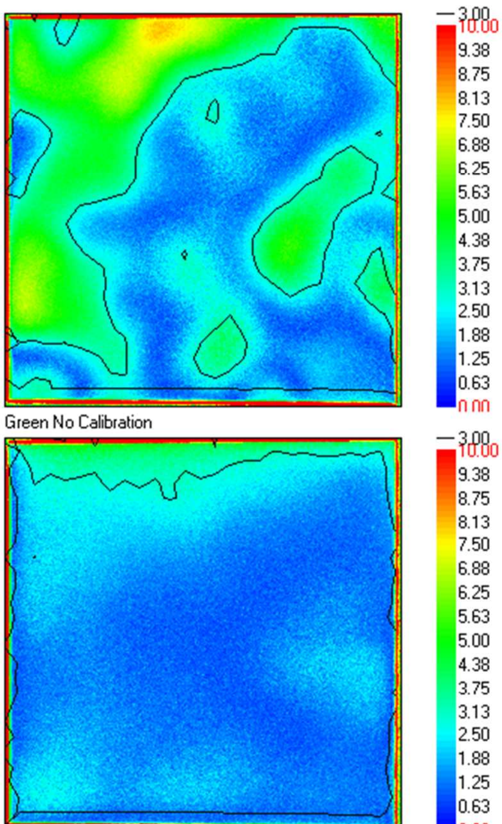

***Figure 4**. Chromaticity of the LEDLamp emission without (top) and with color calibration (bottom) for green primary color*

Illumination calibration for color measurements

In spite of the good homogeneity of the emission of the light source, the illumination of the sample surface is not exactly the same for all the positions. This effect cannot be calibrated with regards to a fixed reference because the gradient depends on the BRDF of the sample under investigation. So, an adapted reference sample needs to be measured in the same illumination conditions to correct from this lack of homogeneity. For near Lambertian surfaces it can be a white reference sample for example and for printed samples the original white paper can be used. The simplest way to use the system is to compute deviations from the reference sample point by point. If X(p),Y(p), Z(p) CIE are component measured for each pixel of the image and Xs(p), Ys(p) and Zs(p) the CIE component measured for each pixel on the reference sample the calibration is made computing the results in the CIELAB space using the formula:

$$L^* = 116 f\left(\frac{Y(p)}{Y_s(p)}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X(p)}{X_s(p)}\right) - f\left(\frac{Y(p)}{Y_s(p)}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y(p)}{Y_s(p)}\right) - f\left(\frac{Z(p)}{Z_s(p)}\right)\right]$$

The function f is the standard nonlinear transformation if the CIELAB space. The measurement is then compensated pixel per pixel to the inhomogeneity of the illumination and the results are directly the color shifts to the reference sample taken as white reference in the L*a*b* color space. The method reported above has the advantage of the simplicity but provide L*a*b* value in a color space that is not conventional in particular when the reference sample has a color that is far to the white. In some cases it can be useful to reference the results to a standard reference white measured in the same illumination conditions. In this case the Xw,Yw, Zw CIE components of the central part of the image measurement on the reference white are extracted and used as reference white for all the pixel of the image. If Xs(0), Ys(0) and Zs(0) are the CIE component measured of the central part of the image measurement on the reference sample we use the formula:

$$L^* = 116 f\left(\frac{Y(p)Y_s(0)}{Y_s(p)Y_w}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X(p)X_s(0)}{X_s(p)X_w}\right) - f\left(\frac{Y(p)Y_s(0)}{Y_s(p)Y_w}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y(p)Y_s(0)}{Y_s(p)Y_w}\right) - f\left(\frac{Z(p)Z_s(0)}{Z_s(p)Z_w}\right)\right]$$

Experimental results

Color repeatability:

The repeatability of the system has been evaluated using a white reference sample and by repeating the same measurement 30 times (cf. figure 5). One spot of 4mm diameter located in the center of the imaging field has been used to evaluate the standard deviations on the measurements. Results are comparable to the best standard non-imaging colorimeters on the market.

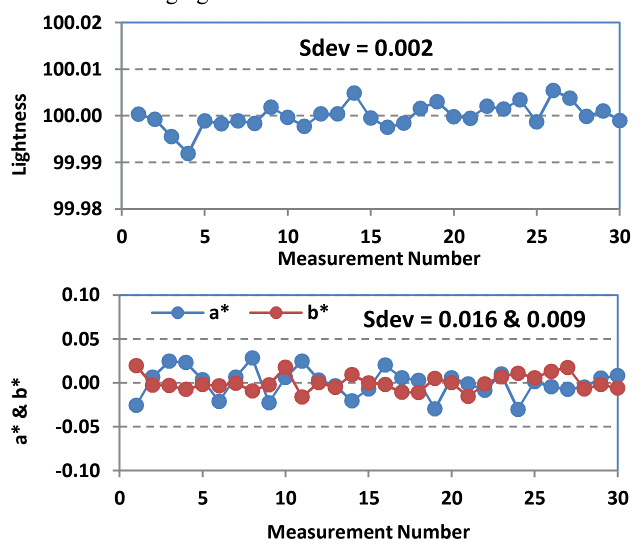

***Figure 5**. Lightness (top) and color coordinates (bottom) measured 30 times on reference white*

Color accuracy:

To check the accuracy of the system we have made measurements on one color checker using a high precision spectrophotometer [8] in the same conditions (illumination and detection) and compared the results. A summary of the results is reported in Table I. The accuracy is excellent on all the zones.

Table I: Differences of color between SR3 spectrophotometer measurements and VGC100 measurements on 17 zones of a color checker: Lambertian white reference is used for illumination calibration

	Differences				
Zone	ΔL*	Δa*	Δb*	ΔC	ΔHue
Blue	0.001	0.099	0.472	-0.437	0.267
Green	-0.007	-1.118	0.140	1.048	0.418
Red	-0.003	0.695	0.521	0.855	0.115
Yellow	-0.003	-0.597	2.248	2.111	0.833
Magenta	-0.004	0.790	-0.525	0.794	-0.482
Cyan	-0.015	0.132	-0.677	0.262	0.861
Orange	-0.001	0.434	0.328	0.542	-0.040
Purplish Blue	0.002	-0.157	-0.392	0.364	-0.311
Moderate Red	-0.010	1.122	0.872	1.342	0.405
Purple	-0.015	-0.175	-0.760	0.107	-1.663
Yellow Green	0.002	-0.043	-1.257	-1.017	0.720
Orange Yellow	-0.007	0.638	0.719	0.944	-0.172
Neutral 8	0.002	-0.191	-0.277	0.324	/
Neutral 6.5	-0.007	-0.422	-0.256	0.493	/
Neutral 5	-0.004	0.074	-0.464	0.409	/
Neutral 3.5	-0.010	-0.035	-0.149	0.149	/
Black	-0.042	-0.243	-0.110	0.119	/

Gloss measurements on black coated papers:

We have used a series of black coated papers with decreasing gloss characteristics (3C Conseil). The specular gloss has been measured with a standard Zethner gloss-meter at 20° and 60° (cf. table II). Results are expressed in gloss unit (gu), given by the ratio of the flux reflected, in a given diaphragm centered on the specular direction at the surface of the sample to the flux reflected, in the same conditions, at the surface of a standard black glass [2]. Of course each incidence angle provides a different gloss scale more or less adapted to mirror like or glossy samples.

Table II: Summary of the gloss measurements using standard gloss-meter at 20° and 60° and VGC100 system: the data analysis is made on the histogram adjusting an asymmetric Gaussian.

	Glossmeter		VGC100 collimated 25°		
Sample	20°	60°	Gloss	FWHM Min	FWHM Max
1	63.30	90.90	85.03	24.92	56.92
2	34.20	75.90	48.77	16.32	33.22
3	23.00	61.60	31.85	9.70	19.79
4	13.20	51.30	20.67	5.71	12.13
5	11.00	47.20	17.08	4.55	9.81
6	6.10	36.00	10.20	2.45	5.11
7	3.10	24.50	5.16	1.18	2.32
8	1.50	11.80	1.94	0.37	0.67
9	0.80	4.60	0.60	0.09	0.15
10	0.50	1.30	0.17	0.02	0.03

We have measured these samples using the VGC100 system and calibrated the results in the same way using a black glass. One example of measurement is reported in figure 6 with the gloss distribution adjusted with a symmetric Gaussian. A summary of the results obtained on the 10 samples is also reported in Table II and figure 7. As already reported in the literature [9], imaging gloss data allow statistical analysis of the distribution of gloss and not only averaged values. In particular the skewness of the distribution that's play a role in the human observer judgment can be easily extracted.

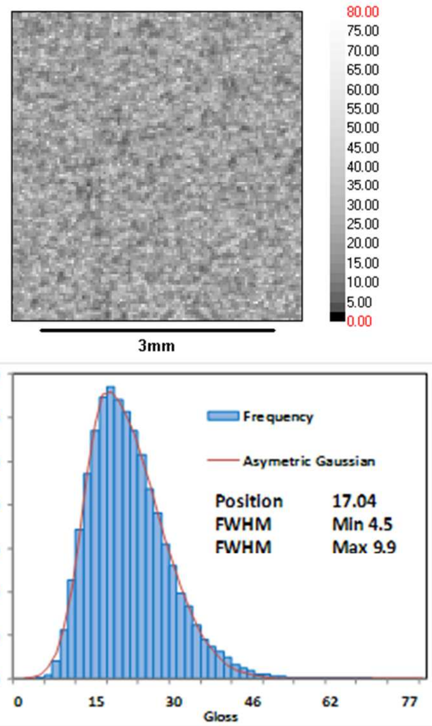

Figure 6. Gloss measurements on sample 5 (top) and corresponding histogram (bottom).

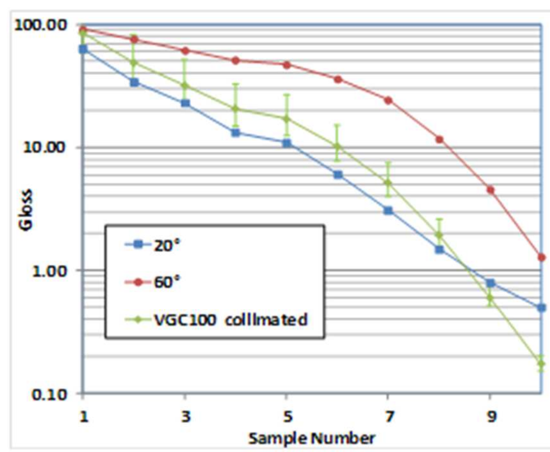

Figure 7. Gloss measurements obtained with a gloss-meter at 20° and 60° and using VGC100 system.

Color measurements on printed paper:

Color pattern used for the print tests is reported in figure 8. Height homogeneous zones with black, white, red, green, blue, cyan, magenta and yellow saturated colors are surrounded by four linear graded zones from white to black, cyan, magenta and yellow. One Brother J5910DW printer is used for the tests and the measurements have been calibrated with a measurement made in the same conditions on the same white paper. Specular and diffused illuminations with D65 at 800cd/m^2 have been used.

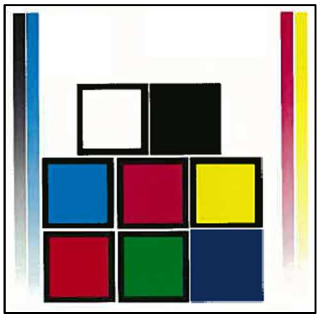

Figure 8*. Color pattern used for the printing tests.*

Color gamut for the two illumination conditions are reported in figure 9. The lightness behavior is also reported in figure 10. The impact of the paper quality can be easily determined. In the present case, the important differences between the two illumination conditions are mainly due to the relatively high gloss of the paper. High resolution imaging allows precise analysis of the printing imperfections in particular at the edges of each homogeneous zone as shown in figure 11.

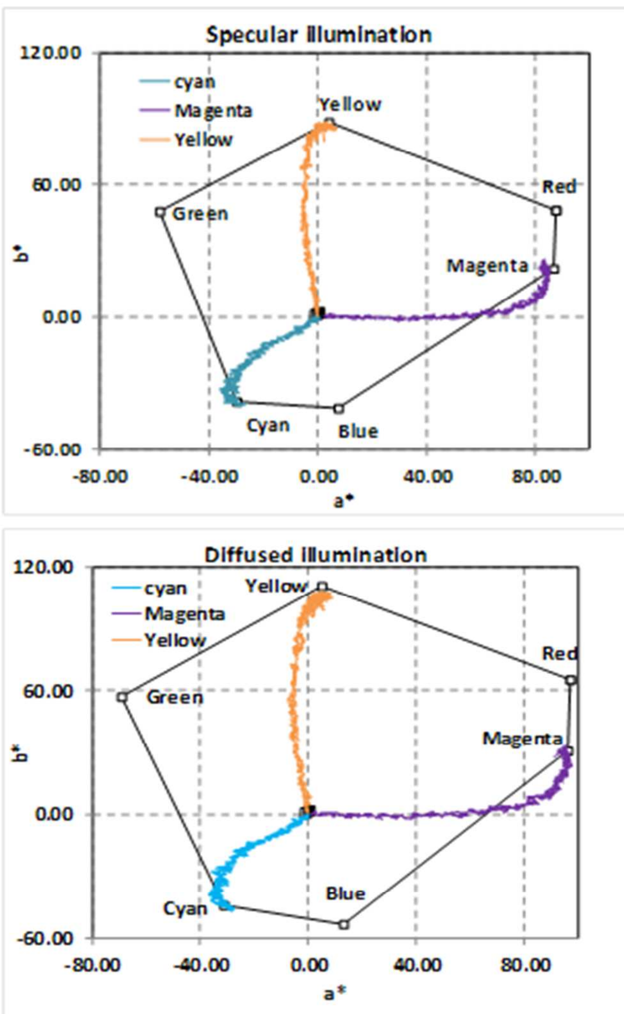

Figure 9. Gloss measurements obtained with a gloss-meter at 20° and 60° and using VGC100 system.

Conclusions

A new imaging gloss-meter and colorimeter has been presented. Combination of a highly accurate video colorimeter, an innovative tilted imaging objective and a versatile LED illumination, it allows precise color and gloss measurements on several cm^2 with high spatial resolution. The collection angle is fixed at 25° and all the field of view can be focused simultaneously thanks to a tilted double telecentric objective. Special care has been taken to the quality of the illumination that can be applied in three different configurations. Quality control of the gloss and color on small parts becomes possible with this new system.

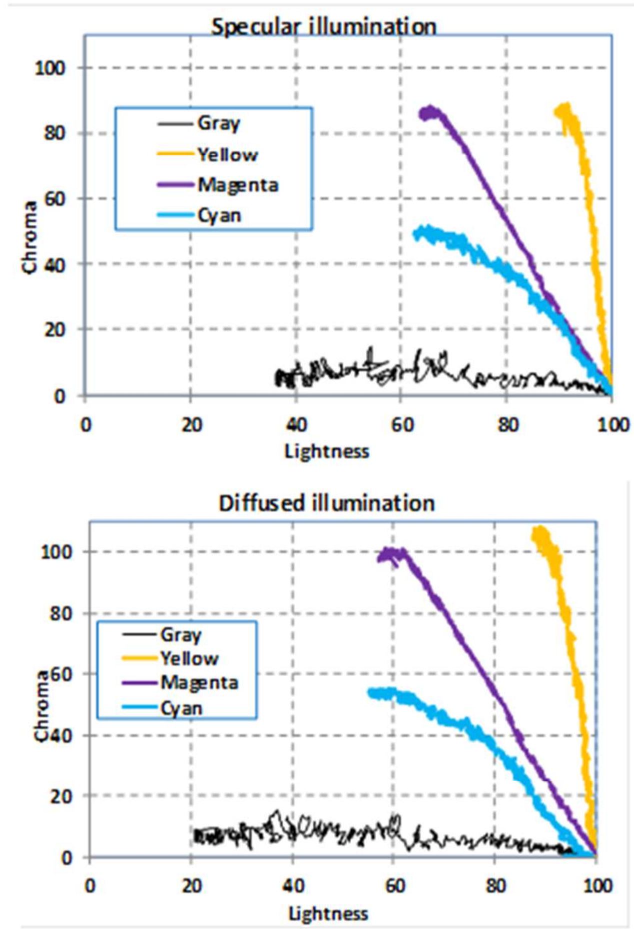

Figure 10. Chroma versus lightness for the different graded regions measured with specular illumination (top) and diffused illumination (bottom).

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Author Biography

Pierre Boher earned an Engineer degree at the ECP (Ecole Centrale des Arts et Manufactures) in 1982. After earning his Ph.D. in material sciences in 1984, he worked in the French Philips Laboratories during nine years on the deposition and characterization of very thin films and multilayers. R&D manager at SOPRA between 1995 and 2002, he participates to the development of different metrology tools for non-destructive characterization mainly for microelectronics. He joined ELDIM in 2003 to be involved in the research and development of new metrology heads..

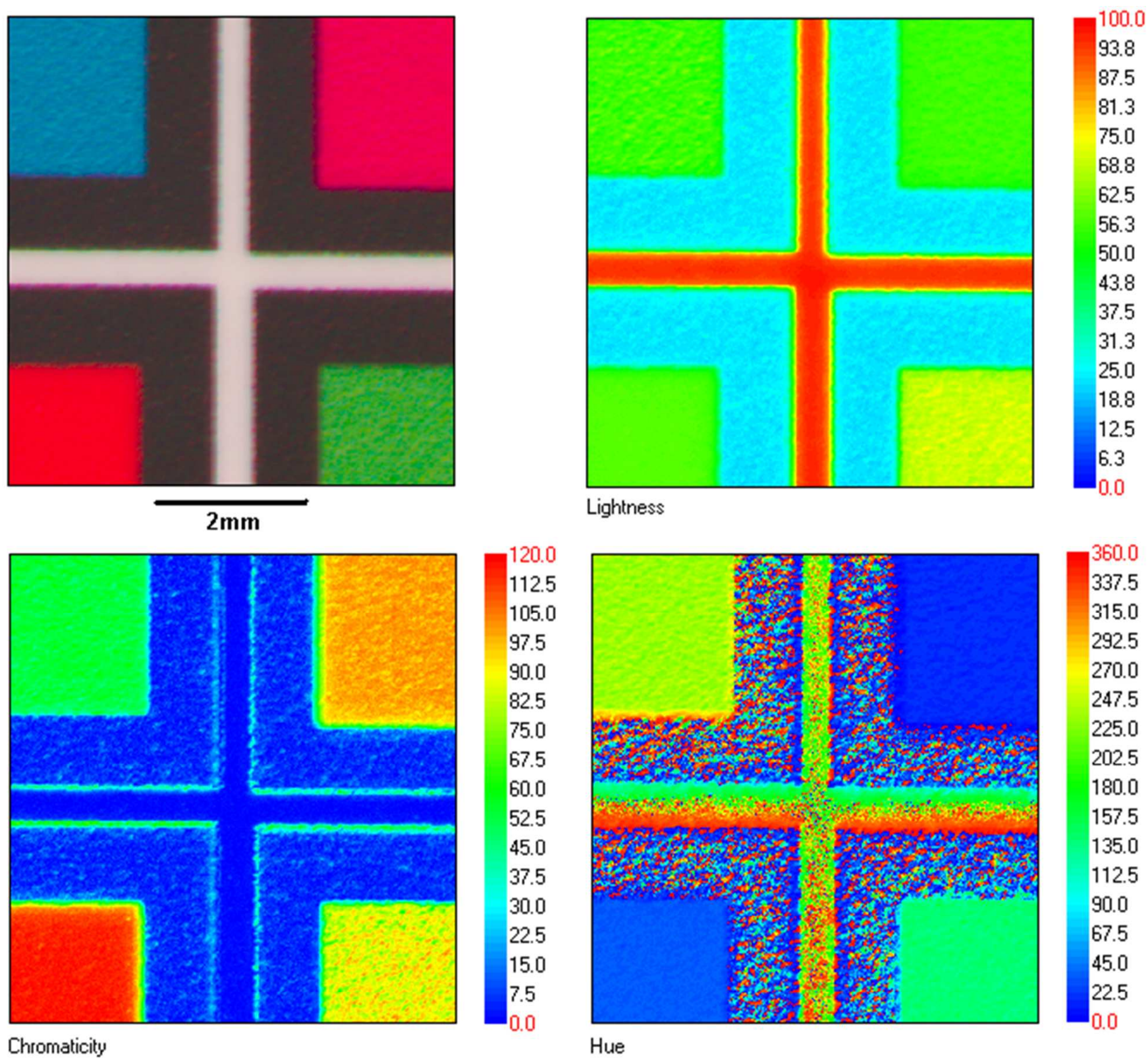

Figure 11. *Enlargement of the color measurement made under diffused illumination on the printed pattern of figure 8: in addition to the color image, the lightness, chromaticy and hue mapping are also reported.*