WHITEPAPER

FluxGage Photometric Test System offers enhanced functionality

Measuring color uniformity

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The color uniformity of light generated by LED luminaires plays a major role in many lighting applications. This makes it an important parameter to measure in both the R&D stage and during the quality assurance process. MKS Instruments has stayed abreast of this challenge by developing a new feature for its FluxGage photometrical system: the color uniformity measurement function. It allows quick evaluation of optical assemblies for color mixing and beam shaping. This whitepaper presents this novel feature of the system.

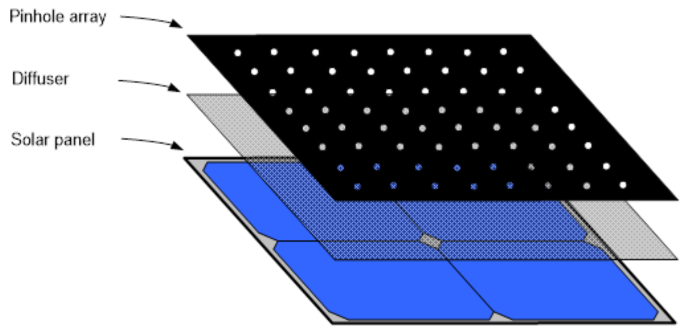

Figure 1. Absorber structure

The technology

What makes the FluxGage system (for a detailed introduction, see [1]) unique is its use of solar panels that are covered with a very finely perforated black layer (see Fig. 1). These diffusive pinholes create the effect of hundreds of radiometers surrounding a light source. In the FluxGage system, all these ‘radiometers’ are electrically connected, so the data obtained are not angularly resolved but measure the total flux, so far field conditions are not required. This makes the FluxGage a very compact instrument for measuring total luminous flux – smaller than an integrating sphere, and certainly much smaller than a goniophotometer.

In addition to the radiometer array, a spectrometer senses the spectrum of the DUT (device under test), which is used for calculating color parameters such as CCT, CRI, TM30, etc. A fast photodiode is used to measure flicker. The spectrum is also used in calculating the total flux for correcting the non-photopic spectral response of the solar panels according to Equation (1),

where: R(λ) is the responsivity of the solar panels (including the pinholes) in [A/W·nm]; Φe(λ) is the spectral flux of the DUT in [W/nm]; S(λ) is the normalized measured spectrum; and V(λ) is the photopic function [1].

$$(1)\ \Phi_v = \int \Phi_e(\lambda)V(\lambda)d\lambda = I\frac{\int S(\lambda)V(\lambda)d\lambda}{\int R(\lambda)S(\lambda)d\lambda}$$

Because the spectrum is measured at only one position, it is not averaged as with an integrating sphere, and the above calculation assumes uniform spectra are emitted by the DUT in all directions. While this assumption is justified when measuring luminaires that are well color-mixed [2], it may be inaccurate for measuring bare LEDs, for example.

The latest enhancement of the FluxGage integrates smart color sensors into the system: The AS7261 spectral sensing engine from AMS [3] is a tristimulus XYZ+NIR (near infrared) sensor device that relies on silicon interference filters to accurately reproduce the tristimulus spectral functions. Built into the bottom of the device, the four AS7261 sensors serve several purposes:

- Adding four extra measurement points for color, thus improving the accuracy of the measured color.
- Measuring color uniformity: Since the color is sampled in five positions, this addition is useful for measuring color-mixed luminaires – information that is simply not available when using an integrating sphere.
- Measuring illuminance at several positions from below the DUT. While the measurement is done in near field and therefore not useful for obtaining precise angular data, it can be used in production testing.

In the next sections, we review this new feature in detail.

Color uniformity measurement

Instrument geometry

An image of the FluxGage system is presented in Figure 2. The solar panel absorbers on the inside walls define the measurement cavity. The small, white baffle in the center indicates the position of an optical fiber placed behind a diffuser; it guides light to a spectrometer that is mounted inside the system. The small orange dot indicates the position of a photodiode that is used to measure the light's temporal characteristics, i.e., flicker. The four blue circles indicate the position of four diffusers that are positioned above the AS7261 color sensors.

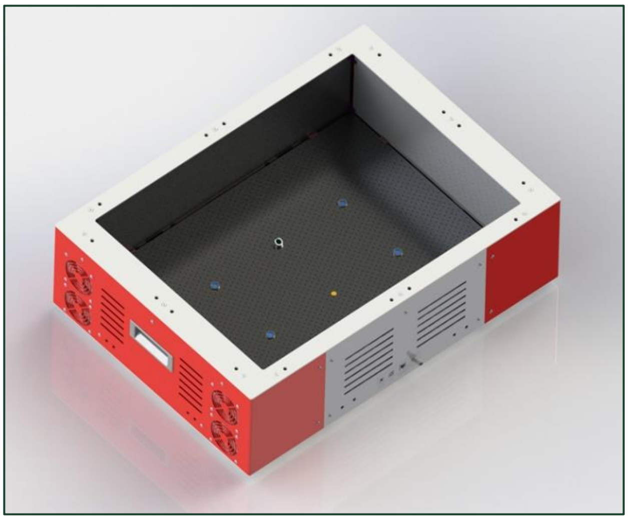

Figure 2. The FluxGage system

In this configuration, the diffusers provide a cosine corrected angular sensitivity for each of the color sensors, and a metal ring slightly limits the field of view of each sensor. By making the metal rings taller, the field of view of the color sensors can be limited to a defined area directly above them.

Software integration

The FluxGage's dedicated software has been upgraded to support the new color-sensing functions. Now it also displays – in real time – colorimetric parameters like CCT, Duv and the color coordinates of each sensor.

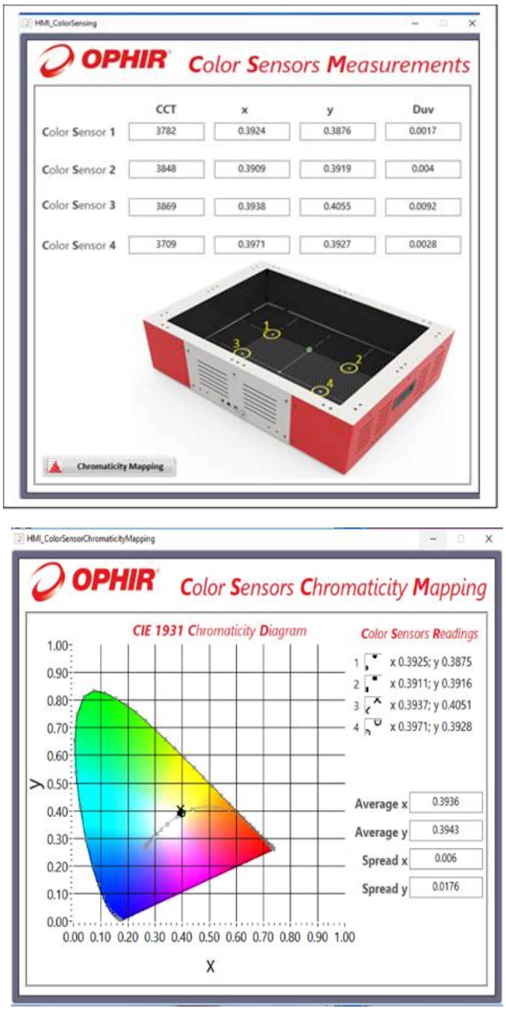

Figure 3. Color coordinates real-time measurements.

The software devopment kit (SDK) was further updated to include color data for seamless integration into existing projects and automation.

Calibration

All AS2761 sensors come factory pre-calibrated; that means a calibration matrix is already stored in each sensor. This matrix is used to translate the raw signal from the sensor's independent channels into calibrated XYZ tristimulus values, from which color parameters such as CCT and Duv can be calculated. Since the color sensors are placed below the PTFE diffuser and the glass plate that cover the photovoltaic cells (see Figure 1), a two-step in-situ calibration process is needed to improve their performance. In the first step, three thermally stabilized LED sources (CCTs of 2,700K, 4,000K, and 5,600K) are placed above the FluxGage's calibrated spectrometer port and measured exactly. From the XYZ tristimulus values read for each LED source, a reference matrix M is built:

$$M = \begin{pmatrix} X_{2700K} & X_{4000K} & X_{5600K} \\ Y_{2700K} & Y_{4000K} & Y_{5600K} \\ Z_{2700K} & Z_{4000K} & Z_{5600K} \end{pmatrix},$$

In a second step, the LED sources are placed, one after another, above each one of the sensors. From the tristimulus signals measured by the color sensors, we build a sensor response matrix R:

$$R = \begin{pmatrix} X_{2700K} & X_{4000K} & X_{5600K} \\ Y_{2700K} & Y_{4000K} & Y_{5600K} \\ Z_{2700K} & Z_{4000K} & Z_{5600K} \end{pmatrix}$$

The correction matrix C, which satisfies:

$$M=C*R,$$

is calculated via:

$$C=M*R^{(-1)}$$

The correction matrix is calculated for each sensor and then saved in the sensor's internal memory. If we measure the three calibration LED sources with each sensor after calibration, we can evaluate the residual error introduced by noise during the calibration.

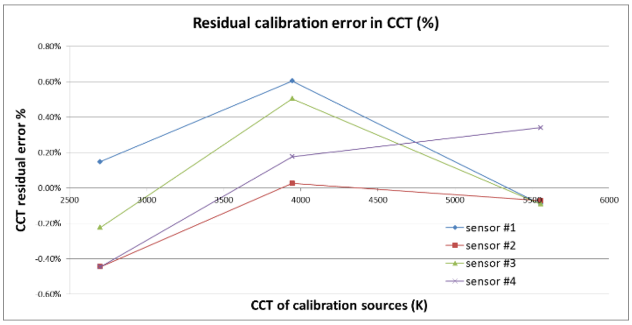

Figure 4 presents the residual error in CCT for each sensor, it shows the residual error in CCT (K) is ±0.6% for the three tested CCTs of 2,700K, 4,000K and 5,600K.

Experimental results and validation

Validation

An Ophir FGC100 FluxGage calibration LED source was used to verify the validity of the calibration. The Ophir FGC100 is a stabilized, broad-spectrum, white-light LED with a CCT of 3,770 K; it is spectrally uniform in its angular distribution, meaning that it emits the same spectrum in all directions. The FGC100 is first positioned over the FluxGage's spectrometer, and its spectrum and CCT are recorded.

In the next step, we place the FGC100 precisely over each color sensor and record the XYZ and CCT values. The results are shown in Table 1

	Spectrometer	Color S. # 1	Color S. # 2	Color S. # 3	Color S. # 4
CCT (K)	3775	3790	3762	3774	3755
CCT error (%)	**0**	**0.40%**	**-0.35%**	**-0.03%**	**-0.53%**

Table 1. Validating the color sensor calibration

Presicion of the color sensor's measurement

To assess the color sensor's repeatability and short-term noise effects, an Ophir FGC100 stabilized LED source with a CCT of 3,768 K is placed over color sensor # 4 and measured every 10 seconds over a time span of 10 minutes. The FluxGage software's data logging function is used to record the data.

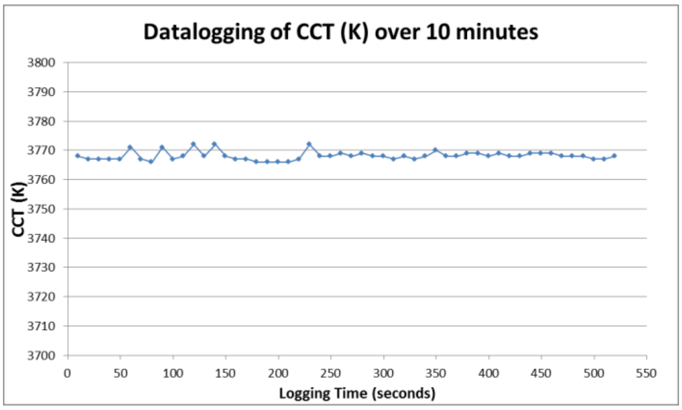

Figure 5. CCT datalogging over a 10-minute time span.

The average CCT is found to be 3,768K ±0.04% (one standard deviation). The precision of the color sensor can be defined as ±0.08% at a k=2 (95%) confidence level.

Dynamic range

In addition to measuring colorimetric parameters, the FluxGage color sensors can also be calibrated for measuring illuminance, providing illuminance measurements at five different points under the tested luminaire. Each sensor is thus effectively an independent photometer integrated into the FluxGage. The illuminance data can be used to understand and validate the angular distribution of the luminaire. The RGB sensors integrated in the FluxGage system have adjustable gain and integration time, which allows for a large dynamic range: 140lux-5Mlux.

Conclusions

The latest addition of smart tristimulus color sensors to the FluxGage boosts the measurement system's capabilities and makes it ideal for fast testing, both in the R&D stage and for quality control testing in a production environment. Total flux, color parameters, flicker, illuminance and color uniformity can now be accurately measured with a single system. The color distribution of LED assemblies and luminaires are easily evaluated with the FluxGage. In addition, this new color-sensor functionality enables useful comparison of the color-mixing performance of LED lenses, reflectors, diffusers and homogenizers, among others. This allows the optics that provides the best color uniformity to be selected for particular applications.

In-house calibration provides high accuracy (±0.6% in CCT) and high repeatability (±0.1%) in the 2,700K – 5,600K range for color measurements, as well as a large dynamic range for illuminance measurements.

An intuitive user interface makes it possible to use the stored results for analysis – easily and automatically, if desired. With this enhanced capability offered by the system, users can additionally gain a fast understanding of the angular properties of the light and the color- mixing performance of the measured luminaires.

References

[1] Efi Rotem, Raphael Cohen, Shimon Elstein, Daniel Sebbag, Ephraim Greenfield. “FluxGage: A Photometric Test System for LED Luminaires Based on Solar Panels,” Proceedings of LED Professional Symposium 2016, Bregenz, Austria.

[2] "Accuracy Validation of FluxGage," White Paper, https://www.ophiropt.com/led/white-paper-articles

[3] https://ams.com/as7261

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