AIP | Review of Scientific Instruments

ARGon3: "3D appearance robot-based gonioreflectometer" at PTB

A. Höpe, T. Atamas, D. Hünerhoff, S. Teichert, and K.-O. Hauer

Citation: Review of Scientific Instruments **83**, 045102 (2012); doi: 10.1063/1.3692755
View online: http://dx.doi.org/10.1063/1.3692755
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/83/4?ver=pdfcov
Published by the AIP Publishing

ARGon³: "3D appearance robot-based gonioreflectometer" at PTB

A. Höpe,[a)] T. Atamas, D. Hünerhoff, S. Teichert, and K.-O. Hauer
Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

(Received 25 January 2012; accepted 19 February 2012; published online 3 April 2012)

At the Physikalisch-Technische Bundesanstalt, the National Metrology Institute of Germany, a new facility for measuring visual appearance-related quantities has been built up. The acronym ARGon³ stands for "3D appearance robot-based gonioreflectometer". Compared to standard gonioreflectometers, there are two main new features within this setup. First, a photometric luminance camera with a spatial resolution of 28 μm on the device under test (DUT) enables spatially high-resolved measurements of luminance and color coordinates. Second, a line-scan CCD-camera mounted to a spectrometer provides measurements of the radiance factor, respectively the bidirectional reflectance distribution function, in full $V(\lambda)$-range (360 nm–830 nm) with arbitrary angles of irradiation and detection relative to the surface normal, on a time scale of about 2 min. First goniometric measurements of diffuse reflection within 3D-space above the DUT with subsequent colorimetric representation of the obtained data of special effect pigments based on the interference effect are presented.
 [http://dx.doi.org/10.1063/1.3692755]

I. INTRODUCTION

In reflectometry, as a subdivision of the metrological domains of radiometry and photometry, both the spectral and the spatial distribution of radiation reflected by the surfaces of materials and artifacts are measured and characterized with the indication of specific physical properties. In the case of optical reflection, this is done by indication of the spectral dependent quantities reflectance $\rho(\lambda)$, reflection factor $R(\lambda)$, and radiance coefficient $q(\lambda)$, which is similar to the bidirectional reflectance distribution function (BRDF) or the radiance factor $\beta(\lambda)$.[1] If colored samples comes into account also the chromatic coordinates in a variety of different color spaces have to be specified.[2,3] These classification numbers are thereby not only material-specific quantities, they depend on a multiplicity of parameters, e.g., the spectral distribution of the irradiating light (called illuminant), the direction of irradiation and reflection as well as the associated flare angles.

The visual appearance of commercial products is becoming more and more relevant to industry. There are increasing requirements from such different branches such as for instance automotive, cosmetics, and printing industry. Driving force behind this common ground are a variety of new goniochromatic materials which have a strong angular dependent reflection behavior and hence show a color impression that depends on the spatial arrangement of illumination and observation relative to the surface of the artifact.[4,5]

This behavior of the materials is produced by their composition based on special effect pigments. These pigments are predominantly flaky particles consisting of a substrate coated with a thin intense refracting layer which can be oriented parallel to the object surface. Typical values for the refractive index of the substrate are $n = 1.5$–1.6 and for the coating medium $n = 1.8$–2.9.[5] The goniochromatic colors are produced based on the interference effect in which the incoming light is partly reflected from the particle surface and partly refracted through it. Depending on the coating thickness and variation of the angle of incidence of the applied radiation, a colorful appearance of the reflected light at various spatial directions is produced.

Based on this conditions an increased demand on multi-geometry calibrations exceeding the conventional geometries of 45:0 and 0:45 (45:0 denotes irradiation with an incident angle of 45° onto a sample with a subsequent measurement of reflection under 0°, 0:45 is defined vice versa) recommended by the Commission Internationale de l´Eclairage, International Commission on Illumination (CIE) are noticed.[6] In order to describe the colorimetric behavior of effect pigmented surfaces, multitude reflection spectra for varying geometric configurations must be recorded. This is a time-consuming procedure and new concepts for reducing measurement time are required. Typical calibration times for the spectral radiance factor as an absolute quantity in a certain spatial geometry in $V(\lambda)$-range (360 nm–830 nm) can easily exceed several hours. With repetitive measurements in order to improve statistical significance, a whole day for data acquisition from only one geometry must be estimated. With these constraints it is nearly impossible to adequately describe goniochromatic materials where dozens of geometric configurations must be mapped.

This was the starting point for setting up a new facility at the Physikalisch-Technische Bundesanstalt (PTB) especially for research and measurement on appearance-related quantities. The main goals concerning the design and development of the setup were to speed up measuring time and to improve the spatial resolution on the device under test (DUT).

II. TECHNICAL DATA OF THE NEW FACILITY

A. Basic concept of diffuse reflection measurements at PTB

The basic optical layout of all facilities at PTB related to the measurement of diffuse reflection properties are

[a)]Author to whom correspondence should be addressed. Electronic mail: andreas.hoepe@ptb.de.

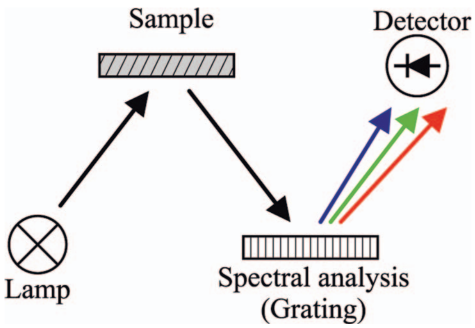

FIG. 1. Schematic illustration of the realization of diffuse reflection measurements at PTB.

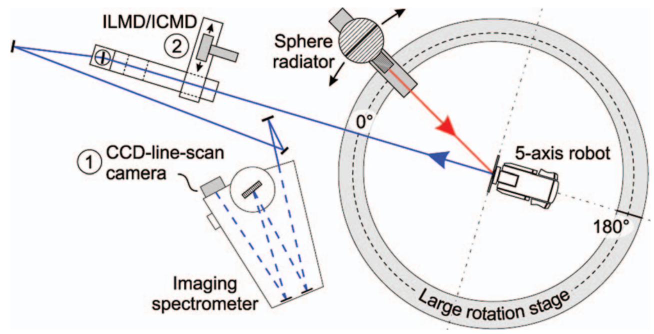

FIG. 3. Schematic diagram showing the optical table (1.5 m × 3.0 m) of the ARGon^3 facility with focusing optics for measurements with respect to the spectral radiance factor $\beta(\lambda)$.

following the same design concept. Unfiltered broadband radiation produced by a quartz halogen lamp is directed onto the DUT. The diffuse reflection signals, more precisely the measurand spectral radiance factor $\beta(\lambda)$ in case of the facilities realized at PTB are measured within a very narrow half cone aperture angle ω. This aperture angle ω is well below 1° for all setups at PTB in order to emulate the differential directional definition of the radiance factor itself.[7]

The required spectral selection for performing a wavelength resolved measurement is carried out in the detection path via grating based monochromator/spectrometer devices, as illustrated in Figure 1.

The basic construction of the new ARGon^3 facility (3D appearance robot-based gonioreflectometer) is similar to the robot-based standard gonioreflectometer at PTB.[8–11] This well-established device, which is the German national measurement standard for directed/directed diffuse reflection geometries, is used for calibrations with respect to the measurand spectral radiance factor $\beta(\lambda)$, as mentioned previously.

The setup of the ARGon^3 facility is shown in Figures 2 and 3. The construction consists of a large rotation stage carrying the replaceable irradiating lamps and a small five-axis industrial robot for the three-dimensional orientation of the DUT. For measurements of the spectral radiance factor $\beta(\lambda)$ in $V(\lambda)$-range with the line-scan camera (number (1) in Figure 2), a mirror-based imaging system is used (see Figure 3). In cases where the combined imaging luminance measurement device/imaging color measuring device (ILMD/ICMD) camera system (2) is used, this device is positioned via a translation stage into the beam path of the optical axis of the system.[12] In the following, a brief description of the constituent parts is given.

B. Irradiation: Large rotation stage with different light sources

The ARGon^3 facility can be equipped with two different light sources for the various measurement applications, a broadband light source consisting of a small integrating sphere and a filtered tungsten lamp producing a D65-like illuminant (light source with a correlated color temperature of about 6500 K). Both lamps can be mounted to a large rotation stage with a diameter of 1300 mm, which can be rotated 360° around the five-axis-robot serving as the sample holder (see Figure 3). The angular range of the incident radiation directed on the sample is $\phi_i = 0°$–$360°$, $\theta_i = 0°$–$90°$. Reflected radiation can be detected in the angular range $\phi_r = 0°$–$360°$, with $\theta_r = 0°$–$85°$. The definition of the angles of incidence and reflection within a spherical polar coordinate system connected to the DUT can be seen in Figure 4. Due to the construction of the facility, the minimum angular spacing between incident and reflected radiation is 7°. For smaller angles the detection path is blocked by the lamp.

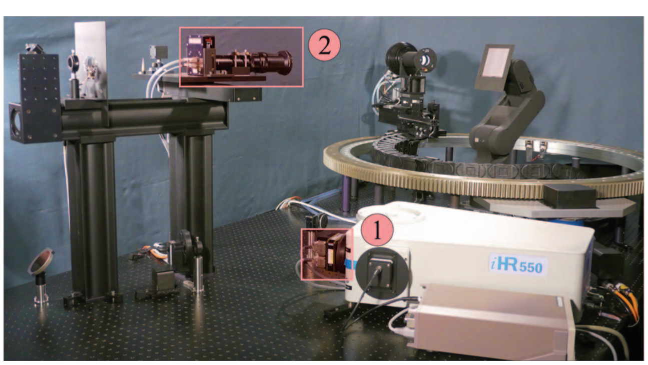

FIG. 2. Photo showing the setup of the ARGon^3 facility. (1) is a CCD line-scan camera module attached to an imaging spectrometer. (2) is a high-resolution combined imaging luminance (color) measuring device.

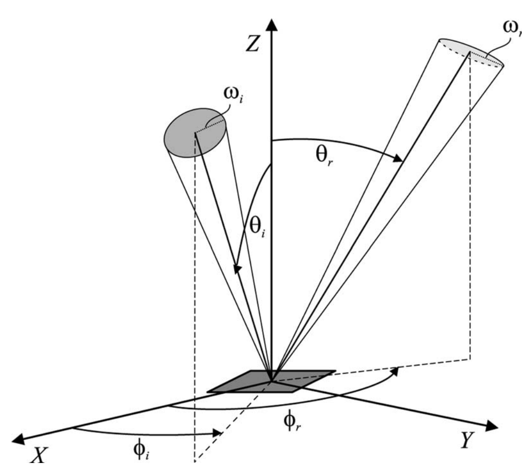

FIG. 4. Definition of incident and reflected beams of the gonioreflectometer within a spherical polar coordinate system.

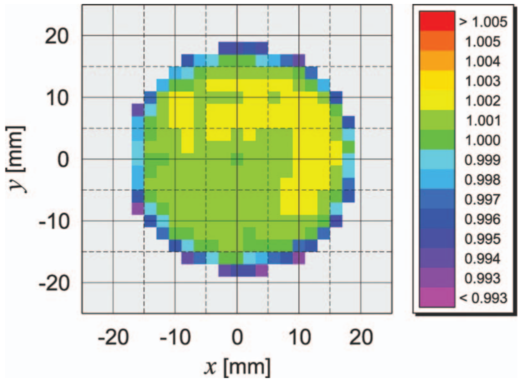

FIG. 5. Two-dimensional homogeneity plot of the emitted radiance of the sphere radiator. The measured signals are normalized to the center position at $x = y = 0$.

The broadband light is delivered by a special kind of lamp, denoted as homogeneous sphere radiator.[13] It consists of a water cooled small integrating sphere with an inner diameter of 150 mm, equipped with an internal 400 W quartz halogen lamp. The sphere itself can be divided into two parts and is a PTB in-house development and manufacturing. It was precision machined from two solid aluminum blocks on a computerized numerical control (CNC) turning lathe. The inner coating of the sphere is made of pure barium sulfate powder diluted in distilled water and sprayed to the inside with an air brush pistol.[14,15] The sphere radiator is equipped with an internal reflector mounted by four stainless steel wires at the center of the sphere in the equatorial plane. The reflector itself is a flat aluminum plate also coated with barium sulfate. The homogeneous output of the whole system is ensured by overall proper alignment of this arrangement. Light generated by the internal lamp can leave the setup only after a minimum of three internal reflections at the wall and the center mounted reflecting plate. This sphere radiator has a radiance homogeneity of the emitted radiation of 99.8%, measured in the plane of the limiting aperture ($\o = 40$ mm) at the output of the device (see Figure 5).[16,17] The distance between the limiting aperture at the output of the homogeneous sphere radiator and the DUT is kept constant at a value of 784.2 mm.

The second lamp producing the D65-like illuminant is used for measurements with the luminance camera system. The D65-lamp is also a home-build system. It consists of a 12 V, 50 W tungsten halogen lamp with a MR-16 reflector attached to a special filter element producing the D65-like spectrum. The special filter element is taken from a portable desktop view booth (GretagMacbeth SpectraLight Jr.). It is a colored glass filter with a dedicated interference coating, which produces in conjunction with the tungsten halogen lamp a good representation for the theoretically defined D65 illuminant.[17] The lamp-filter combination is mounted into a convection cooled lamp housing composed of cooling fins as can be seen in Figure 6.

Figure 7 shows the spectra of the theoretical defined CIE standard illuminant D65 (solid line) and the experimental realization via lamp and filter combination (dashed line). The agreement is quite good with significant discrepancies only below 400 nm and above 700 nm, which are both out of or at the edges of the visibility range of the human eye.

FIG. 6. Photo showing the construction of the lamp producing the D65-like illuminant.

C. Sample alignment: Five-axis-robot

In the center of the rotation stage a small five-axis industrial robot (Mitsubishi RV-2AJ) with an acromial height of only 550 mm is located. The robot is able to carry and position even large samples with an outer diameter of up to 500 mm and a maximum weight of up to 2 kg. The spatial position accuracy is 0.02 mm for arbitrary movements within

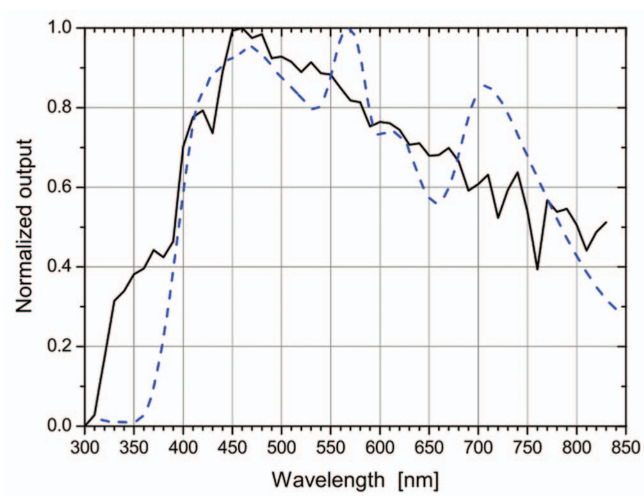

FIG. 7. Normalized spectrum of the D65-lamp (dashed line) in relation to the theoretical defined D65 illuminant (solid line).

the whole operating range. The rotation accuracy of the base axis of the robot is 0.002°. The flexibility and ease of use of the robot system largely comes from the manufacturer implemented three internal coordinate systems (world-, base-, and tool-coordinate system) with the capability of making direct coordinate transformations between them. Due to this fact, there is no need for the operator to go into the details of coordinate transformations, such as Eulerian angles, etc. This makes the programming of the movements, translations, and rotations necessary for the 3D alignment of the DUT relatively simple. During measurements the robot is operated in a quite unusual position for an industrial robot, with the hand flange above the basic platform collinear with the base axis of the system (see Figure 2). The robot axes are positioned in such a way as to ensure that the measured point within the surface of the sample is always located within the common rotation axis of the rotation stage and the base axis of the robot.

The combined adjustment of the rotation stage and the robot allows full angular control of the incident and reflected radiation within the full half space above the surface of the sample, accomplishing also measurement of "out-of-plane" reflection, where the direction vectors of irradiation and observation and also the vector of the sample normal are not lying in a common plane (see Figure 4). Especially these "out-of-plane" geometries are gaining more and more interest from industry driven by new goniochromatic materials, which have a strong angular dependent reflection behavior. In real life viewing sceneries including arbitrary angles for the incident and observed radiation, the visual appearance of objects is strongly influenced by these conditions. In the past, measurement geometries of commercial spectrophotometers were mostly restricted to the standardized geometries of 45:0 and 0:45, which are inadequate for a comprehensive characterization.

D. Detection

1. Line-scan camera

The main features of the ARGon[3] facility are the improved detection possibilities with two different camera systems as can be seen in Figure 2. Device number (1) is a 1036 pixel, 16 bit, back-thinned full frame transfer CCD line-scan image sensor (Hamamatsu Photonics K.K.) attached to a $\frac{1}{2}$-meter Czerny-Turner imaging spectrometer in the detection path for measuring the spectral radiance factor $\beta(\lambda)$. The CCD image sensor is a one-stage TE-cooled version which can be cooled down to −9 °C for improving the signal-to-noise ratio. The spectrometer is equipped with a 150 lines/mm grating for measurements with the line-scan camera system, resulting in a 290 nm spectral coverage. For measurements in full $V(\lambda)$-range an overall spectral coverage of 470 nm (360 nm–830 nm) is needed. In order to fulfill this requirement, the measurement of the spectral radiance factor $\beta(\lambda)$ is separated into two parts. The center wavelengths of the both recordings are adjusted to 500 nm and 700 nm (see arrows in Figure 8) giving the solid and dashed curves which result together in the required full $V(\lambda)$-range coverage.

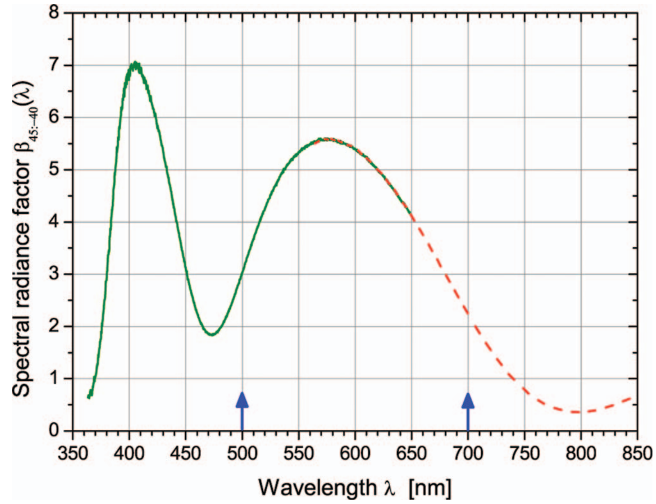

FIG. 8. Spectral radiance factor $\beta(\lambda)$ of an effect pigment (MERCK Colorstream® Viola Fantasy applied on a black background) measured in 45:40 in-plane geometry with the line-scan CCD-camera system.

The imaging from the surface of the DUT into the spectrometer system is accomplished with mirror-based focusing optics. The schematic diagram of the setup is displayed in Figure 9. By use of this optics a circular area, with a diameter of 20 mm (at position 0) is imaged in two steps to the 2 mm wide entrance slit of the spectrometer (at position 8). The focusing optics consists of 5 mirrors, three of them are plane ones (# 2, 3, 6), the other two are concave with radii of curvature of 1220 mm and 350 mm. At position 5 an intermediate image is created. With an aperture of ø = 5.6 mm at this position, the size of the measurement area on the DUT is determined. At position 1, a second aperture with a diameter of ø = 18 mm is mounted, defining the detection flare angle with a half cone of only 0.28°. The overall optical path length (distance 0 to 8) of the imaging system is 4.5 m.

Measurements of surface colors viewed from above must be related to a white standard in order to specify the correct white balance in the given illumination situation. The ultimate

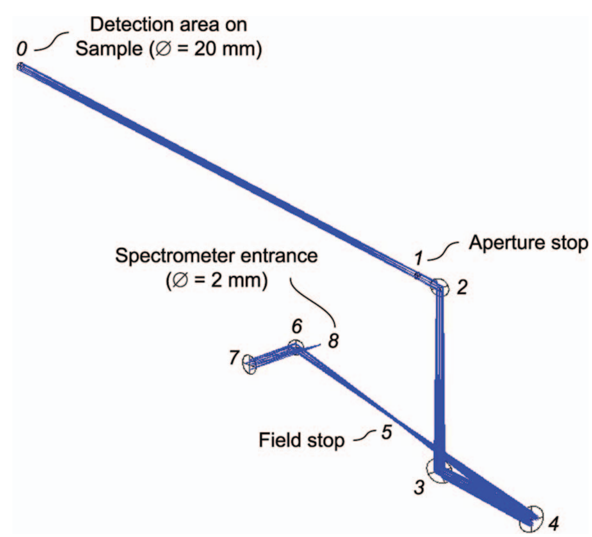

FIG. 9. Schematic diagram of the focusing optics into the spectrometer for measurements with respect to the spectral radiance factor $\beta(\lambda)$.

standard in the field of radiometry and photometry is the so-called perfectly reflecting diffuser (PRD), which has by definition a radiance factor β equal to unity independent of the wavelength and geometric configuration,

$$\beta_{PRD}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) \equiv 1. \tag{1}$$

The PRD is a theoretical concept only and is defined as a surface which reflects the incoming radiation loss-free, completely diffuse and with Lambertian direction characteristics.[18] The PRD cannot be materialized, since there is no material with such characteristics. The realization of this primary standard is carried out with physical methods, i.e., by the measuring apparatus itself, in the context of an absolute measurement.

Therefore, it is not sufficient only to measure the radiance signal L_r in a given spatial direction. Required is the normalization of L_r to the theoretical signal L_r^{PRD} of the perfectly reflecting diffuser,

$$\beta(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{L_r(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)}{L_r^{PRD}(\lambda)}. \tag{2}$$

The parameter $L_r^{PRD}(\lambda)$ can be derived from geometrical quantities of the apparatus in conjunction with the measurement of the spectral radiance $L_i(\lambda)$ of the irradiating lamp,

$$L_r^{PRD}(\lambda) = \frac{A_Q \cos\theta_i}{\pi R^2} L_i(\lambda). \tag{3}$$

The relevant geometrical quantities are the aperture area A_Q of the irradiating lamp, the distance R between the lamp and the DUT, and the polar angle θ_i defining the angle of incidence relative to the surface normal. With the additional measurement of the spectral radiance $L_i(\lambda)$ of the irradiating lamp all required values are present. The spectral radiance $L_i(\lambda)$ of the homogenous sphere radiator can be measured directly by rotating the large rotation stage to the 180° position (see Figure 3), moving the robotic hand with the mounted DUT out of the beam path and then "look" with the focusing optics directly into the ø = 40 mm aperture of the lamp assembly. The cross section of the detection beam at this position is 37 mm, i.e., fitting well into the aperture opening of the lamp. Thus, one gets

$$\beta(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{\pi R^2}{A_Q \cos\theta_i} \cdot \frac{L_r(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)}{L_i(\lambda)}. \tag{4}$$

The dynamic range between the radiances $L_i(\lambda)$ and $L_r(\lambda)$ depends on the geometrical configuration and on the reflectivity of the DUT itself and might have potential values in the range 10^2–10^6. The dynamic range of the CCD line-scan camera is 16 bit, i.e., equivalent to 6.5536×10^4 assembly levels. This fact makes it necessary to use a pivoting grey filter of known transmittance $T_{\mathrm{Filter}}(\lambda)$ to balance the signal spectra of the irradiating lamp and the diffuse reflection

$$\beta(\theta_i, \phi_i, \theta_r, \phi_r, \lambda) = \frac{\pi R^2}{A_Q \cos\theta_i} \cdot \frac{L_r(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)}{L_i^{Filtered}(\lambda)} \cdot \frac{1}{T_{Filter}(\lambda)}. \tag{5}$$

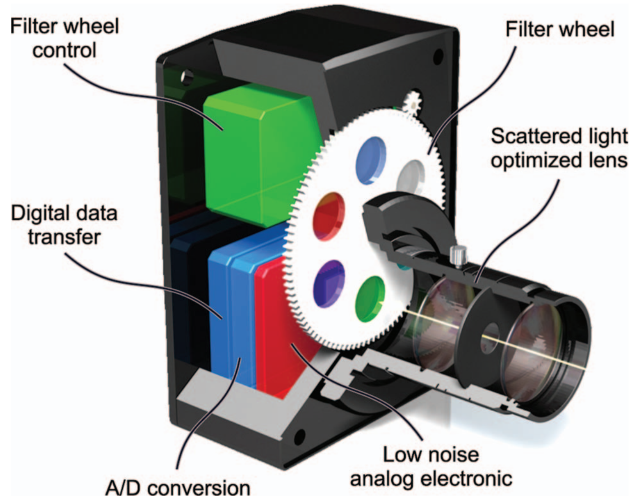

FIG. 10. Schematic diagram of the main components of the luminance camera.[19]

2. Combined imaging luminance (color) measurement device

Device number (2) is a commercial combined ILMD/ICMD.[12] This camera system ("LMK 98-4 Color" manufactured by TechnoTeam Bildverarbeitung GmbH, Germany) has an implemented CCD-sensor containing 1364 × 1030 pixels.[19] The lens based imaging system of the luminance camera with a focal length of 210 mm was especially designed in order to achieve high resolution images. In our setup, we obtain a resolution of approximately 28 μm on the DUT. The field of view of the objective lens is 28 × 38 mm (equivalent to an angular range of 1.15° × 1.55°). Figure 10 shows a schematic view of the main components of the camera system.

This luminance camera has high dynamic range capability, enabling measurements with an electronic dynamic range with a ratio of up to 1:10^7 (~140 dB). The ILMD/ICMD system is adapted to the color matching functions of the 2° CIE standard observer (CIE 1931) through a filter wheel. Not only luminances can be determined but also tristimulus values. This permits the imaging measurement of chromaticity coordinates, which can be given in different color spaces. The filter wheel has 6 filter positions, with 4 filters being required for color measurements according to the color matching functions $x_1(\lambda)$, $x_2(\lambda)$, $y(\lambda)$, and $z(\lambda)$.[20] Figure 11 shows the spectral matching of the camera (measured points) to the theoretical values (solid lines) of the CIE 2° standard observer, which fits very well.[21] Furthermore, the remaining two positions can be equipped with additional filters, for instance, for the scotopic luminance $V'(\lambda)$, for the circadian principal function C(λ), with an IR filter (for measurements in the near infrared range λ = 780 nm−1000 nm), with a filter for blue light hazard or with a clear glass filter.

With a dedicated software package (LMK LabSoft Color), the complete functionality of luminance measuring is also available for the assessment of chromaticity values out of three channel color images. The measured X-, Y-, and Z-color values can be converted into a variety of different color spaces (e.g., RGB, sRGB, EBU-RGB, Lxy, Luv, L*a*b*, HIS, and

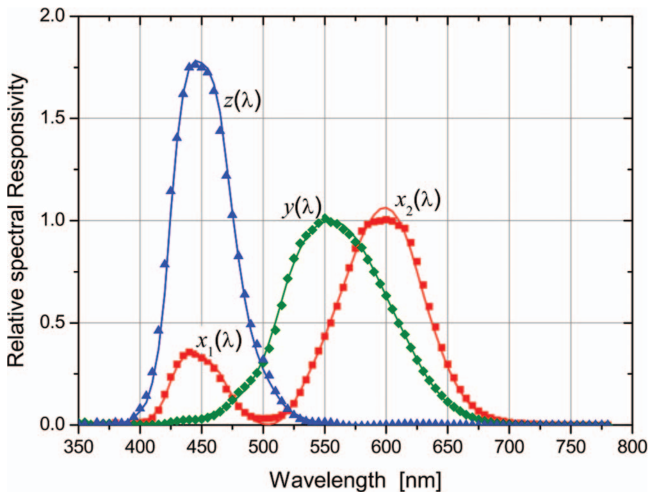

FIG. 11. Spectral matching of the spectral responsivity of the "LMK 98-4 Color" ILMD/ICMD camera system according to the specifications of the color matching functions of the CIE 2° standard observer.

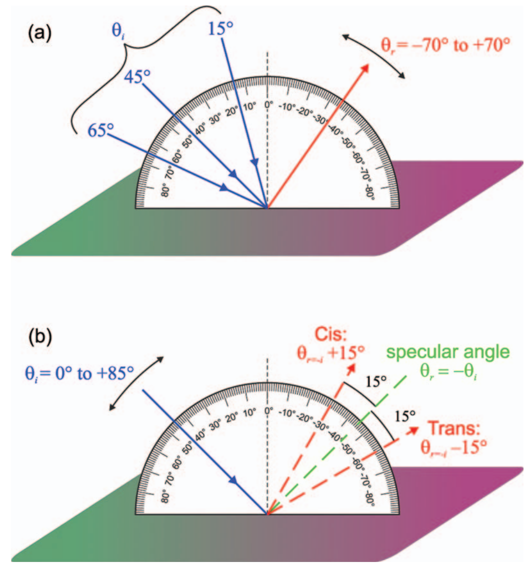

FIG. 12. Sketches showing the geometrical configurations for measurements of the aspecular line (a) and the interference line in cis- and trans-configuration (b).

HSV). It is possible to calculate color distances and color differences in these color spaces. Among the standard graphical forms of showing measured values in graphs and diagrams, the chromaticity coordinates can be represented in a color space diagram (e.g., horse shoe view), which shows the color gradient and statistical accumulation points.

III. FIRST MEASUREMENTS

Reflection measurements in general can be divided into two categories, so-called "in-plane" and "out-of-plane" measurements. The differentiation between both configurations is based on the orientation of the vectors of incident and reflected radiation as well as on the orientation of the sample normal. If all three vectors are in a common plane this is designated as the "in-plane" configuration. If they are not in a common plane, which is in fact valid for most of "real life" geometrical configurations, this is denoted as "out-of-plane".

In Secs. III A and III B, first in-plane measurements with the two new camera systems of the ARGon[3] facility are presented. All measurements were performed on metal sheet plates lacquered with effect pigments manufactured by MERCK KGaA, Germany.

A. Measurements with the line-scan camera system

The DUT within the accomplished measurements is a metal sheet coated with Viola Fantasy, an effect pigment from the MERCK Colorstream® family, which is based on synthetically produced transparent silicon dioxide platelets coated with titanium dioxide.[22] The angle-dependent color travel spans the range from lilac through silver and green to blue. The pigment was applied onto a black primer coating. The in-plane measurements were performed for three different incident angles of 15°, 45°, and 65° relative to the surface normal. These incident angles are recommended in standards of Deutsches Institut für Normung e.V. (DIN) and American Society for Testing and Materials (ASTM) and are most common to commercially available multi-angle spectrophotometers.[23,24] While the incident angle was fixed, the so-called aspecular line was measured for polar in-plane reflection angles ranging from $\theta_r = -70°$ to $+70°$ relative to the surface normal on a measuring grid with 5° spacing, see Figure 12(a). Aspecular means in this interrelationship angular configurations that are related to the angles of the specular reflections at −15°, −45°, and −65°. The accomplished measurements are restricted to the 0° to 180° plane of Figure 4, in doing so in the present diagrams of Figure 12 angles on the left side are denoted with a positive sign, angles on the right side with a negative sign.

Also the 15°-interference lines in cis- and trans-configuration for varying incident angles $\theta_i = 0°$ to 85° (step size also 5°) were determined, Figure 12(b). The notations cis- and trans- are chosen in adaption to chemistry and denotes once more the orientation of the reflection angle relative to the specular peak. Here, 15°-cis means the measurement at an angle of 15° in the direction towards the light source and 15°-trans denotes an angle in the opposite direction, away from the source.[25,26]

From the measured spectra color coordinates in CIE 1976 ($L^*a^*b^*$) color space (also denoted as CIELab, whose coordinates are actually L^*, a^*, and b^*) were calculated, for the 10° standard observer under illuminant D65. In this color space, the positive direction of the a^* axis points approximately in the direction of red color stimuli, the negative direction approximately in the direction of green stimuli. The positive direction of the b^* axis points approximately in the direction of yellow stimuli; negative b^*-values are approximately in the direction of blue stimuli. L^* is coupled to the luminance L of the stimulus, thus it is a crude correlate of lightness.[2] For a better visualization and understanding of the measured color coordinates in the a^*b^*-plane, a picture showing approximately the color gradients in the different directions was superimposed to the measured data of Figure 13.

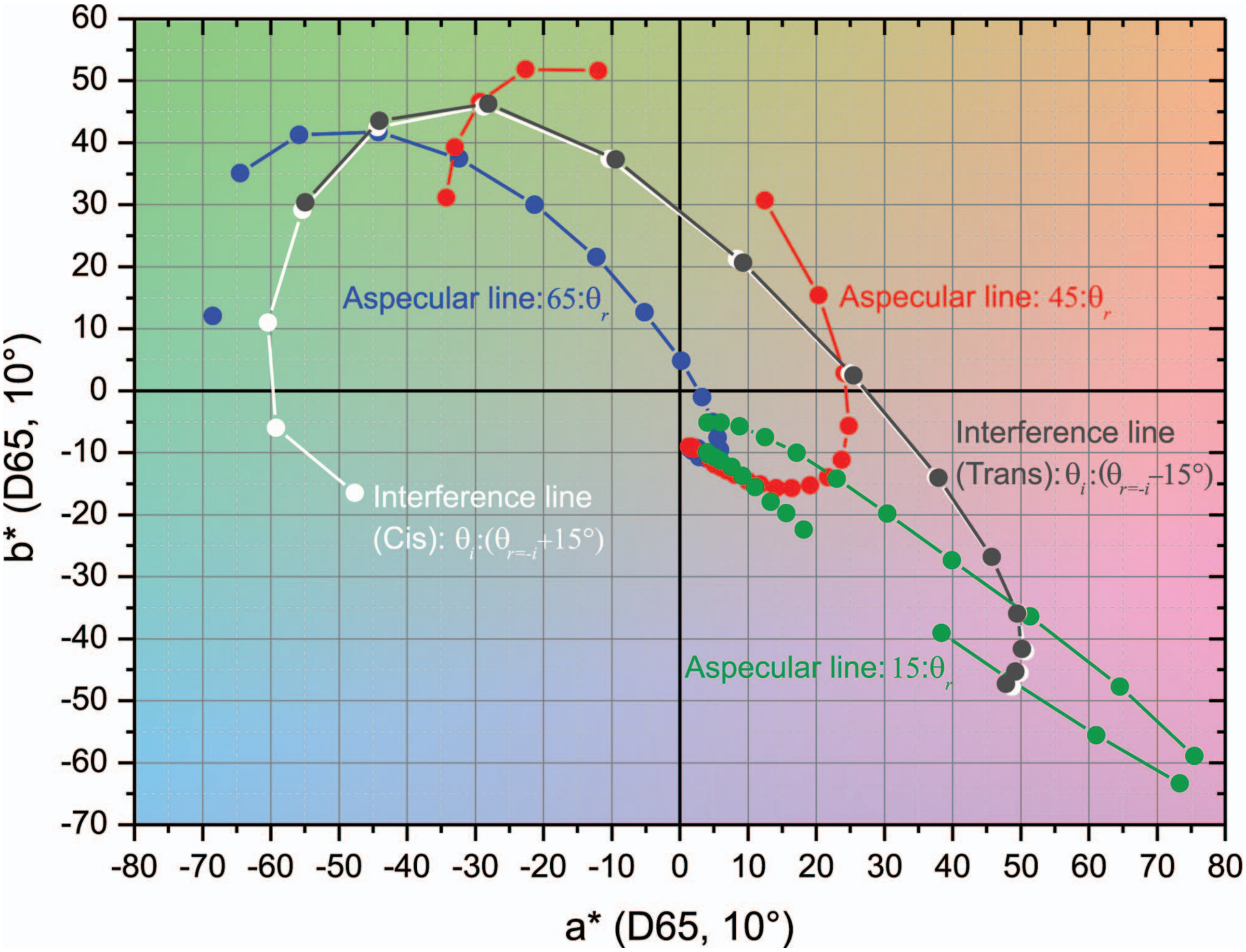

FIG. 13. CIELab color coordinates of an effect pigment (MERCK Colorstream® Viola Fantasy applied on a black background) measured in different in-plane geometrical configurations.

The data recorded in the different geometrical configurations span a wide range within the a^*b^*-plane, covering all four quadrants. This clearly shows the need for multi-geometry measurements in order to fully describe the goniochromatic behavior of effect pigments.

The angular resolved surface color data measured in three-dimensional space for an incident angle of 45° onto the sample for Viola Fantasy as displayed in Figure 13 cover lightness coordinates L^* from 11.7 to 177.6. The L^* coordinate for "normal" reflective colors is only defined in the range from $L^* = 0$ (black) to $L^* = 100$ (white in terms of the PRD). These high values for L^*, even outside of the specular reflection direction, demonstrate the need for new adapted concepts in order to describe color and lightness in CIELab color space.[27]

B. Measurements with the imaging luminance (color) camera system

The camera system enables imaged based measurement of luminances and chromaticity coordinates with high spatial resolution. The chromaticity coordinates can be specified in a variety of predefined and user-related color spaces. Figure 14 shows a high resolution luminance image displayed in 3D-false color presentation of an effect pigmented lacquering measured in 15:0 "in-plane" geometry. This is a measurement with the camera system in ILMD-mode. The pigment (MERCK Xirona® Volcanic Sparks) is applied on two different backgrounds, black (left) and white (right).

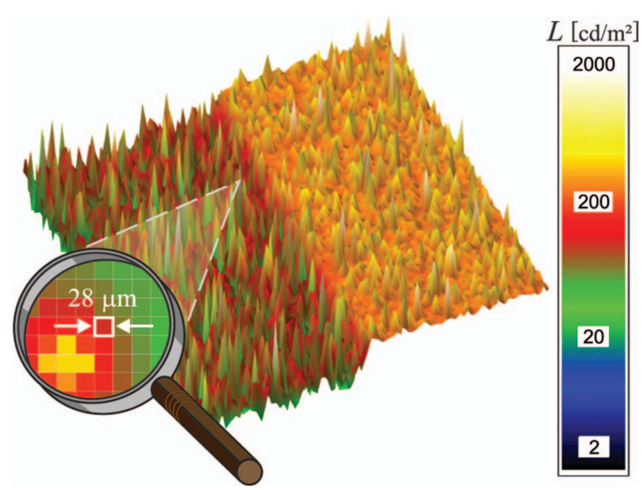

FIG. 14. Spatially high resolved luminance distribution in false color representation of an effect pigment (MERCK Xirona® Volcanic Sparks) applied on two different backgrounds, black (left) and white (right).

ent groundings (black and white) where the lower luminance values on the left side belong to the black background. As can be seen in the graphics of Figure 14, the luminance L within this experimental situation is covering 3 orders of magnitude, from 2 cd/m^2 to 2000 cd/m^2.

The needle-like structure, which is designated with the term "sparkling", comes from semitransparent or transparent layers applied on metal oxide-coated aluminum or mica. If one zooms into the picture, the luminance distribution $L(x,y)$ can be determined with a resolution of about 28 μm (see Figure 14).

IV. CONCLUSION

At PTB, a new facility denoted as ARGon^3 for measuring quantities related to optical appearance has been set up. The apparatus is capable to perform measurements within the full hemisphere above the device under test. Two camera systems provide great flexibility in spectrally and spatially high resolved measurements of visual appearance of test objects. A combined imaging luminance/imaging color camera system with a spatial resolution of 28 μm enables spatially high-resolved measurements of luminance and color coordinates. A line-scan CCD-camera mounted to a spectrometer provides measurements of the radiance factor, respectively, the BRDF, in full $V(\lambda)$-range (360 nm–830 nm) with arbitrary angles of irradiation and detection relative to the surface normal, on a time scale of about 2 min.

In order to demonstrate the technical capabilities of the facility, first measurements of the spectral radiance factor in three-dimensional space for an effect pigmented metal sheet coated with the MERCK Colorstream® pigment Viola Fantasy were performed. The measured data in the different geometrical "in-plane" configurations span a wide range within the a^*b^*-plane of the CIE-$L^*a^*b^*$ color space, covering all four quadrants within the plane and thereby showing the need for multi-geometry measurements in order to fully describe the goniochromatic behavior of effect pigments.

ACKNOWLEDGMENTS

The authors thank B. Campe for construction and building several parts of the new facility. T. A. appreciates the support of the Braunschweig International Graduate School of Metrology (IGSM).

[1] International Electrotechnical Commission/Commission Internationale de L'Eclairage, *International lighting vocabulary*, 4th ed. (Journal de Genève, Geneva, 1987).
[2] *Colorimetry: Understanding the CIE-system*, edited by J. Schanda (Wiley-Interscience, NJ, 2007).
[3] M. D. Fairchild, *Color Appearance Models*, 2nd ed., (Wiley-IS & T, Chichester, UK, 2005).
[4] W. R. Cramer and P. W. Gabel, Farbe und Lack **107**, 42 (2001).
[5] G. Pfaff, *Special Effect Pigments: Technical Basics and Applications*, 2nd ed. (Vincentz Network, Hannover, 2008).
[6] CIE 15:2004, *Colorimetry*, 3rd ed., International Commission on Illumination.
[7] F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Ginsberg, and T. Limperis, "Geometrical Considerations and Nomenclature for Reflectance," NBS Monogr. 160, (1977).
[8] D. Hünerhoff, U. Grusemann, and A. Höpe, Metrologia **43**, S11 (2006).
[9] A. Höpe, D. Hünerhoff, and K.-O. Hauer, in *Industrial Robotics: Programming, Simulation and Applications*, edited by K.-H. Low (Pro Literatur-Verlag, Mammendorf, 2007), p. 623.
[10] S. Holopainen, F. Manoocheri, E. Ikonen, K.-O. Hauer, and A. Höpe, Appl. Opt. **48**, 2946 (2009).
[11] A. Höpe and K.-O. Hauer, Metrologia **47**, 295 (2010).
[12] CIE TC 2-59, *Characterization of Imaging Luminance Measurement Devices (ILMDS)*, Draft No: 1.5 (2011).
[13] W. Erb and L. Mücke, Lichttechnik **4**, 210 (1972).
[14] W. Erb, Lichttechnik **27**, 250 (1975).
[15] K.-O. Hauer, Diploma thesis, Fachhochschule Lübeck, Germany, 2005.
[16] K.-O. Hauer and A. Höpe, MĀPAN – J. Metrology Soc. India **24**, 175 (2009).
[17] ISO 11664-2:2007(E)/CIE S 014-2/E:2006: Joint ISO/CIE Standard: Colorimetry - Part 2: CIE Standard Illuminants for Colorimetry.
[18] CIE Standard 044-1979, *Absolute Methods for Reflection Measurements*.
[19] LMK Video Photometer, Imaging Light and Colour Measuring Technique, Product Information, TechnoTeam Bildverarbeitung GmbH, Werner-von-Siemens-Str. 10, 98693 Ilmenau, Germany, 2009.
[20] J. L. Gardner, J. Res. Natl. Inst. Stand. Technol. **112**, 129 (2007).
[21] U. Krüger, B. Ruggaber, and F. Schmidt, in *Proceedings of the 27th Session of the CIE, Sun City, South Africa, 9–16 July 2011*, p. 186.
[22] Colorstream T10-01 Viola Fantasy, Product Information, Merck KGaA, Pigments Division, Business Unit Coatings, Frankfurter Str. 250, 64293 Darmstadt, Germany, 2002.
[23] *Tolerances for Automotive Paints–Part 2: Goniochromatic Paints*, DIN 6175-2:2001-03, Beuth Verlag GmbH, Berlin.
[24] *Standard Practice for Multiangle Color Measurement of Interference Pigments*, ASTM E2539 – 08, ASTM International, West Conshohocken, PA, 2008.
[25] W. R. Cramer, Farbe und Lack **118**, 34 (2012).
[26] E. Kirchner and W. Cramer, "Making sense of measurement geometries for multi-angle spectrophotometers," Color Res. Appl. (to be published).
[27] L. Simnot, M. Hebert, and D. Dupraz, Color Res. Appl. **36**, 169 (2011).