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Robot-based Gonioreflectometer

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1. Introduction

Measurements of diffuse reflection are important for a variety of applications in optical metrology. In reflectometry both the spectral and the spatial distribution of radiation diffusely reflected by solid materials are measured and characterised with the indication of classification numbers. In practice, reflection measurements of diffuse reflecting materials are accomplished predominantly relative to a standard. As primary standard for this purpose the perfectly reflecting diffuser (PRD) is established, which reflects the incoming radiation loss-free, completely diffuse and with a lambertian direction characteristic. The PRD is a theoretical concept only, which cannot be realised experimentally respectively materially. Since there is no material with these characteristics, the realisation of primary standards is carried out with physical methods, i.e. by the measuring apparatus itself, in the context of an absolute measurement. In contrast to the directed, specular reflection, the incoming light in diffuse reflection is distributed over all directions in space. If the radiance L of the reflected radiation is independent of the direction, one speaks of a lambertian emitter.

The classification numbers, in the case of reflection are the reflectance ρ , the radiance factor β and the BRDF "bidirectional radiance distribution function" f_r . These classification numbers are not material-specific but depend on a multiplicity of parameters, e.g. the wavelength of the radiation, the direction of irradiation and reflection as well as the aperture angle.

There are, in principle, nine different measuring geometries for a reflection measurement. They consists of all possible combinations, where the incident and the reflected radiation is in each case hemispherical, conical or directional. Therefore it is always necessary to specify the measurement geometry for a material classification number. The hemispherical measuring methods can be accomplished thereby with an integrating sphere whereas directional geometries are realised with a gonioreflectometer. The name gonioreflectometer is used in this context for a device which allows the precise control of the angles of the incident and reflected optical beams in a reflection measurement. This publication deals with the first time utilization of a commercial 5-axis industrial robot as a sample holder in a gonioreflectometer.

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2. General information about reflectometry

At the Physikalisch-Technische Bundesanstalt (PTB), the National Metrology Institute of Germany, a new robot-based gonioreflectometer (Fig. 1) for measuring radiance factor and BRDF has been set-up (Hünerhoff et al., 2006). The facility enables measurements of the directed reflection characteristics of materials with arbitrary angles of irradiation and detection relative to the surface normal.

Measuring directional diffuse reflection allows one to describe the appearance of a material under user-defined lighting conditions. This includes calibrations for a variety of different customers, like paper, textile and colour industry, companies producing radiometric and photometric instruments, as well as measurements for radiometric on-ground calibration of remote sensing instruments for space-based applications on satellites.

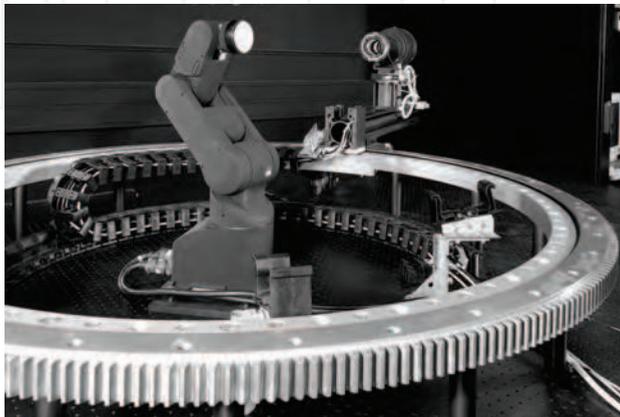


Fig. 1. Photograph of the gonioreflectometer showing the main components large rotation stage and 5-axis-robot.

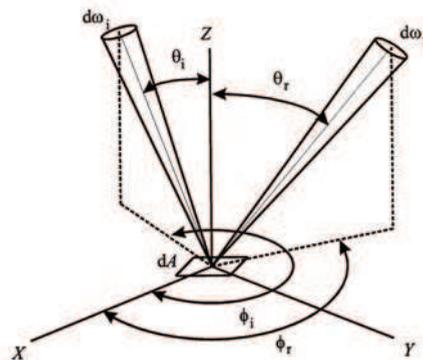


Fig. 2. Geometry of incident and reflected beams at the gonioreflectometer.

The former "old" gonioreflectometer of PTB was completely home-made (Erb, 1980). It was constructed from steel with a air bearing rotation stage of approximately 3 m in diameter. Also the sample holder was self constructed. Due to the layout of the instrument only specific

reflection measurements were possible, where the vectors of the incoming radiation, the reflected radiation and the vector of the surface normal formed a plane. The same situation is true for a variety of gonioreflectometer facilities in other National Metrology Institutes (Proctor & Barnes, 1996), (Chunnillal et al., 2003), (Nevas et al., 2004). The measurement of the appearance of surfaces under arbitrary lighting conditions as in every day life, however, requires a gonioreflectometer with multi angle capabilities. Such a gonioreflectometer was set-up in PTB using standard laboratory and engineering equipment.

As mentioned in the introduction one important classification number for the diffuse reflection is the radiance factor. The radiance factor β is defined as the ratio of the radiance L_r of the specimen to that of the perfect reflecting diffuser L_r^{PRD} identically irradiated.

Fig. 2 shows the geometrical conditions of a gonioreflectometer. The incoming radiation is denoted with index i and the reflected radiation from the sample area dA is denoted with index r . For a measurement in an arbitrary geometry the spectral radiance factor β depends besides the wavelength on all of these geometrical quantities:

$$\beta(\theta_i, \phi_i, \theta_r, \phi_r, d\omega_i, d\omega_r, \lambda) = \frac{L_r(\theta_i, \phi_i, \theta_r, \phi_r, d\omega_i, d\omega_r, \lambda)}{L_r^{PRD}} \quad (1)$$

As mentioned above the radiance of the PRD cannot be measured directly but it has to be calculated from other quantities. This can be accomplished using the radiance L_i of the irradiating lamp.

$$L_r^{PRD} = \frac{\cos \Theta_i}{\pi} \cdot \frac{A_Q}{R^2} \cdot L_i \quad (2)$$

Here, the area of the radiator is denoted by A_Q and R is the distance between the irradiating lamp and the sample, where Θ_i is the angle between the incident beam and the surface normal of the sample. The radiance L_i of the irradiating lamp can be measured by looking with the detection system directly into the lamp. The lamp has to be rotated to the 180 degree position and the sample has to be moved out of the beam path. This is something which can be carried out easily with the robot (see Fig. 3).

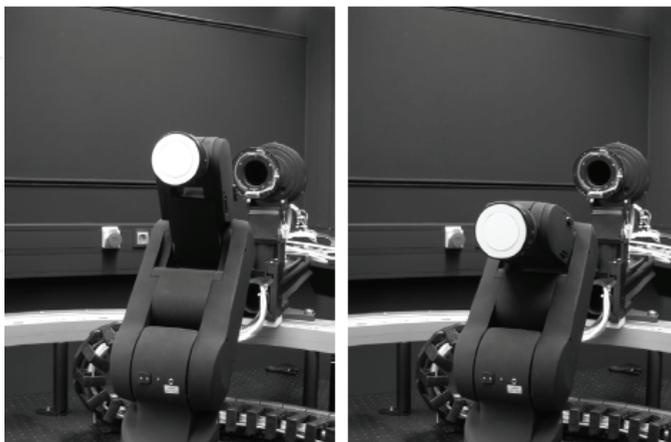


Fig. 3. Moving the robot head with a sample attached out of the detection beam path.

A Multi angle gonioreflectometer can be constructed either classically where several rotation and translation stages are assembled in order to achieve the desired degrees of freedom or using a robot as a sample holder for the device under test. It is expensive to stack several rotation and translation stages with lots of motor control units. We estimated the threefold price for such an arrangement. For economical reasons, we selected the robot solution.

3. Description of the gonioreflectometer facility

The gonioreflectometer facility consists of three major parts (see Fig. 1). A large rotation stage carrying the irradiating lamp, the 5-axis-industrial-robot as a holder for the sample under test, and the detection system (not visible in Fig. 1) consisting of a mirror-based imaging system and a monochromator for the spectrally resolved detection of the reflected radiance of the sample. In the following, these three major parts are presented in more detail.

3.1 The rotation stage with sphere radiator

The facility uses broadband irradiation of the sample with spectrally selected detection of the reflected radiation. The unfiltered broadband irradiation is generated by a special sphere radiator (Erb, 1979). This sphere radiator consists on a small integrating sphere 150 mm in diameter with an internal 250 W quartz tungsten halogen lamp. It is located on the large rotation stage with a diameter of 1.5 m and can be rotated 360° around the 5-axis-robot serving as the sample holder. The distance between sample and a precision aperture inside the lamp is 781.84 mm.

The combined adjustment of the rotation stage and the robot allows full angular control of the directed beams of incident and reflected radiation within the full half space above the surface of the sample, accomplishing also the measurement of out-of-plane reflection. The angular range of the directed radiation incident on and reflected from the sample is 0° to 85° for θ_i , θ_r and 7° to 353° for ϕ_i , ϕ_r (see also Fig. 2). The aperture angle of the source is 1.50° (solid angle $2.16 \cdot 10^{-3}$ sr), and the aperture angle of the detector 0.32° (solid angle $96.45 \cdot 10^{-6}$ sr). The rotation accuracy of the rotation stage is $\Delta\phi = \pm 0.0002^\circ$ as measured with an indicating calliper.

3.2 The 5-axis-robot

The main part of the new gonioreflectometer is the small 5-axis-industrial-robot, model RV-2AJ from Mitsubishi Electric with an acromial height of only 550 mm. For the facility a small robot for table mounting in a conventional laboratory room was needed. To our knowledge it is the smallest 5-axis robot on the market. The robot serves as the specimen holder for the device under test, as shown in Fig. 1. The flexibility of the robot arm enables not only in-plane reflection measurements of characteristics of materials as is the case in many other national metrology institutes (Proctor & Barnes, 1996), (Chunnillal et al., 2003), (Nevas et al., 2004), but also out-of-plane configurations with arbitrary irradiating and detection angles are possible. The robot has three internal coordinate systems with the capability of making direct coordinate transformations between them.

These three coordinate systems are: A so called world coordinate system relative to the installation site, a base coordinate system relative to the footprint of the robot arm and a hand flange coordinate system relative to the hand flange. The hand flange system can be linear relocated in order to transform it into a tool coordinate system if required. The different axes of the robot are shown in Fig.4.

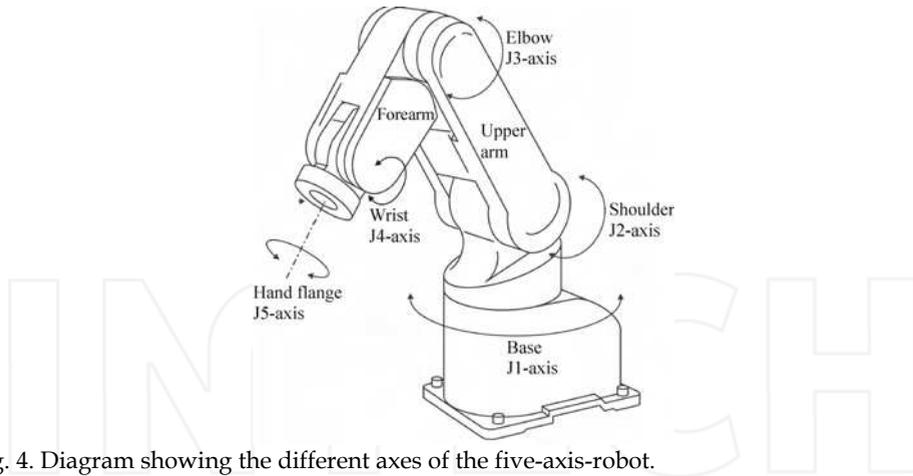


Fig. 4. Diagram showing the different axes of the five-axis-robot.

The coordinate system transform capability substantially facilitates the programming of the movements, translations and rotations of the robot system since no details like Euler's angles have to be considered. It is possible to address rotations of the 5 axis directly and also to use one of the three coordinate systems in order to execute compound movements of different axis simultaneously.

The mode of operation for the robot in the gonioreflectometer facility is atypical for an industrial robot. Normally a robot is working in front or beside his base unit, like in industrial production. In the present case the robot is part of a scientific measurement system and responsible for the positioning of the device under test, respectively the sample. In order to do that the hand flange of the robot is working above the base unit, one can say above his head. The robot is working in Master-Slave operation for our application. This is also unusual for an industrial robot. The standard case for a robot is to develop a sequence program and transfer it into the MCU (micro controller unit). The robot is than autonomous and is cyclical doing his work, only influenced by control inputs or the handing over of software parameter. In the given case we consulted the manufacturer, Mitsubishi Electric, and asked for expanded control command capabilities. They communicated us some special, normally unpublished control commands for Master-Slave operation. These are commands normally only used by the manufacturer for testing of the robot. Using these special control commands the robot system is now only one device upon the other measurement instruments forming the gonioreflectometer facility attached to it via RS-232 interface. The whole facility is fully automated and the measurement operation is controlled by a self-written routine programmed in Visual Basic running on a standard personal computer.

As mentioned above, the robot has to be operated in a slightly unusual position for an industrial robot, as shown in Fig. 1, with the hand flange above the basic platform collinear with the J1 base axis. The other robot axes (J2 to J4) are positioned in such a way as to ensure that the surface of the calibration sample is always located within the common rotation axis of the rotation table and the J1 axis of the robot which can only be achieved for a limited range with a sample thickness of up to 60 mm.

The robot is able to carry and position large samples with an outer diameter of up to 0.5 m and a maximum weight of up to 2 kg. The position accuracy is 0.02 mm for arbitrary movements within the whole operating range. The rotation accuracy of the J1 base axis is $\Delta\phi = \pm 0.002^\circ$.

3.3 The detection system

The direction of the detection path is fixed due to the fact that a triple grating half-meter monochromator is used for spectral selection of the reflected radiation. The current wavelength range for measurements of diffuse reflection is 250 nm to 1700 nm.

The facility uses two-stage mirror-based 10:1 imaging optics to map a 20 mm circular area on the sample onto the 2 mm wide entrance slit of the monochromator. This results in a 3 nm spectral resolution within the spectral range 250 nm to 900 nm and a 6 nm bandpass within the 900 nm to 1700 nm range, depending on the gratings used.

Four different detectors behind the monochromator are used for detecting the radiance signals of the incident and reflected beams. All the signals are detected with a picoammeter and transferred to a computer for data storage and analysis.

4. Example for an out-of-plane measurement

As mentioned above, the flexibility of the robot arm allows for out-of-plane measurements of reflection characteristics of materials with arbitrary incident and reflection angle within the whole half space above the sample surface. Thus, the appearance of surfaces can be quantified under arbitrary angles between light source and observer.

In order to position the robot and the large rotation stage in the right angular position for such an out of plane measurement one has to calculate several dot products. These are the dot products between the vector of the direction of the incident radiance L_i , the vector of the surface normal of the sample N and the vector of the direction of the reflected radiance L_r . This has to be calculated in two different coordinate systems. In the first coordinate system with an orientation similar to Fig.2, the three different vectors are expressed in a simple way. The sample is located in the xy -plane with the vector of the surface normal in z -direction. The angles of the incident and reflected radiation can easily be expressed via the angle pairs ϕ_i, Θ_i and ϕ_r, Θ_r .

The second coordinate system corresponds to the specific geometrical conditions at the robot gonioreflectometer, see Fig. 5. The initial position of the sample is now tilted around 90° and located in the yz -plane.

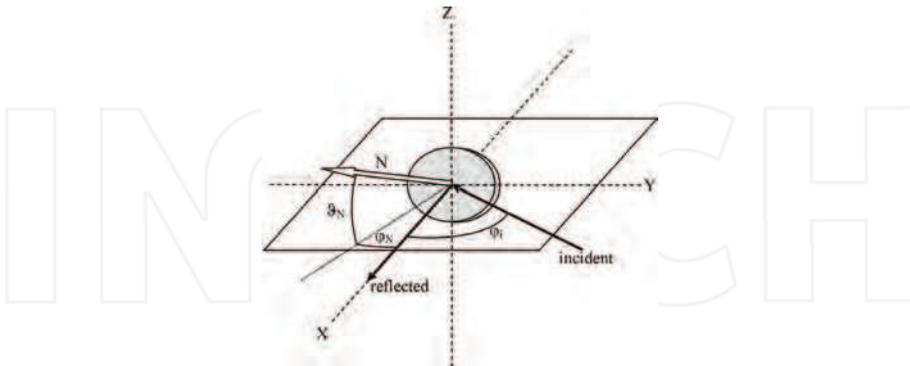


Fig. 5. Coordinate system and angles for out of the plane measurements at the robot gonioreflectometer facility.

The both vectors of the incident and reflected beams are restricted to the xy -plane (i.e. $z = 0$) according to the construction of the gonioreflectometer. The lamp generating the

incident light is mounted on the large rotation stage and can only be rotated in this plane. The detection path for the reflected radiation lies also in this plane and is fixed due to the table mounted mirror optics. This fixed direction coincides with the zero degree position of the rotation stage. The orientation of the surface of the sample is characterised due to the vector N of the surface normal which is perpendicular to the surface and can be rotated with the robot to every angular position φ_N, ϑ_N within the whole hemisphere above the xy -plane. With the calculation of these three dot products in the two different coordinate systems and some conversion of the equations it is possible to compute the required angles φ_i, φ_N and ϑ_N which had to be adjusted at the facility for an off-axis measurement.

$$\varphi_i = \arccos(\sin \Theta_i \sin \phi_i \sin \Theta_r + \cos \Theta_i \cos \Theta_r) \tag{3}$$

$$\varphi_N = \arctan\left(\frac{\cos \theta_i - \cos \theta_r \cos \varphi_i}{\cos \theta_r \sin \varphi_i}\right) \tag{4}$$

$$\vartheta_N = \arcsin\left(\frac{\cos \theta_r}{\cos \varphi_N}\right) \tag{5}$$

Fig. 6. shows the results of two measurements in an out-of-plane configuration of the radiance factor of an opal glass (glossy and matt side). The incident angle is varied from 0° to 85° in 5° steps in the xz -plane perpendicular to the yz -plane where the reflection angle (fixed at $\theta_r = 25^\circ$) is located, see Fig. 7. It can be seen that the radiance factor of the matt and glossy side of the opal glass is quite different in this configuration.

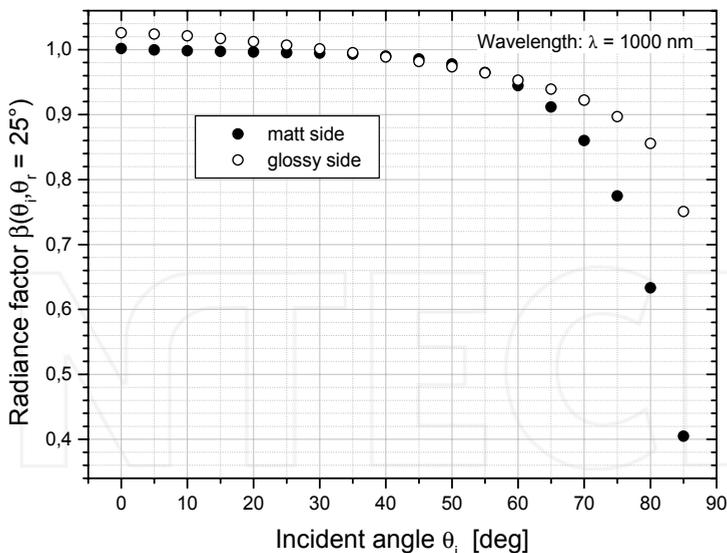


Fig. 6. Out of plane measurement on two sides of an opal glass reflection standard.

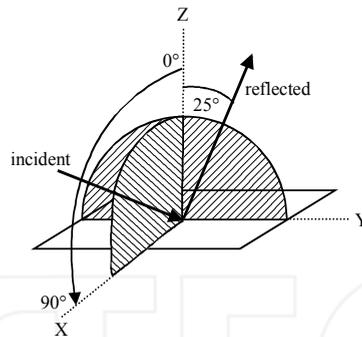


Fig. 7. Diagram showing the geometrical conditions of an out of plane measurement. The incident angle is varied from 0° to 85° in a plane perpendicular to the plane of the reflection angle (fixed at $\Theta_r = 25^\circ$).

In order to vary the incident angle in this manner, three angles of the facility, the angle of the rotation stage φ_i and the angles of the sample surface normal φ_N and ϑ_N had to be adjusted simultaneously. For this measurement the angle of the rotation stage φ_i varies from 25° to 90° , the angle φ_N of the surface normal from 25° to 0° and the angle ϑ_N from 0° to 25° , see Tab. 1 and Fig. 8.

Incident angle of radiation on the sample [°]	Angle of rotation stage φ_i [°]	Angel of surface normal φ_N [°]	Angle of surface normal ϑ_N [°]
0	25	25	0
10	26.81	23.28	9.37
20	31.61	19.46	16.01
30	38.29	15.40	19.94
40	46.03	11.85	22.18
50	54.37	8.86	23.47
60	63.05	6.31	24.24
70	71.94	4.06	24.69
80	80.95	1.98	24.93
90	90	0	25

Table.1. Values of the involved angles (in 10 degree steps) for the presented out of plane reflection measurement.

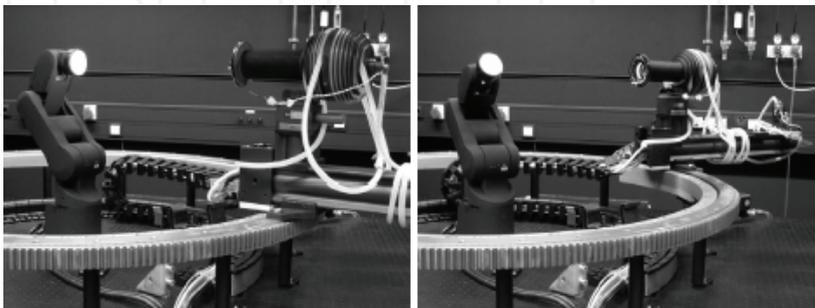


Fig. 8. Photo of the starting and end position for the explained out of plane measurement.

5. Rotational radiance invariance of diffuse reflection standards

Another measurement which can be easily realized with the robot as a sample holder are measurements of the rotational invariance of the sample reflection signal. In order to do that only the J5-axis of the robot has to be rotated around 360°.

Standards for diffuse reflection calibrations must not have any texture, i.e. their reflection behaviour should be independent of their rotational orientation. Explicit goniometric measurements on a selection of samples made of different materials showed variations in the reflected radiance of up to 2.5 % depending on the rotational orientation of the sample despite the absence of an obvious internal structure.

Different reflection standards were measured. Their radiance was recorded while they were rotated 360° around an axis collinear with their surface normal (J5-axis of the robot). The radiance signal was taken from a circular area 20 mm in diameter. The measurements were taken at a wavelength of 950 nm. The reflection geometry was 45/0, that is an angle of 45° between the irradiating radiation and the surface normal of the sample and a reflection under 0° degree from the sample, in an in-plane configuration for all of the measurements.

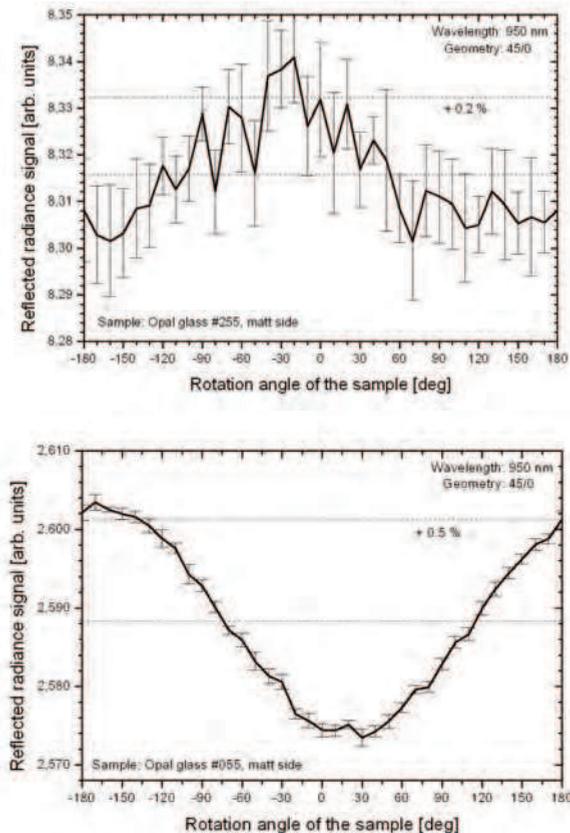


Fig. 8. Orientation dependence of the reflected radiance for two different opal glasses.

Fig. 8 shows the results of measurements on two samples. The samples are in both cases opal glasses from the same manufacturer but with different batch numbers. The reflected radiance signal from the samples should be in both cases independent of the rotation angle, which is only the case for the opal glass with #255, where the variances are in the range of the measurement uncertainty. The reason for this differences has to be analyzed in more detail in the future. Via visual inspection there is no obvious difference between the two samples.

From these measurements the following can be deduced. Standard materials of diffuse reflection should be handled with caution when there are used in directional reflection geometries. The absolute reflection depends on the rotational orientation of the sample relative to the plane spanned by the beams of the incident and reflected radiation. Even small rotations about the surface normal can lead to deviations in the reflected radiance almost in the percent range. This is more than the measurement uncertainties of most of the goniometric calibration facilities. This underlines the necessity to indicate the orientation of samples during their calibration and also to reproduce this orientation when making adjacent measurements using the calibration data.

6. Conclusion

The new gonireflectometer of the PTB enables high precision goniometric measurements of diffuse reflecting samples within the whole hemispheric range above the surface of the sample, due to its out-of-plane capabilities, by using a 5-axis-robot.

The whole facility was build using standard laboratory and engineering equipment. The five-axis robot model RV-2AJ from Mitsubishi Electric could be used without any modification for this unusual field of application.

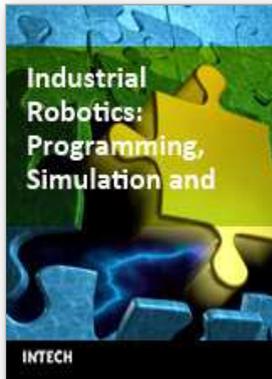
The current wavelength range for measurements and calibrations is 250 nm to 1700 nm. It is planned to extend this wavelength range up to 2500 nm in the near future. It is also planned to install an additional lamp with increased UV output power in order to improve the current uncertainty budget for measurements in the UV range.

7. Acknowledgments

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

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