Scientific Research Publishing

Optics and Photonics Journal, 2025, 15(3), 21-34
https://www.scirp.org/journal/opj
ISSN Online: 2160-889X
ISSN Print: 2160-8881

Establishment of a Robot-Based Bidirectional Reflectance Distribution Function Measurement System and Realization of Measurements at a Normal Incident Angle

Bazkir Ozcan*, **Meric Seval**

National Metrology Institute (TUBITAK-UME), Kocaeli, Türkiye
Email: *ozcan.bazkir@tubitak.gov.tr

How to cite this paper: Ozcan, B. and Seval, M. (2025) Establishment of a Robot-Based Bidirectional Reflectance Distribution Function Measurement System and Realization of Measurements at a Normal Incident Angle. *Optics and Photonics Journal*, **15**, 21-34.
https://doi.org/10.4236/opj.2025.153003

Received: February 20, 2025
Accepted: March 25, 2025
Published: March 28, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

In this work, the establishment of a bidirectional reflectance distribution function (BRDF) measurement system, which was developed in TUBITAK UME Optical Laboratory, and the measurements performed by this system are described. This system basically consists of two main components: a spectrometer and a robot-based goniometer. The internal structure of the spectrometer, which is used to provide light for the BRDF measurements, was modified such that the light intensity, uniformity, and stability were improved. The robot-based goniometer system, which consists of a robot arm, a rotation ring, a detector, and a control unit, is a new system designed and developed to perform BRDF measurements in TUBITAK UME Optical Laboratory. The robot arm can provide all necessary angles for absolute measurements with its 6-axis movement capability. The rotation repeatability of this robot was calculated as less than 0.01 degrees. The detector rotation ring has a diameter of 690 mm, and it also has the rotation ability between −85˚ and +85˚ around the robot arm. The 690 mm diameter was determined such that both to obtain uniform light on the sample surface and to ensure that the light beam reflected from the sample remained within the detection limit of the detector. The detector unit is an integrating sphere with two color detectors, covering the 250 nm to 2500 nm wavelength range. After this system was established and all optical characterizations were done, the BRDF measurements were carried out at normal incidence angle and at 500 nm wavelength, with accuracy varying from 0.2% to 0.6% depending on the detection angle of the detector.

Keywords

BRDF, Robot-Based Goniometer, Diffuse Reflectance

1. Introduction

The visual properties, such as color and gloss, of the products produced in the food, clothing, automotive, construction, and other sectors in the industry have always been at the forefront, and efforts to improve these properties are always increasing. The color and gloss values of the products can be scientifically derived from the specular and diffuse reflections of the materials.

The specular reflection is the situation where the light is reflected at the same angle as the normal of the surface on which it falls, and it usually occurs on mirror-like surfaces. For this kind of reflection, the reference reflectance standards, which are the source of the traceability of the gloss unit, have been realized based on the method described in the ISO standard [1] and related scientific works [2]-[5]. The measurements in these methods are based on the principle of fixed incidence and observation angles. However, in practice, since no sample has 100% specular reflectance, there is a possibility that some of the light may not be measured. For this reason, instead of this technique, goniometric-based measurement techniques have recently become widely used [6].

The other type of reflection, which is called diffuse reflection, generally occurs on rough surfaces and is the reflection of light at angles different from the normal of the surface it falls on. For these kinds of surfaces, the reference reflectance standards, which are the source of the traceability of color, have been realized based on the method described in [7] and related scientific works [8]-[14]. The measurement techniques of these works comprise integrating sphere-based measurements. However, the dimensions of the spheres, their port openings, reflection losses, etc., are the parameters that limit the accuracy of the measurements. In order to eliminate these losses, the goniometric-based BRDF measurement technique has been developed and has been widely used in metrology institutes in recent years [15]-[19]. In this technique, the reference diffuse reflectance standards can be absolutely realized through BRDF measurements, which are the measurements of diffuse reflectance under a unit solid angle in all directions.

In addition to the color and gloss properties of materials, the appearance that can be created with many other properties (sparkle, translucency, and fluorescence) is very important, and hence, studies on appearance calculations have been increasing in recent years. The BRDF measurement system, which was developed to measure diffuse reflectance absolutely, can also be used for appearance measurements. In a BRDF measurement system, replacing the detector with a camera allows appearance measurements to also be performed [20] [21].

In this work, in order to carry out absolute reflectance measurements and thus to obtain the traceability of color and gloss scales, a robot-based BRDF measurement system was developed and established at TUBITAK UME. The tasks handled within the content of this work are realized basically in three stages. At the first stage, the design, production, and installation of the BRDF system; at the second stage, optical characterizations of all the components of the BRDF system; and at the third stage, the BRDF measurements and the calculations of absolute diffuse reflectance were done.

2. Materials and Methods

2.1. The Robot-Based Goniometer System

The robot-based BRDF measurement system developed within the scope of this work is a primary-level measurement system to be used in spectrophotometric measurements in the TUBITAK UME Optics Laboratory. This system consists of two basic components: a modified spectrometer and a robot-based goniometer, as shown in **Figure 1(a)**. The BRDF is not a commercially produced measurement system; it is a system designed and developed according to the measurement needs. The work done related to the design and modification of the spectrometer and robot-based goniometer of this system is given in detail in the relevant sections.

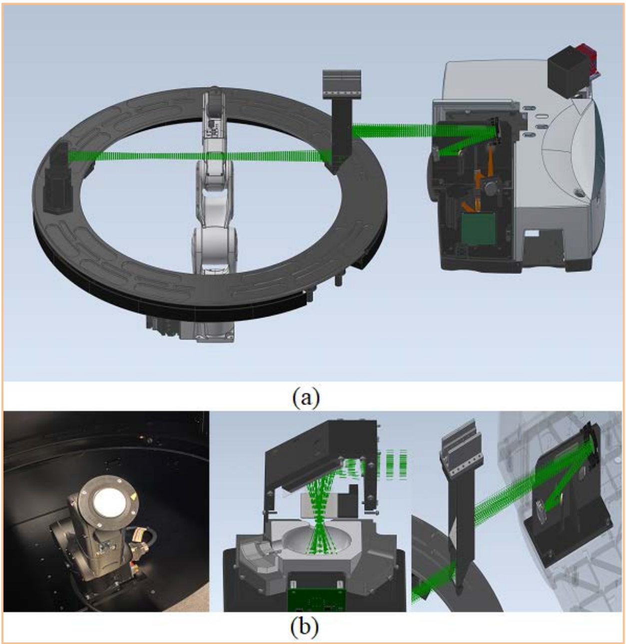

Figure 1. Robot-based BRDF measurement system's (a) internal structure, (b) components.

Robot-based goniometer system; consists of a control unit, robot arm, detector rotation ring, and detector unit. The control unit is the unit that can control the robot arm, detector rotation ring, and detector unit movements (**Figure 1(b)**).

The robot arm is the most important component of the goniometer system, where the samples on which reflectance measurements need to be performed will be placed, and it can provide all the necessary angles for absolute measurements. The robot arm used in this system has the capacity to carry samples weighing up to 2.5 kg, 6-axis movement capability, and ±0.02 mm positioning accuracy.

The diameter of the detector rotation ring is about 690 mm, which was determined by optimizing it to obtain uniform light on the sample surface and to ensure that the rays reflected from the sample remained within the detection limit of the detector. The detector rotation ring rotates around the robot arm between −85˚ and +85˚ angles, allowing reflected rays to be measured at all angles.

2.2. Test Measurements of the Robot

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire journal, and not as an independent document. Please do not revise any of the current designations.

After the robot-based BRDF measurement system was established, the alignment of the robot and detector, robot-detector distance measurements at various angles, robot sample holder and sample thickness measurements, robot movement capability, and robot rotation repeatability measurements were carried out.

The alignment of the robot and the detector to the same axis was achieved using a dummy detector and a laser (**Figure 2**). The goniometer detector was replaced with a dummy detector with a laser on it. The dummy detector was aligned at 180˚ relative to the robot arm. At the same time, the light source of the spectrometer was activated. The laser on the dummy detector was activated and adjusted to follow exactly the same path as the light from the spectrometer. Then, the robot arm was placed in the light path coming from the spectrometer, and the necessary adjustments were made to ensure that the mirror placed on the robot arm reflected the light coming from the spectrometer in the same direction.

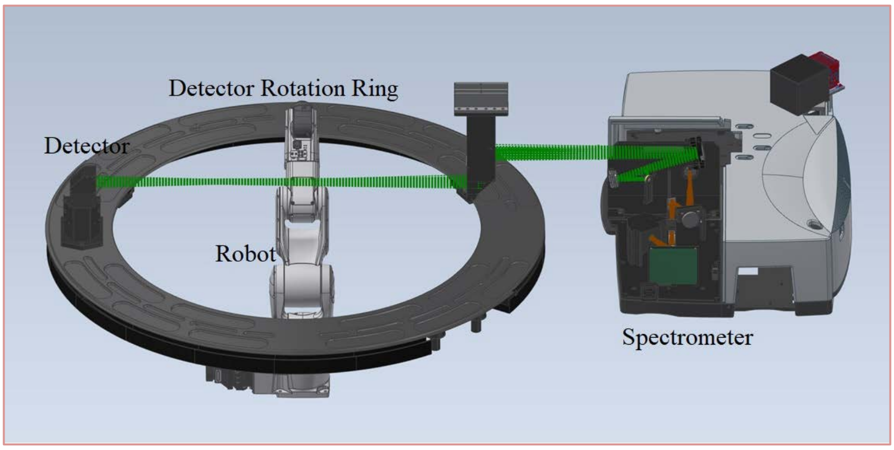

Figure 2. Measurement system for alignment of the robot and the detector to the same axis.

After aligning the robot and the detector to the same axis, the distance from the center of the sample chamber on the robot arm to the entrance of the detector must be the same at all angles on the rotation ring of the detector. For this, special reflective samples were placed in the sample chamber on the robot arm and on the front of the detector. The distances between the sample front surface and the detector front surface were measured by adjusting the center of the sample chamber on the robot arm to +90˚, −90˚, and 5˚ according to the light axis coming from the spectrometer, respectively. The specified measurements were carried out using the special caliper provided for use in this system.

Next, the rotation repeatability measurements of the robot were carried out using the laser on the dummy detector replaced with the goniometer detector, the detector rotation ring, the robot, and a mirror placed on the sample holder of the robot. The laser beam reflected from the robot's sample holder was dropped on a point 690 cm away in the laboratory. After sending the robot to its "home" position and returning it to its previous state, the amount of deviation was measured (**Figure 3**). The deviation in the distance between the points where the light reflected from the sample holder falls (690 cm) was measured as 1 mm and was calculated to correspond to an angular deviation of 0.0083 degrees. This shows that the robot's rotation repeatability is well below 0.01 degrees.

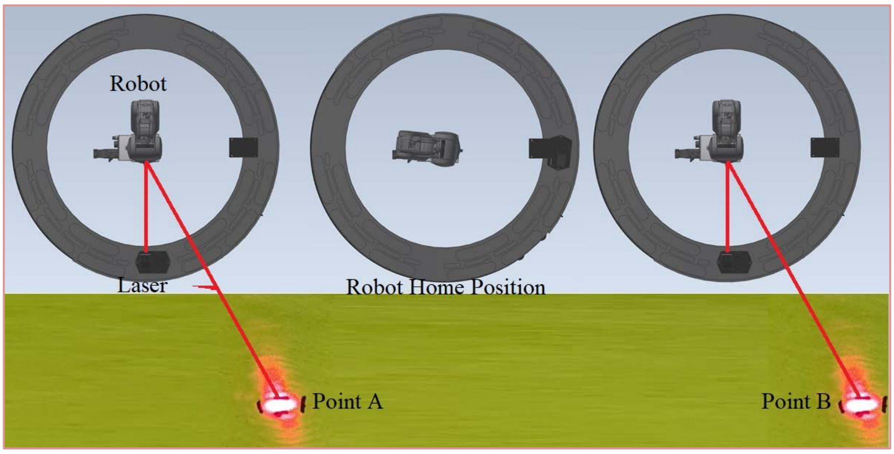

Figure 3. Rotation repeatability measurements of the robot. Point A is the incident point of the laser reflected from the mirror, and Point B is the incident point of the laser after the rotation of the robot.

3. Test Measurements of the Spectrometer

In order to obtain a homogeneous light beam on the sample in diffuse reflectance measurements, the distance between the output of the spectrometer and the surface of the sample must be long enough. Since the beam made homogeneous in this way will spread in all directions after reflecting from the diffuse reflective sample, measurements cannot be carried out accurately because the beam falling on the detector falls below the detection limit of the detector (outside the linear range). In order to increase the intensity of the beam falling on the detector, the need has emerged within the scope of this project to redesign commercially produced standard spectrometers. In classical UV-VIS spectrometers, a tungsten light source is used as the light source. Due to the low radiation intensities of these kinds of light sources in the UV-VIS regions, they are insufficient for a robot-based absolute reflectance measurement system. For this reason, in the redesigned spectrometer, besides tungsten light, a laser-driven plasma-based light source was also used, as shown in Figure 4.

The classical spectrometers, in general, have low performance in the UV region. This is due to the total performance of detectors, gratings, and the light sources (mostly tungsten) used in these spectrometers. Therefore, the image of the light beam at the exit of the spectrometer can be very weak, as given in Figure 5(a). In order to improve the beam intensity in the spectrometer used in this work, a laser-driven plasma-based light source was added to the redesigned spectrometer for the measurements of the UV region. With this light source, the image of the light beam at the exit of the spectrometer was improved, as shown in Figure 5(b).

For the alignment of these light sources, the light beams coming out of the system were directed to the detector input gap (port) through the optical system of the spectrometer. At the same time, instead of the detector, a dummy detector with a laser light source was placed on it, and it was checked whether the laser light followed the same path as the light coming out of the spectrometer, and the beams coming out of the spectrometer were aligned to follow exactly the same path as the laser light.

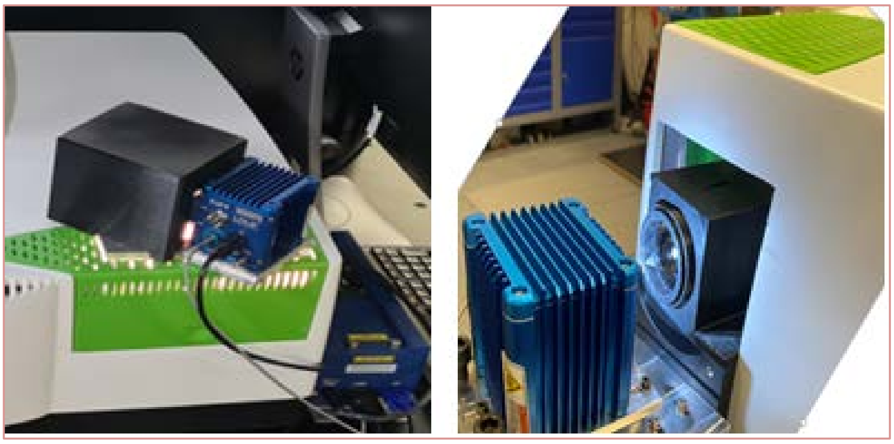

Figure 4. Changes were made to the spectrometer's radiation source.

After the alignment of light sources, polarization, and attenuator controls were completed, the reason is that the spectrometer components (mirrors, gratings, etc.) can polarize the light beam as they reflect it. If these effects cannot be eliminated, they may cause signal jumps, especially at filter, grating, and detector change points. In this redesigned spectrometer, this effect was eliminated with the depolarizer placed in the spectrometer right at the entrance of the sample chamber (Figure 6(a)). In addition, when measuring samples with very low reflectance levels, the high signal difference between the reflected light and the light falling on the sample causes a high dynamic range difference and affects the measurement accuracy. To eliminate this effect, attenuators that can change the power of the light beam between 100% and 0.1% have been placed in this redesigned device (Figure 6(b)). In the measurements, the performances of depolarizers, polarizers, and attenuators were tested.

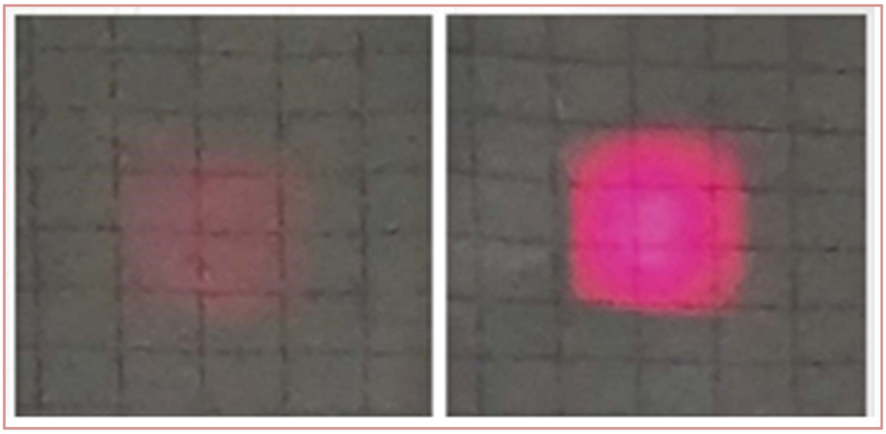
(a) (b)

Figure 5. Signal levels of light sources at the exit of the spectrometer: (a) tungsten light source image; (b) laser-driven plasma light source image.

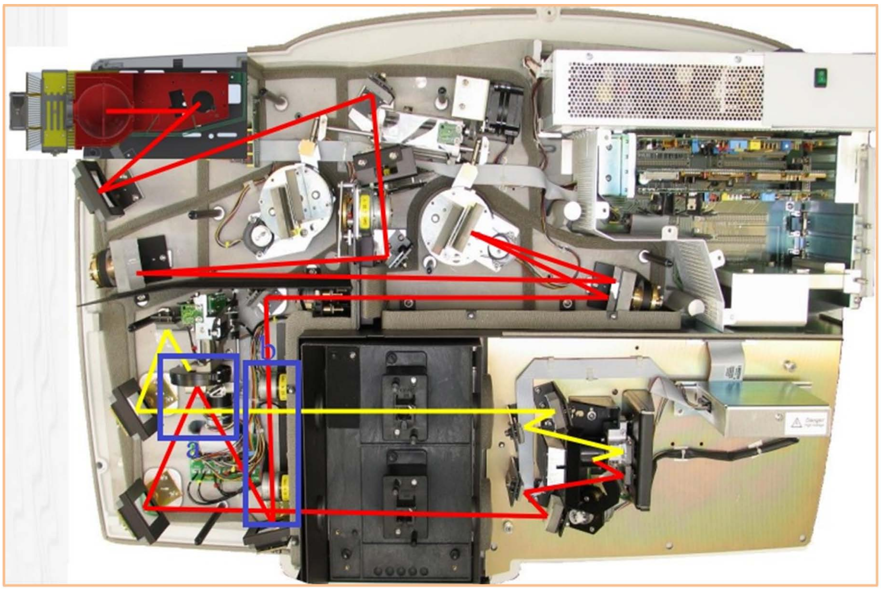
(a) (b)

Figure 6. Modifications in the spectrometer components: (a) in the polarizer; (b) in the attenuator.

Finally, non-uniformity measurements of the laser-driven plasma-based light source were performed. Non-uniformity measurements of the laser-driven plasma-based light source were conducted at the location of the sample chamber on the robot arm in the robot-based absolute diffuse reflectance measurement system. Measurements were made using a full-frame and an 8 mm aperture camera sensor. The center of the beam is defined as the location with approximately equal energy on both sides of the beam and is shown with red dotted lines. This position is +/− 0.3 mm (13.4 - 13.9) for the full slit mode of the spectrometer (**Figure 7**), and for the reduced slit, it was calculated to vary between +/− 0.2 mm (14.23 - 14.56) (**Figure 8**).

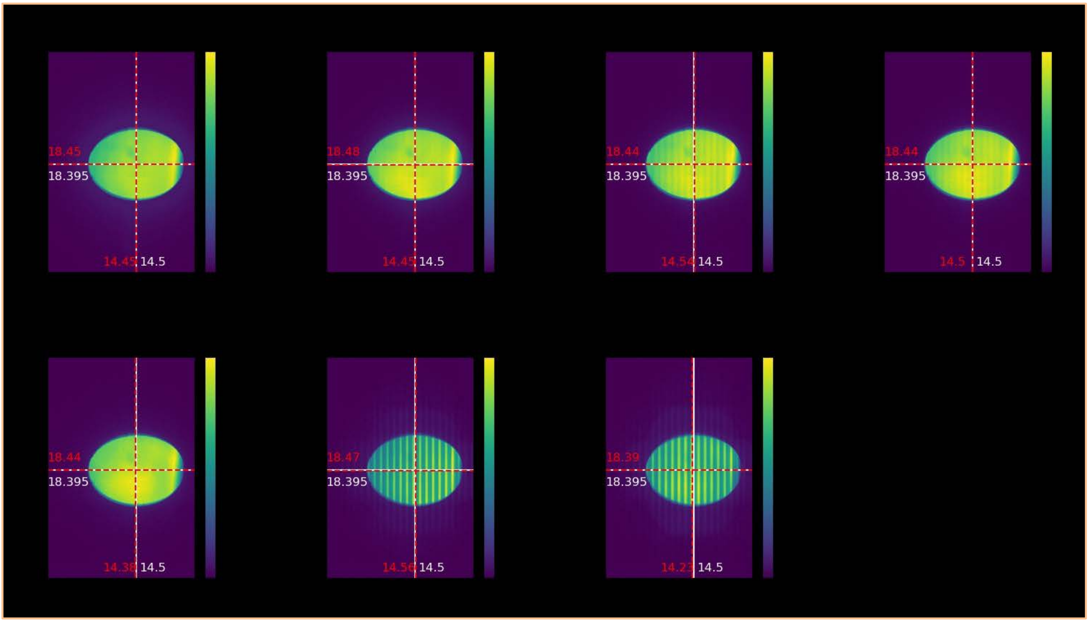

Figure 7. Non-uniformity measurements for full slit width mode.

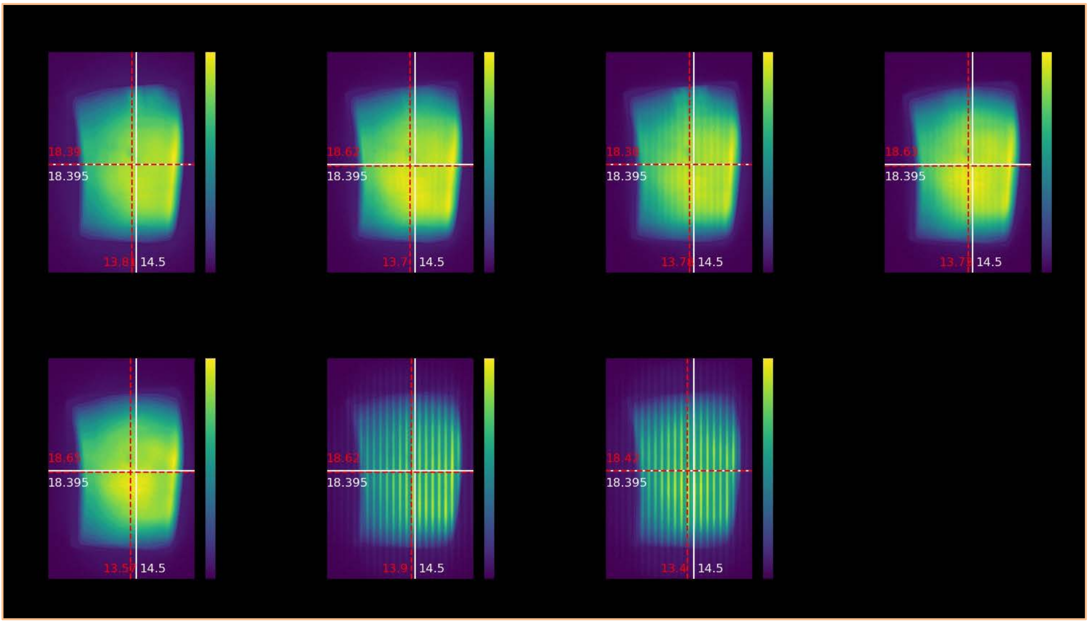

Figure 8. Non-uniformity measurements for half-slit-width mode.

4. BRDF Measurements with a Robot-Based Absolute Diffuse Measurement System

For the BRDF measurements, the first step is the measurement of the robot sample holder and sample thickness so as to apply them as the correction factor to the software. The measurements of the sample holder and sample thickness of the robot arm shown in **Figure 9** were carried out using the optical method in TUBITAK UME Dimension Laboratory. These parameters (t1, t2, and t3) were then uploaded to the software and used in measurements.

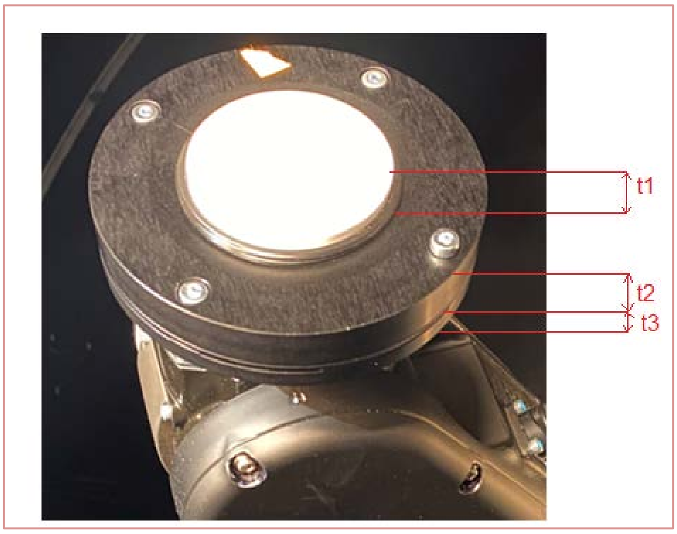

Figure 9. Shows measurements of the sample holder and the sample thickness of the robot arm.

The second step for the BRDF measurements is the preparation of the measurement recipe. The recipe was prepared as shown in **Figure 10**, and was entered into the software of the spectrometer (UV Winlab) and the goniometer (BRDF). The UV Winlab and BRDF Goniometer interfaces are designed to program both the robot's movements and the spectrometer parameters.

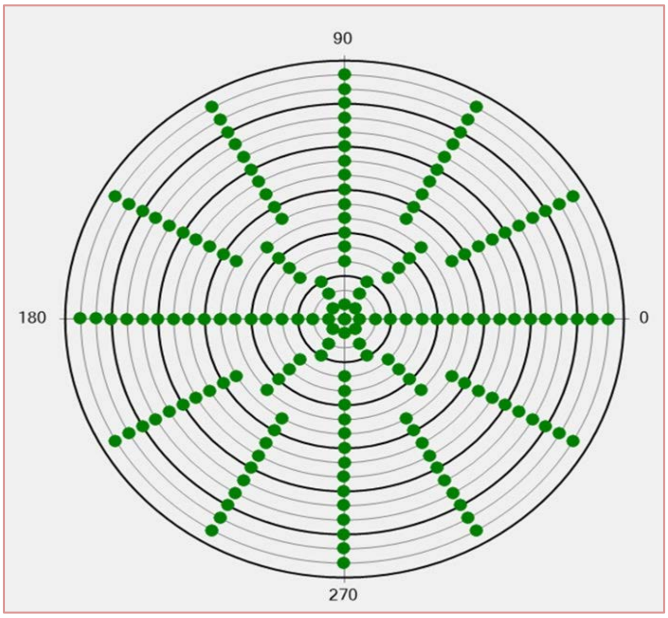

Figure 10. Schematic representation of the measurement recipe prepared using the BRDF Goniometer interface.

Following the mentioned preparations, the BRDF measurements were carried out at 5˚ intervals between −85˚ and 85˚ using the TUBITAK UME diffuse reflective reference standard and the measurement recipes prepared in the previous section. Since the change in large angles between −85˚ and 85˚ is greater than the change in small angles, it was decided that the number of measurements at large angles (such as 85˚) should be more than the number of measurements at small angles (such as 5˚), as shown in **Figure 10**. The angle-dependent change of the BRDF factor calculated according to the measurements performed is shown in **Figure 11**. From these results, the evaluated angle-dependent BRDF results of the diffuse reflection sample are given in **Table 1**.

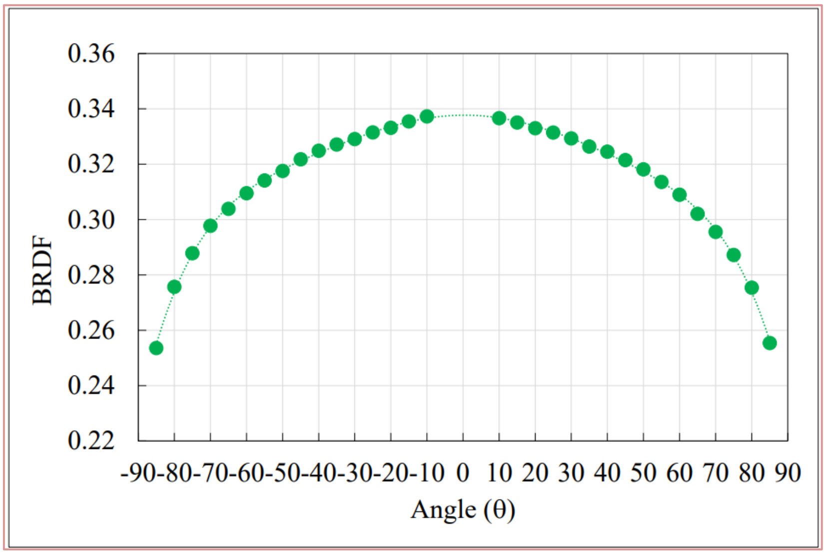

Figure 11. Shows the graphical representation of the angle-dependent BRDF measurement results of the diffuse reflection sample.

Table 1. Angle-dependent BRDF measurement results of the diffuse reflection sample.

Observation Angle [˚]	BRDF [sr^{-1}]	Uncertainty [sr^{-1}]
85	0.2554	0.0008
80	0.2754	0.0008
75	0.2872	0.0007
70	0.2955	0.0007
65	0.3021	0.0008
60	0.3090	0.0008
55	0.3136	0.0005
50	0.3181	0.0005
45	0.3215	0.0006
40	0.3245	0.0006
35	0.3264	0.0005
30	0.3293	0.0005
25	0.3315	0.0006

Continued

20	0.3330	0.0008
15	0.3351	0.0008
10	0.3367	0.0005
−10	0.3373	0.0004
−15	0.3355	0.0004
−20	0.3332	0.0008
−25	0.3315	0.0008
−30	0.3291	0.0004
−35	0.3271	0.0006
−40	0.3248	0.0005
−45	0.3218	0.0006
−50	0.3175	0.0003
−55	0.3141	0.0006
−60	0.3095	0.0005
−65	0.3039	0.0009
−70	0.2977	0.0008
−75	0.2878	0.0008
−80	0.2757	0.0008
−85	0.2536	0.0008

5. Results and Discussion

In this work, the optical characterizations performed for the robot-based bidirectional reflectance distribution function (BRDF) measurement system developed at the TUBITAK UME Optical Laboratory are explained. This system consists of two basic components, a modified spectrometer and a robot-based goniometer.

The spectrometer used in this system is a spectrometer whose optical performance has been improved by modifying many components of the commercially produced spectrometer. With commercially produced spectrometers, especially at short wavelengths, due to low light intensities, the measurement uncertainties are high. To overcome this problem, a laser-driven plasma-based light source was added to the spectrometer. This enables us to increase the light intensity at these wavelengths and to perform measurements with high accuracy. As a result, both the intensity and stability of the light obtained at the exit of the spectrometer were increased. By increasing the intensity and stability, measurements with improved repeatability were achieved.

Two other important changes that were made to the spectrometer are the addition of polarizers and attenuators. The reason for adding the polarizer is that spectrometer components like mirrors, gratings, etc., can polarize the light beam as they reflect it. If these effects cannot be eliminated, they may cause signal jumps, especially at filter, grating, and detector change points, resulting in high uncertainties. Similarly, the reason for adding attenuators is to reduce the intensity difference between the sample and reference beams. Since the samples to be measured with the BRDF system are diffuse samples, the reflected beams from them have very low intensity compared to the reference beam intensity. Therefore, this high dynamic range difference affects the measurement accuracy. To eliminate this effect, attenuators that can change the power of the light beam between 100% and 0.1% have been placed in this redesigned device.

The other important component affecting the repeatability of measurements is the repeatability of the robot and detector ring rotation together. In order to avoid any measurement deviations due to the weight of samples, the carrying capacity of the robot (2.5 kg) used in this system was selected to be at least 10 times greater than the weight of the samples to be used in the measurements to be done with this system. In addition, care was taken to ensure that the robot had high movement capacity (6-axis movement capability) for any angular positioning of the sample. The rotation repeatability of the robot and rotation ring was obtained at about 0.0083˚, which is very low compared to most of the published results, for which the robot rotation repeatability is around 0.01˚. This rotation repeatability is valid for sample weights up to a maximum of 2.5 kg.

The developed BRDF measurement system is controlled by two different software programs. One software controls the spectrometer and the other controls the robot. In order to make high-accuracy measurements with this BRDF system, first of all, the thickness of the sample must be measured correctly and entered into the software. Then, a well-defined recipe that will describe the measurements to be made must be prepared. The recipe diagram prepared for the BRDF measurement performed in this work is given in **Figure 10**. The number of dots in each circle of this figure indicates the number of measurements needed to be performed between the rotation range (−85˚ and 85˚) of the detector ring and the number of rotations of the sample at each angle. At each step (5˚) of the rotation, the higher the number of rotations of the sample, the higher will be the accuracy of the measurements, but with a long measurement time. As the scattering at high angles (close to −85˚ and 85˚) will be more compared to small angles (close to −10˚ and 10˚), it will be better to set the number of sample rotations to be varied according to the observation angles so as to optimize both the measurement time and the measurement accuracy.

As a result, with this specially designed and developed BRDF system, high-accuracy measurements can be obtained, as shown in **Table 1** and **Figure 11**. **Figure 11** shows the graphical representation of the BRDF measurements performed with this developed system, and **Table 1** shows the measured BRDF values within −85˚ and 85˚ rotation angles of the detector. Using these BRDF data, the absolute reflectance value of the sample at the relevant wavelength is obtained. The uncertainties of the data shown in **Table 1** vary between 0.2% and 0.6%, depending on the detector's collection angle. At the normal incident angle, it is just between 0.2% and 0.3% between +10˚ and −10˚. This uncertainty capability is only valid for the diffuse reflective samples having a 10 cm × 10 cm size and geometrically flat surfaces.

The most important parameters determining this measurement uncertainty are the robot's rotational repeatability, the stability of the light source, and the detector's linearity.

6. Conclusions

In this study, the establishment and optical characterization of the developed robot-based BRDF system, its optical characterization, and BRDF measurements performed at a single wavelength were conducted to obtain information about its performance. This system's components (light sources, detectors, robot rotation capability, etc.) were chosen such that it has the capability to perform measurements at incident angles from 0˚ to 85˚ and in the wavelength range from 250 nm to 2500 nm. With this BRDF system, reflectance measurements of diffuse reflective materials used as reference standards in spectrometric measurements can be carried out in the absolute wavelength range of 25 nm to 2500 nm. Accordingly, traceability of color and gloss measurements can be ensured.

Currently, in metrology institutes, the traceability of diffuse reflectance reference standards used in spectrometry is achieved with BRDF systems. The main disadvantage of these systems is that measurements are slow and time-consuming. By using a camera instead of a detector, BRDF measurements can be performed more quickly and can also be used for image measurements, a prominent feature of spectrometry.

Funding

The project (23IND14 xDDiff) has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] ISO (2014) BS EN ISO 2813:2014, Paints and Varnishes. Determination of Gloss Value at 20 Degrees, 60 Degrees and 85 Degrees.

[2] Nadal, M.E. and Thompson, E.A. (2000) New Primary Standard for Specular Gloss Measurements. *Journal of Coatings Technology*, **72**, 61-66. https://doi.org/10.1007/bf02720526

[3] Leloup, F.B., Audenaert, J., Obein, G., Ged, G. and Hanselaer, P. (2016) Repeatability and Reproducibility of Specular Gloss Meters in Theory and Practice. *Journal of Coatings Technology and Research*, **13**, 941-951. https://doi.org/10.1007/s11998-016-9813-5

[4] Budde, W. (1980) The Calibration of Gloss Reference Standards. *Metrologia*, **16**, 89-93. https://doi.org/10.1088/0026-1394/16/2/004

[5] Ferrero, A., Gevaux, L., Jurgo, I., Manoocheri, F., Kübarsepp, T., Nilsson, A., *et al.* (2023) Preliminary Study for Traceability on Specular Gloss. *CIE x*050:2023 *Proceedings of the* 30*th Session of the CIE*, Ljubljana, 15-23 September 2023, 783-792. https://doi.org/10.25039/x50.2023.pp005

[6] Gevaux, L., Dupiau, A., Morvan, K. and Obein, G. (2023) The Measurement of Specular Gloss Using a Conoscopic Goniospectrophotometer. *London Imaging Meeting*, **4**, 10-14. https://doi.org/10.2352/lim.2023.4.1.04

[7] Barkman, E.F. (1970) Specular and Diffuse Reflectance Measurements of Aluminum Surfaces. In: Barkman, E.F., Ed., *Appearance of Metallic Surfaces*, ASTM International, 46-58. https://doi.org/10.1520/stp47443s

[8] Shitomi, H., Mishima, Y. and Saito, I. (2003) Development of a New Integrating Sphere with Uniform Reflectance for Absolute Diffuse Reflectance Measurements. *Metrologia*, **40**, S185-S188. https://doi.org/10.1088/0026-1394/40/1/342

[9] Zwinkels, J.C. and Erb, W. (1997) Comparison of Absolute D/O Diffuse Reflectance Factor Scales of the NRC and the PTB. *Metrologia*, **34**, 357-363. https://doi.org/10.1088/0026-1394/34/4/9

[10] Zerlaut, G.A. and Anderson, T.E. (2003) Multiple-Integrating Sphere Spectrophotometer for Measuring Absolute Spectral Reflectance and Transmittance. *Applied Optics*, **40**, 185-188.

[11] Hanssen, L. (2001) Integrating-Sphere System and Method for Absolute Measurement of Transmittance, Reflectance, and Absorptance of Specular Samples. *Applied Optics*, **40**, 3196-3204. https://doi.org/10.1364/ao.40.003196

[12] Nevas, S., Manoocheri, F. and Ikonen, E. (2004) Gonioreflectometer for Measuring Spectral Diffuse Reflectance. *Applied Optics*, **43**, 6391-6399. https://doi.org/10.1364/ao.43.006391

[13] Obein, G., Bousquet, R. and Nadal, M.E. (2005) New NIST Reference Goniospectrometer. *SPIE Proceedings*, **5880**, 241-250. https://doi.org/10.1117/12.621516

[14] Hünerhoff, D., Grusemann, U. and Höpe, A. (2006) New Robot-Based Gonioreflectometer for Measuring Spectral Diffuse Reflection. *Metrologia*, **43**, S11-S16. https://doi.org/10.1088/0026-1394/43/2/s03

[15] Rabal, A.M., Ferrero, A., Campos, J., Fontecha, J.L., Pons, A., Rubiño, A.M., *et al.* (2012) Automatic Gonio-Spectrophotometer for the Absolute Measurement of the Spectral BRDF at In- Out-of-Plane and Retroreflection Geometries. *Metrologia*, **49**, 213-223. https://doi.org/10.1088/0026-1394/49/3/213

[16] Höpe, A., Koo, A., Verdu, F.M., Leloup, F.B., Obein, G., Wübbeler, G., *et al.* (2014) "Multidimensional Reflectometry for Industry" (XD-Reflect) an European Research Project. *SPIE Proceedings*, **9018**, Article ID: 901804. https://doi.org/10.1117/12.2035981

[17] Leloup, F.B., Forment, S., Dutré, P., Pointer, M.R. and Hanselaer, P. (2008) Design of an Instrument for Measuring the Spectral Bidirectional Scatter Distribution Function. *Applied Optics*, **47**, 5454-5467. https://doi.org/10.1364/ao.47.005454

[18] Baribeau, R., Neil, W.S. and Côté, É. (2009) Development of a Robot-Based Gonioreflectometer for Spectral BRDF Measurement. *Journal of Modern Optics*, **56**, 1497-1503. https://doi.org/10.1080/09500340903045702

[19] Lanevski, D., Manoocheri, F. and Ikonen, E. (2022) Gonioreflectometer for Measuring 3D Spectral BRDF of Horizontally Aligned Samples with Traceability to SI. *Metrologia*, **59**, Article ID: 025006. https://doi.org/10.1088/1681-7575/ac55a7

[20] Atamas, T., Hauer, K.O. and Höpe, A. (2012) Appearance Measurements of Goniochromatic Colours. In: Padilla, S., Ed., *Predicting Perceptions*: *Proceedings of the* 3*rd International Conference on Appearance*, International Society for Presence Re-search, 149-154.

[21] Dong, Z., Walter, B., Marschner, S. and Greenberg, D.P. (2015) Predicting Appearance from Measured Microgeometry of Metal Surfaces. *ACM Transactions on Graphics*, **35**, 1-13. https://doi.org/10.1145/2815618