NRC robot-based gonioreflectometer for spectral BRDF measurement

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Abstract

A new gonioreflectometer has been developed at the National Research Council of Canada to measure spectral bidirectional reflectance distribution functions (BRDF). It incorporates a five-axis robot manipulator and allows the spectral sampling of the BRDF of reflective materials for arbitrary angles of irradiation and detection. One application will be the characterization of calibration and test targets used in 3D multispectral image acquisition systems.

Introduction

The spectral bidirectional reflectance distribution function (BRDF; $f_r(\lambda;\theta_i,\varphi_i,\theta_r,\varphi_r)$) describes the ratio of reflected radiance exiting from a surface in a particular direction (defined by the angles θ_r,φ_r in Figure 1) to the irradiance incident on the surface from direction θ_i, φ_i , at a particular wavelength.

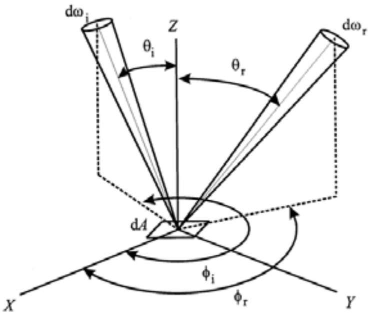

Figure 1. *Geometry of incident and reflected beams for a surface element. (Taken from Referece [1]).*

BRDF allows the description of object appearance under user-defined lighting conditions. It is commonly used in computer graphics for the realistic colour rendering of 3D scenes. Applications that generate 3D and colour content from sensed data (Virtualized Reality) are affected by the BRDF of scene elements and must take it into consideration. For example, NRC Institute for Information Technology (IIT) has designed a high resolution sensor that uses laser triangulation to extract the 3D shape and colours of objects. The system received much attention recently when it was used to scan the Mona Lisa at Musée du Louvres in Paris. The colour captured by the sensor is extracted from the ratios of monochromatic light signals reflected back from the sensed object to the signals from a white diffuser used for calibrating the system [1]. The laser scanner can act as a spectral BRDF sampling instrument if it takes into consideration the actual spectral BRDF of the calibrating diffuser. Instruments like this can be called "relative instruments" and the calibration diffusers they use act as transfer standards. Eventually, transfer standards must be measured from first principles according to some recognized methodology, and be traceable to the SI Units maintained at National Metrology Laboratories. It is the role of NRC Institute for National Measurement Standards (INMS) to provide such capability and, in anticipation of a growing number of applications requiring traceable BRDF data, INMS recently initiated the construction of a robot-based gonioreflectometer for absolute measurements of spectral BRDF. This paper describes the current status of that system and provides future directions.

Principle

Spectral radiance $L(\lambda;\theta,\varphi)$ is the fundamental radiometric quantity of interest here. It is defined as the amount of radiant power per unit wavelength being carried along a direction, per unit area perpendicular to that direction and per unit solid angle around that direction. A direction is defined here by an elevation angle θ and an azimuth angle φ. Spectral radiance can be measured with an imaging spectroradiometer by making the defining direction, area and solid angle fit respectively with the optical axis, the field stop, and the aperture stop of the instrument. The response of the instrument is then proportional to the mean spectral radiance over the finite defining area and solid angle, and can be scaled properly using standard reference sources. Uniform light sources can be made with integration spheres to show constant spectral radiance over their exit port. The important property of spectral radiance is that in free space it remains constant along the direction of a ray path. It changes abruptly however when a reflecting surface is encountered. Equation (1) relates the spectral radiance reflected in direction (θ_r,φ_r) to the spectral radiance incident from all directions (θ_i,φ_i) at the intersection with the surface:

$$L_r(\lambda;\theta_r,\varphi_r) = \int f_r(\lambda;\theta_i,\varphi_i,\theta_r,\varphi_r) L_i(\lambda;\theta_i,\varphi_i)\cos(\theta_i)d\omega_i \quad . \qquad (1)$$

Figure 1 illustrates the geometry. The integral is carried over the hemisphere above the surface element, and the BRDF is seen as a kernel that operates a redistribution of the incident radiance. When the incident radiation comes from the exit port of a uniform light source centered and perpendicular to a given (θ_i,φ_i), and when $f_r(\lambda;\theta_i,\varphi_i,\theta_r,\varphi_r)$ does not vary much over the angular extent of that port, Eq. (1) simplifies to

$$L_r = f_r(\lambda;\theta_i,\varphi_i,\theta_r,\varphi_r)\cos(\theta_i)L_s\frac{\pi r^2}{R^2+r^2}, \qquad (2)$$

where r, L_s , and R are the radius, the spectral radiance and the distance to center of that port. Equation (2) allows the calculation of f_r for one pair of directions when L_r, L_s, R and r are known. L_r and L_s can be measured with a spectroradiometer, r and R can by obtained by dimensional metrology, and the various angles can be set with a goniometer. This method of calculation is good for building a primary level

BRDF measuring instrument as it works from first principles and does not require the use of calibration targets for which the BRDF is already known.

Instrument Description

Figure 2 shows the laboratory setup rendered from our CAD drawings. A five-axis robot is used to hold the sample and to control its orientation. A large rotation stage (bearing) holds an extended uniform light source at distance *R* from its center, with the circular exit port (radius *r*) facing the sample. The robot and the rotation stage together provide six degrees of freedom, which is sufficient to bring the front surface of the sample in coincidence with the axis of the bearing and to control the four angles in equation (2). An imaging spectroradiometer measures the spectral radiance from the sample (Figure 2-top) and directly from the source (Figure 2-bottom). The spectroradiometer is carried by a linear stage in order to keep its focusing distance constant between these two measurements. $f_r(\lambda;\theta_i,\varphi_i,\theta_r,\varphi_r)$ is obtained from equation (2).

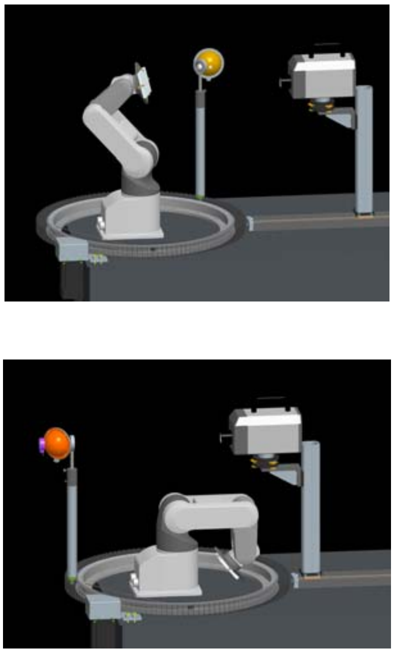

Figure 2. *System configuration for sample (top) and source (bottom) measurement.*

Our system is largely based on a system built at the Physicalisch-Technische Bundesanstalt (PTB) in Germany [2, 3]. Notable differences of the NRC system are the use of a smaller bearing, a smaller source and a faster and more compact spectroradiometer mounted on a linear stage. Figure 3 shows a picture of our system at the construction phase, and Table 1 summarizes some key parameter values.

The extended uniform light source is realized by a water-cooled integration sphere internally coated with barium sulphate and housing a 100W quartz tungsten halogen lamp. The exit port holds a precision aperture which is kept at constant temperature. An internal white baffle made of sintered PTFE prevents direct illumination of the sample by the lamp. Instead, the sample sees only the PTFE baffle through the exit port. The quasi-Lambertian property of sintered PTFE combined with the quasi-uniform illumination

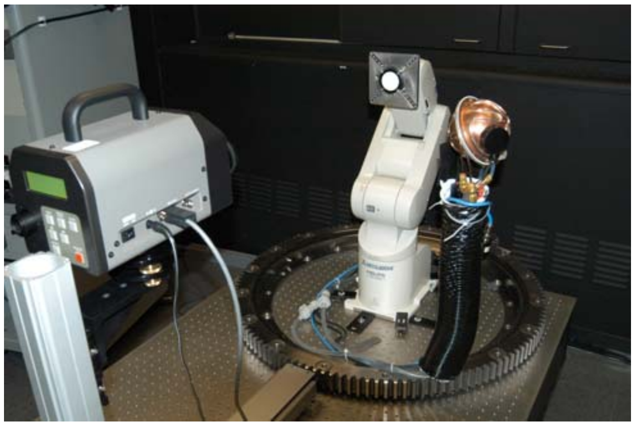

Figure 3. *Laboratory setup.*

Table 1: Key parameter values

Parameter	Value
Apperture angle, irradiation	2.9°
Apperture angle, detection	1.6°
Spectroradiometer field of view	1°
Source-sample distance (*R*)	391.27 ± .03 mm
Source aperture radius (*r*)	10.000 ± .002 mm
Wavelength range	380nm-780nm
Wavelength interval	1nm
Wavelength accuracy	.2nm
Bandwidth	5nm

from the inside wall of the sphere together provide the radiance uniformity at the exit port. A silicone photodiode equiped with a V_λ filter monitors the sphere luminance to allow the compensation of the slow fluctuations and drift of the lamp. The light output from the sphere is expected to be unpolarized due to the multiple reflections and the symmetrical construction.

The spectroradiometer is a commercial array-type instrument which is calibrated against NRC reference lamps. A stray light correction similar to the one described in Reference [4] is applied to the radiance signal in order to reduce the internal stray light of the instrument to less than 10^{-4}. The spectroradiometer incorporates an internal optical fiber bundle whose purpose is to make the field response uniform and to depolarize light. The spectroradiometer is mounted on a carrying stage at 65 cm from the bearing center, and it is focused at this distance. The 1° field of view spans 11 mm on the sample when viewing from normal. A full spectral radiance spectrum, from 380nm to 780nm, is captured in a single measurement, taking up to 2 minutes at most.

The robot is used as a sample holder and has a load capacity of 2 kg. The use of the robot for our type of configuration is well described in Reference [3]. The robot is used in a posture where the center of the sample measuring area is kept at the intersection of the source aperture axis, the spectroradiometer optical axis, and the bearing vertical axis. Positioning accuracy is of the order of .02 mm. The normal to the sample is varied in the up-down direction by adjusting the robot's shoulder, elbow and wrist joint angles in a way to keep the sample centered on the vertical axis and at a constant height. The robot rotates on its base around the central axis. The fifth degree of freedom of the robot is a hand twist that rotates the sample surface on itself. This adjustment is

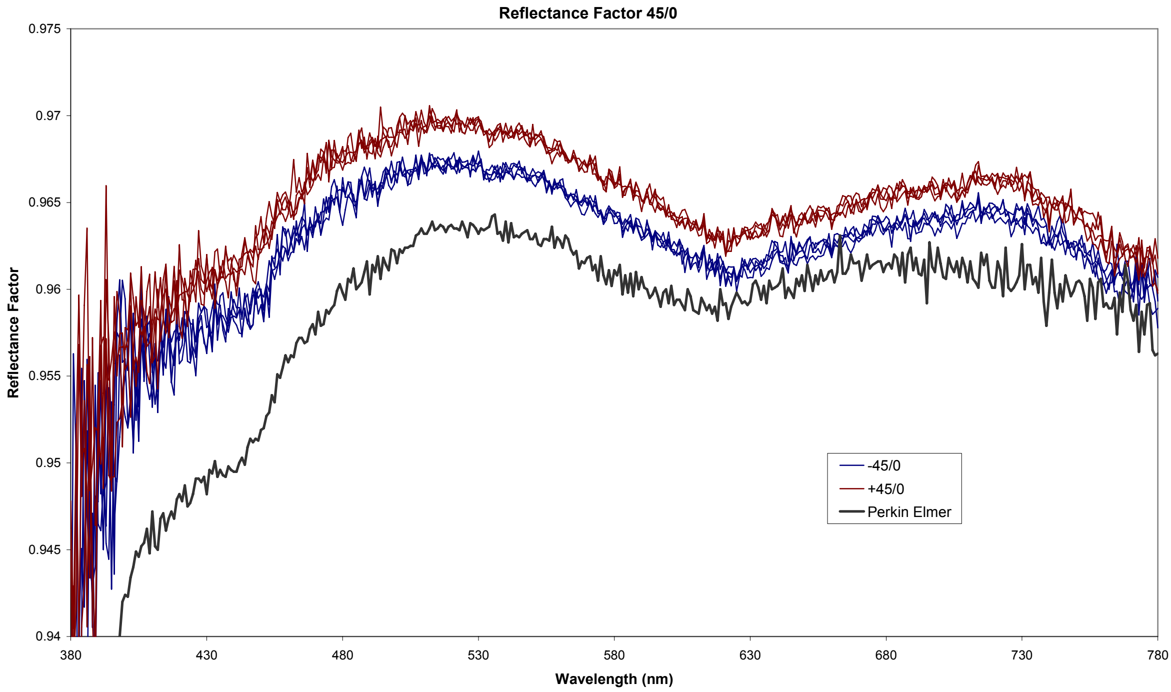

Figure 4. *Comparison of the 45/0 reflectance factor measured with the gonioreflectometer and with a spectrophotometer equipped with a 0/45 annular reflection accessory.*

necessary for out of plane measurements in order to keep the sample fixed in the defining XY plane of Figure 1. The angular accuracy of the robot and bearing angles far exceed the irradiation and detection aperture angles.

Dedicated software was developed to interface the various components to a computer and to allow unattended sequential BRDF acquisition from a predefined list of angles. The software converts $\theta_i,\varphi_i,\theta_r,\varphi_r$ into robot and bearing angles using rotation transforms. There are formally two solutions: one has the normal to the sample pointing upward, like in Figure 2, the other has the sample facing downward and twisted half a turn on itself, with the bearing angle and robot base angle set in the opposite directions as for the first solution. The two solutions can be measured and averaged together to reduce residual misalignment and off-centering errors.

The whole system is housed in temperature-controlled Class 100000 clean room with walls painted black to minimize stray light.

Instrument validation

The system just described is in testing phase, where we are trying to identify the key influential factors and how they affect the accuracy of the method. One test has been to measure an Opal Glass sample for the in-plane 45/0 geometry. Comparison values for this sample have been measured with a Perkin Elmer Lambda 19 spectrophotometer calibrated against a pressed PTFE standard. This instrument measures the reflectance factor, noted β, for 0° illumination and 45° annular detection, with an expanded (k=2) uncertainty of 0.4%. The BRDF f_r and the reflectance factor β are related by the formula $f_r = \beta / \pi$. Provided that the sample is perfectly homogeneous and thanks to the reciprocity law which states that bidirectional reflectance measurements are equivalent when the source and the detector are inverted, our gonioreflectometer data should match the spectrophotometer data. Figure 4 shows some representative results. The topmost set of four curves corresponds to four gonioreflectometer measurements for the first realization of the 45/0 geometry. The sample is directly facing the spectroradiometer and the lamp/bearing is rotated clockwise (+45°). The middle set of four curves correspond to the second realization of the 45/0 geometry, with the lamp/bearing rotated counterclockwise (-45°) and the sample twisted 180°. The systematic offset of 0.0025 between the two sets of curves is attributed to the spectroradiometer 1° measuring field not being exactly centered with the rotation axis. The source at 45° creates a small gradient of irradiance across the sample because the distance to the source varies. This gradient is reversed when switching from +45° to -45°. Averaging between the two realizations eliminates the offset, but at the cost of doubling BRDF capture times.

The bottom curve in Figure 4 is for the spectrophotometer measurement and it is not inconsistent with the other curves considering that the uncertainty of this measurement is 0.004. This preliminary comparison serves only to validate our approach. A detailed uncertainty budget for the gonioreflectometer is currently being developed using equation (4) as the “measurement equation”, and will be independent of the spectrophotometer results. The repeatability of the gonioreflectometer signal is seen in Figure 4 to be of the order of 0.0005 from 450 nm to 780 nm, and to degrade noticeably at the blue end of the spectrum. Other important error components are systematic effects including the source aperture area, the source to sample distance, the source non-uniformity, stray light, the spectroradiometer non linearity, and angle setting. This error budget evaluation is currently under way. It is anticipated that the final uncertainty will be smaller than

0.004 and that pressed PTFE can be made traceable to the gonioreflectometer, not the opposite.

Conclusion and future directions

A robot-based gonioreflectometer has been designed in anticipation of a growing demand for traceable spectral BRDF measurements from sectors such as machine vision, remote sensing and colour imaging. Although not fully quantified yet, the instrument performance is foreseen to be comparable with what exists at other National Measurement Institutes, and will allow basic intercomparisons as well as collaborations toward the improvement of the state of the art. Although capable of unattended measurement, the system is currently tied to a list of predefined irradiation and viewing angles. In BRDF modeling applications, this will be somewhat restrictive considering that BRDF is often not a well-behaved function, exhibiting sharp lobes, asymmetries etc., and requiring a very large number of measurements. For this type of application, it is hard to decide a priori what the sampling angles should be. It would be better to have an instrument driver with built-in intelligence to decide the appropriate sampling angles "on the go" making use of a BRDF model and some criteria about the final accuracy required. Data structures and algorithms have already been defined that will support this type of operation and will be implemented in the next stage of the development.

Acknowledgments

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Author Biography

Réjean Baribeau received his B.Sc.(physics) in 1977, his M.Sc.(physics) in 1979, and his Ph.D.(physics) in 1992, all from Université Laval. From 1988 to 1997 he worked with NRC's Institute for Information Technology on the museum application of 3-D laser scanning technology. He joined NRC's Institute for National Measurement Standards in 1997 where he works in the field of color science applied to color imaging technology.

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