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A gonioreflectometer for the measurement of bidirectional reflectance distribution functions in the thermal infrared

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Summary: An in-plane-gonioreflectometer was developed to measure bidirectional reflection distribution functions (BRDF) for opaque surface materials. The emissivity can be determined by integrating the BRDF over the hemisphere for surfaces with diffuse scattering properties. A gonioreflectometer generally consists of a radiation source, a detector and some robotics to vary radiation and viewing angles. An integrating sphere operating in a broadband infrared wavelength was selected as radiation source. An LWIR and an MWIR thermal imaging camera were selected as detectors. The gonioreflectometer and the results of the first measurements are presented here.

Keywords: emissivity, emittance, gonioreflectometry, BRDF, thermal infrared, in-plane-scatterometry

Background, Motivation and Objective

The bidirectional reflectance distribution function (BRDF) is a very useful function for characterising scattering and surface roughness, ray tracing, and determining reflectance of diffuse scattering surfaces [1], the last point being particularly interesting for thermal imaging for emissivity determination. This paper describes an in-plane-gonioreflectometer with thermal imaging cameras as detectors. The measurement procedure is described and the first results are presented.

Description of the Gonioreflectometer

First, the theory about BRDF measurements is presented. Then the measurement device and the measurement procedure is presented.

BRDF Theory

The BRDF for in-plane measurements is defined in radiometric terms as the ratio of the surface radiance in a particular viewing direction $dL(\theta_\mathrm{i}, \theta_\mathrm{o})$ to the surface irradiance resulting from the radiation incident from a particular direction of irradiation $dE(\theta_\mathrm{i})$, see eq. (1)[2].

$$f_\mathrm{r}(\theta_\mathrm{i}, \theta_\mathrm{o}) = \frac{dL_\mathrm{o}(\theta_\mathrm{i}, \theta_\mathrm{o})}{dE_\mathrm{i}(\theta_\mathrm{i})} \quad (1)$$

with θ_i as incident angle and θ_o as viewing angle (see Fig. 1). For a radiation source that can be assumed to irradiate a surface uniformly this simplifies to eq. (2) [1]

$$f_\mathrm{r}(\theta_\mathrm{i}, \theta_\mathrm{o}) = \frac{L_\mathrm{o}(\theta_\mathrm{i}, \theta_\mathrm{o})}{L_\mathrm{i}\cos(\theta_\mathrm{i})\Omega_\mathrm{i}} \quad (2)$$

This means that two radiometric quantities ($L_\mathrm{o}(\theta_\mathrm{i}, \theta_\mathrm{o})$, L_i) and a geometric quantity, the solid angle of irradiation Ω_i, must be determined. Physical plausible isotropic BRDF must have the following properties [3]:

- Positivity, $f_\mathrm{r}(\theta_\mathrm{i}, \theta_\mathrm{o}) \geq 0$
- Helmholtz-reciprocity, $f_\mathrm{r}(\theta_\mathrm{i}, \theta_\mathrm{o}) = f_\mathrm{r}(\theta_\mathrm{o}, \theta_\mathrm{i})$
- Energy conservation $\int_{\phi_\mathrm{o}} \int_{\theta_\mathrm{o}} f_\mathrm{r}(\theta_\mathrm{i}, \theta_\mathrm{o}) \cos(\theta_\mathrm{o}) d\Omega_\mathrm{o} \leq 1$

Positivity means that the BRDF value cannot be negative, Helmholtz-reciprocity guarantees that when radiation and detector angle are exchanged, the resulting BRDF is the same and energy conservation says that the integration of the BRDF detection solid angle Ω_o over the hemisphere with viewing azimuth angle ϕ_o cannot be greater than 1.

Measurement device

The measurement device is shown in Fig. 1. The MWIR thermal imaging camera has two High Dynamic Range (HRD) modes which can measure temperatures between $0°\mathrm{C} - 800°\mathrm{C}$ and $300°\mathrm{C} - 1800°\mathrm{C}$. The integrating sphere is described in [4]. An optical chopper is used to subtract out disturbing ambient radiation and the self radiation of the surface in the thermal images. Two rotary tables are used to rotate the sample holder and integrating sphere with respective angles α, β, which are converted to the BRDF angles $\theta_\mathrm{i}, \theta_\mathrm{o}$. The source angle θ_i is determined by its rotary table. Before a measurement run the average radiance L_i from the exit port of the Integrating sphere is measured. The exit port radius r is known and with distance d_i the incident irradiation solid angle can be determined with $\Omega_\mathrm{i} = \frac{\pi r^2}{r^2 + d_\mathrm{i}^2}$.

Measurement procedure

Thermal images are taken for source angles $\theta_\mathrm{i} \in [1°, 89°]$ in $1°$ steps and detection angles $\theta_\mathrm{o} = \{10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°\}$. Then a circle Region-of-Interest (ROI) with the same

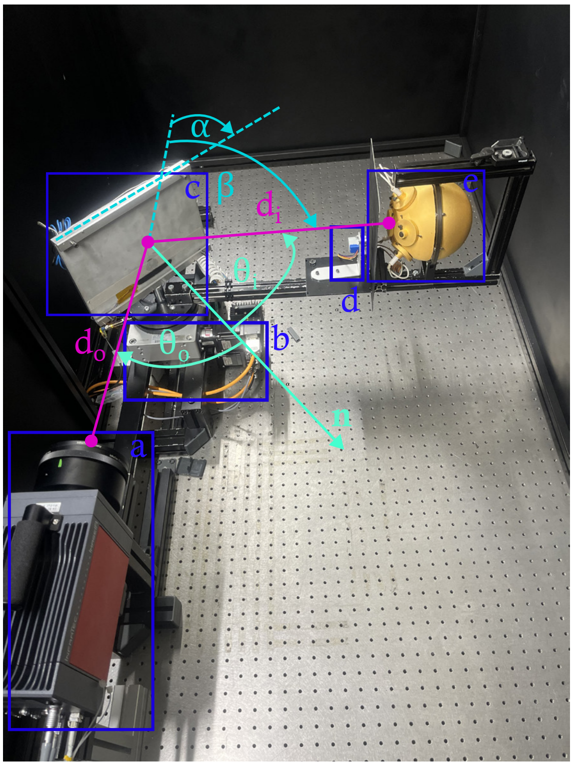

Fig. 1: Gonioreflectometer setup on an optical table in a dark room: a) Thermal imaging camera b) Rotary tables c) Sample holder d) Optical chopper e) Integrating sphere with an aperture

radius as the exit port around the specular reflection center $\theta_\mathrm{i} = \theta_\mathrm{o}$ is defined and the average radiance is taken as $L_\mathrm{o}(\theta_\mathrm{i}, \theta_\mathrm{o})$, which is weighted by $\cos(\theta_\mathrm{o})$ to account for the projected solid angle.

Results

The BRDF measurements of sandblasted steel (Fig. 2) and sandblasted aluminium (Fig. 3) for three different camera angles are presented here. Both show typical behaviour of diffuse reflecting surfaces. Sandblasted steel also has a specular component, especially recognizable for $\theta_\mathrm{o} = 20°$, $40°$. For $\theta_\mathrm{o} = 60°$ the specular peak is less noticeable because of the rise of the diffuse BRDF component for growing detector angles. The measured BRDF with diffuse scattering properties show physical plausibility.

Conclusions

A measurement device was built for BRDF measurements in thermal infrared. The measurement procedure was described. First results were shown. The measurement device has to be validated by a sample with known BRDF and the uncertainty has to be analyzed. It must be tested for which surfaces emission values can be determined.

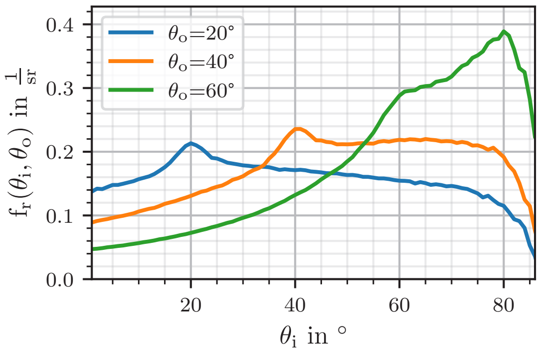

Fig. 2: BRDF measurements of sandblasted steel for $\theta_\mathrm{o} = \{20°, 40°, 60°\}$ with visible specular peaks.

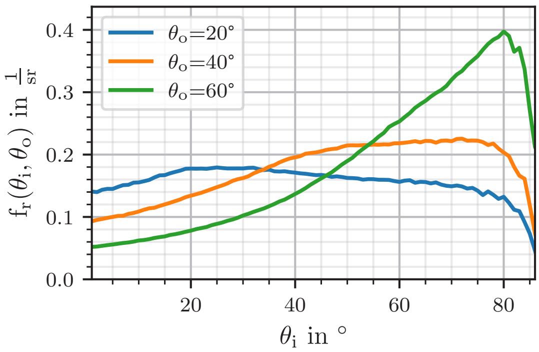

Fig. 3: BRDF measurements of sandblasted aluminium for $\theta_\mathrm{o} = \{20°, 40°, 60°\}$.

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