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Characterization and data-driven modeling of a retro-reflective coating in RADIANCE

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ABSTRACT

Retro-reflective coatings applied to blinds of reduced geometric complexity promise to provide view to the outside while effectively controlling solar gains and glare. To characterize the reflection characteristics of such coatings over the entire solar spectrum, a novel extension to a scanning gonio-photometer is developed. The extended instrument is tested and applied to measure a coating's Bidirectional Reflection Distribution Function including the region of the retro-reflected peak. The measured datasets are compiled into a data-driven reflection model for the daylight simulation software RADIANCE. This model is applied to illustrate the coating's effect in a comparison to purely diffuse and specular surface finishes on geometrically identical, flat blinds. Daylight supply, the probability of glare, and solar gains are assessed for an exemplary, South-oriented office under sunny sky conditions. The results indicate the potential of the coating to effectively shade direct sunlight even if applied on blinds with minimalistic geometries. The modeling technique is shown to be a general means to replicate the irregular optical properties of the coating, which cannot be represented by the standard models in daylight simulation software.

1. Introduction

1.1. Background and objectives

The effective shading of direct sunlight is a key requirement for fenestration systems aiming for high thermal and visual performance. Solar gains shall be avoided at most times to prevent over-heating effects in well-insulated buildings. Exposure to direct sunlight, while desirable to a certain degree in residential buildings [1], can cause discomfort and veiling glare and severely affect the visual comfort e.g. in offices. Yet the supply of daylight and a view to the outside are essential performance criteria in facade design since they address energy efficiency targets as well as the comfort and well-being of occupants [2,3].

Venetian blinds comprising profiles of often high geometric complexity address the dilemma to minimize the obstruction of view and daylight aperture, but exclude sunlight from being transmitted directly or by reflections in the fenestration [4,5]. However, the use of simple geometries appears to be desirable for at least two reasons. First, the manufacturing process to produce blinds with complex profiles is elaborate, if low tolerances shall be maintained. Second, any profile deviating from an ideal, flat slat occludes the view to the outside.

As an innovative approach to decouple shading performance from profile geometry, the application of a retro-reflective coating to the slats of Venetian blinds, and its effect on the daylight supply to an attached office, shall be tested.

1.2. Retro-reflection

Retro-reflection forms a special case of irregular light scattering by devices that "reflect incident light back toward the direction of the light source, operating over a wide range of angles of incidence" [6,pp. 31–32]. The effect is utilized in a range of applications such as traffic signs and reflectors attached e.g. to clothes enhancing visibility.

When applied to complex fenestration systems (CFS), the term retro-reflection is often used in a broader sense, including devices that deflect light by altering only the elevation angle [7,8]. Since the horizontal azimuth angle is not affected by such CFSs, retro-reflection according to the formal definition given above occurs

Abbreviations: BS, beam splitter; BSDF, Bidirectional Scattering distribution function; CBDM, climate-based daylight modeling; CFS, complex fenestration system; DGI, Daylight Glare Index; DGP, Daylight Glare Probability; DSF, differential scattering function; IGDB, International Glazing Database; NIr, near infrared light 780–2500 nm; sDA, spatial Daylight Autonomy; SHGC, solar heat gain coefficient; Vis, visible light 380–780 nm; XML, extensible markup language.

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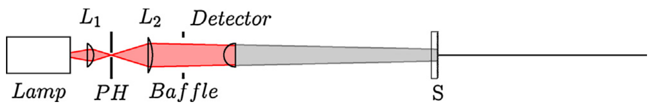

Fig. 1. A naive approach to measure retro-reflection leads to shading by the detector.

only for one given cardinal direction. Examples are retro-reflecting blinds, formed by extrusion of two-dimensional profiles. Such slats with configurable inclination angle are employed in CFSs to block direct sunlight. Complex profile geometries, combining sections that retro-reflect light from potential incident sun directions with sections that deflect light upward, allow to balance the daylight supply from direct sunlight with solar gains. The application of small-scale prismatic structures achieves retro-reflection even with simple geometries such as extruded arcs [9,10].

The use of retro-reflective coatings comprising spherical and prismatic micro-structures in buildings has been proposed to mitigate urban heat islands effects [11,12]. A transparent window film applying such prismatic micro-structures has been demonstrated to selectively retro-reflect incident sunlight from high elevation [13].

Applied on the surface of Venetian blinds, retro-reflective coatings have the potential to meet high visual and thermal comfort targets even with simple geometric profiles according to ray-tracing based assessments [14]. Empirical methods are however required to account for effects caused by imperfections in the composition and application of coatings [15], and if the effective micro-structure is unknown or cannot be disclosed.

1.3. Measurement techniques

In typical configurations for reflection measurements, the retro-reflected fraction of scattered light is assumed to be negligible and excluded. An indirect measurement of this retro-reflected fraction by comparing absorption derived from calorimetric measurements with radiometric measurements of diffuse reflection has been proposed as an approximation [16].

A more comprehensive description of the directional distribution of retro-reflected light can be expressed by the Bidirectional Scattering distribution function (BSDF), describing the radiative flux between any pair of incident and outgoing scattered direction [17–20]. However, such directionally resolved characterization of retro-reflection employing gonio-photometers is a particular challenge, since light source and detector occlude each other if incident and outgoing direction are close to equal (Fig. 1). Only a very long distance between sample and detector allows to cover the peak region of highly directional retro-reflection in such direct measurements [21].

The introduction of a plate beam splitter (BS) between light source and sample allows the gonio-photometric measurement of

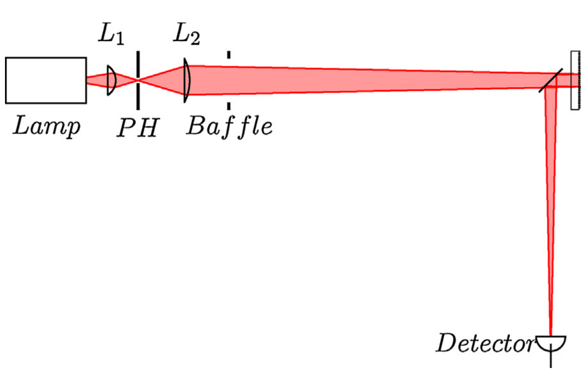

Fig. 2. Configuration employing one beam-splitter.

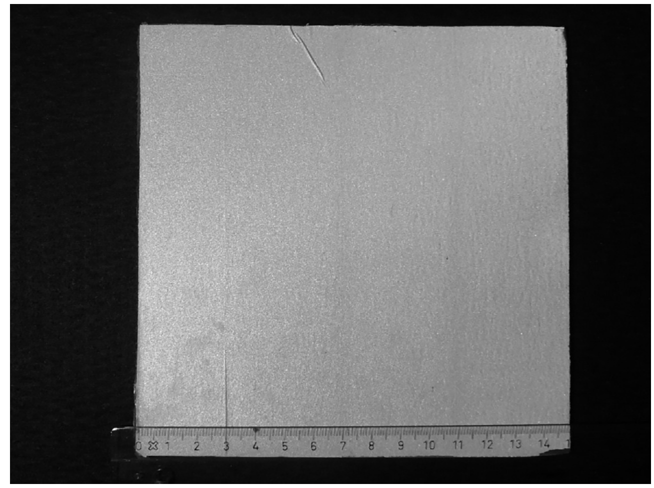

Fig. 3. Sample for the measurement of the retro-reflective BSDF. The coating is applied on a 150 mm × 150 mm metal sheet, which is laminated on a glass pane as rigid support.

retro-reflection (Fig. 2) [22,23]. Light from the illuminator is partially transmitted by the BS to the sample. The retro-reflected light is then partially reflected by the BS to the detector. With an ideal BS, that transmits 50% of the incident light and reflects the other 50% without any absorptive losses, the detected signal would be attenuated to $0.50 \times 0.50 = 0.25$. The method relies on prior knowledge of the exact optical properties of the BS, which depend on the direction as well as the wavelength of light.

1.4. Modelling retro-reflection

To predict the retro-reflective effect caused by geometric structures, computational techniques for the simulation of light propagation such as ray-tracing can be employed with detailed geometric models [24,25]. However, due to the model complexity and size resulting from such approaches if applied to extended CFS, methods hiding the optically complex internal mechanisms are often preferred. Functional descriptions of the BSDF allow to hide the geometric complexity of retro-reflective structures. Numerous analytical [26], numerical [27–29], and empirical [30] models for particular cases of retro-reflection have been proposed but are of no general applicability.

Data-driven models are of general applicability but rely on huge datasets. Basis functions such as wavelets or spherical harmonics provide a means to compress such datasets at resolutions adequate to replicate characteristic features of BSDFs [31–33]. Radiance as a validated lighting simulation software for visual comfort assessment [34] implements a data-driven model based on adaptive data-reduction applied to a discrete representation of the BSDF as a four-dimensional tensor [35,36]. The dimensions of the tensor relate to incident and outgoing direction via an equal-area mapping algorithm between square and disk [37,38]. An interface to measured data is provided, featuring an advanced interpolation algorithm to reconstruct the full BSDF from sparse measurements for few incident directions [39–41]. The model is capable to replicate the characteristics of a retro-reflective coating [14].

2. Materials and method

2.1. Exemplary sample of a retro-reflective coating

For the measurement of its BSDF, the retro-reflective coating was applied to a metal sheet of 150 mm × 150 mm. This sheet was subsequently laminated onto a flat glass pane. The glass as a rigid