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RAY-TRACING SIMULATION OF COMPLEX FENESTRATION SYSTEMS BASED ON DIGITALLY PROCESSED BTDF DATA

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The implementation of Complex Fenestration Systems (CFS) in the day-to-day life by practitioners, such as lighting designers, architects and façade makers is not an easy task. However, computer design tools can reinforce their usage through the determination of the luminous properties of a building interior prior to its construction or refurbishment. This paper presents a methodology based upon computer daylighting simulations carried out with RADIANCE in which the mkillum procedure was improved in order to render the light distribution due to diffuse daylight and sunlight on the inner surface of a fenestration system by the way of BTDF data. For the sake of standardization, the BTDF data accepted as input may be formatted according to the course of IEA Task 31 "Daylighting in Buildings" (e.g. following Tregenza format).

Keywords: Complex Fenestration Systems (CFS) ; Bi-directional Transmission Distribution ; Function (BTDF) ; RADIANCE software ; Backward ray-tracing ; Video-goniophotometer

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Ray-Tracing Simulation of Complex Fenestration Systems Based on Digitally Processed BTDF Data

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Abstract

The implementation of Complex Fenestration Systems (CFS) in the day-to-day life by practitioners, such as lighting designers, architects and façade makers is not an easy task. However, computer design tools can reinforce their usage through the determination of the luminous properties of a building interior prior to its construction or refurbishment. This paper presents a methodology based upon computer daylighting simulations carried out with RADIANCE in which the *mkillum* procedure was improved in order to render the light distribution due to diffuse daylight and sunlight on the inner surface of a fenestration system by the way of BTDF data. For the sake of standardization, the BTDF data accepted as input may be formatted according to the course of IEA Task 31 "Daylighting in Buildings" (e.g. following Tregenza format).

Keywords: Complex Fenestration Systems (CFS), Bi-directional Transmission Distribution Function (BTDF), RADIANCE software, backward ray-tracing, video-goniophotometer

Introduction

Complex Fenestration Systems (CFS) available today on the market are mainly constituted of solar shadings and light redirecting devices. They can contribute to substantial reduction of the heating and electricity loads in non-residential buildings through an optimal use of passive solar gains and daylighting [1]. Their implementation in the day-to-day life by practitioners, such as lighting designers, architects and façade makers is not an easy task, as long as the latter will be unable to: i) integrate and combine CFSs with efficient luminaries for the sake of energy savings (optimal use of daylighting and electric lighting) and ii) improve simultaneously the users' visual comfort and performance in computerized office spaces (avoiding glare risks and excessive task luminance). Computer simulation tools such as RADIANCE [2] can help to achieve these objectives through the determination of the luminous properties of a building interior prior to its construction or refurbishment.

Nowadays, new photometric equipments, such as bidirectional video-goniophotometer [3], can be used to assess the luminous transmission properties of CFSs, the so-called Bidirectional Transmission Distribution Function (BTDF). Measurements can be realized according to the sensitivity of the human eye $V(\lambda)$ [4] and even in the near infrared [5]. A collection of measured BTDFs corresponding to a bunch of CFSs is available today at EPFL [6], but currently not sufficiently used in practice. The collection is stored in an international standard for BTDF data defined in the course of IEA Task 31 "Daylighting in Buildings" [7].

The first approach of CFS simulations with RADIANCE was carried out using an approximation of the measured BTDF data with the *prism2* primitive [8] and successfully applied for sharp redirecting CFS (Laser Cut Panel, Holographic Film and 3M Film) [9]. Recently, RADIANCE has been improved [10] to be able to render the light distribution due to diffuse daylight and sunlight on the inner surface of a fenestration system by the way of BTDF data. The latter is stored in an XML file according to a data format defined at Lawrence Berkeley National Laboratory (e.g. suggested by Klems) [11].

The computer methodology presented in this paper aims at being a link between the international standard for BTDF data storage [7] and the improved RADIANCE version [10]. The paper describes the modifications brought in this prospect to the RADIANCE ray-tracing programme along with simulation results of a non-sharp redirecting CFS (Veglas Lumitop) whose BTDF data were monitored at EPFL.

METHODOLOGY

The RADIANCE *mkillum* routine in the official release 4.0 is able to read and use an XML file that contains BTDF data [10]. However, this XML file format has nothing to do with a prior defined BTDF data standard of goniophotometers such as the one defined in the course of IEA Task 31 "Daylighting in Buildings" [7]. In the latter, a text file is given for each pair of incoming angles (azimuth and elevation) according to the Tregenza subdivision of the hemisphere in 145 zones. In the case of symmetry of the sample (vertical and/or horizontal), the number of measured pairs of incoming angles may be reduced down to 42. The C++ programme *btdf2prism2* [8], that has already been developed by the authors to approximate a BTDF with two main redirecting components using the RADIANCE *prism2* routine, was used as a basis for reading the IEA 21 BTDF file format. The programme was renamed to *btdf2radiance* and modified to generate the BTDF data as a matrix of size (input directions) times (output directions) in the XML file format. As mentioned earlier, with EPFL's goniophotometer the input directions are the centroid of the 145 Tregenza zones, and the output directions are each 5° in azimuth and 5° in elevation leading to 1297 zones. This last number being equal to (90°/5°) times (360°/5°) plus the zenithal zone, the corresponding BTDF matrix is rectangular. Two steps were required to achieve the link between the measurements of EPFL's goniophotometer in IEA 21 format and the BTDF data usable by the RADIANCE routine *mkillum*:

1) Modify the RADIANCE *mkillum* routine to take into account the basis in which the 145 input Tregenza directions and the 1297 (5° by 5°) output directions are defined,
2) Write the *btdf2radiance* routine to convert the IEA 21 BTDF format in the XML file format usable by *mkillum*.

The following two paragraphs present the last points in details.

Modifications in the RADIANCE mkillum routine

The source code of RADIANCE is modular; all what concerns the basis of BTDF data is located in the file /common/bsdf.c. Three existing basis can be found in the latter: LBNL/Klems Full, LBNL/Klems Half and LBNL/Klems Quarter. Those are given by couples of inclination and number of subdivisions of the band that is in between the current and next inclinations. Symbolically the couples can be represented by:

$$\theta_1, 1 \ , \ \theta_2, s_{2\to 3} \ , \ \theta_3, s_{3\to 4} \ , \ldots, \ \theta_n, 0 \quad , \qquad (1)$$

in which θ is the inclination angle (accounted for from the normal, see Figure 1) and $s_{a\to(a+1)}$ is the number of subdivisions between θ_a and θ_{a+1} for $a = 1..(n-1)$. The first number of subdivisions is always 1 in common hemisphere subdivisions, e.g. the zenithal zone is unique. The last number of subdivisions on the other hand is always 0 to end the series. The Tregenza basis, named in the modifications brought to *mkillum* “EPFL/Tregenza Full”, is thus given in this notation by:

$$-6{,}1 \ , \ 6{,}6 \ , \ 18{,}12 \ , \ 30{,}18 \ , \ 42{,}24 \ , \ 54{,}24 \ , \ 66{,}30 \ , \ 78{,}30 \ , \ 90{,}0 \ , \qquad (2)$$

and the 5° by 5° basis, named in the modifications brought to *mkillum* “EPFL/5deg Full”, is given by:

$$-2.5{,}1 \ , \ 2.5{,}72 \ , \ 7.5{,}72 \ , \ 12.5{,}72 \ , \ 17.5{,}72 \ ,\ldots, \ 87.5{,}72 \ , \ 90{,}0 \ , \qquad (3)$$

in which we notice a fixed number of subdivisions of the bands and a fixed step increment of 5° in θ. The first inclination angle of each series is negative and equals in absolute value to the second inclination angle to indicate the extent of the unique zenithal zone. With the basis defined, each zone of the hemisphere is then identified by a unique number which starts by the zenithal zone and follows with the successive bands. The numbering goes according to the right-hand rule associated with the reference frame shown in Figure 1.

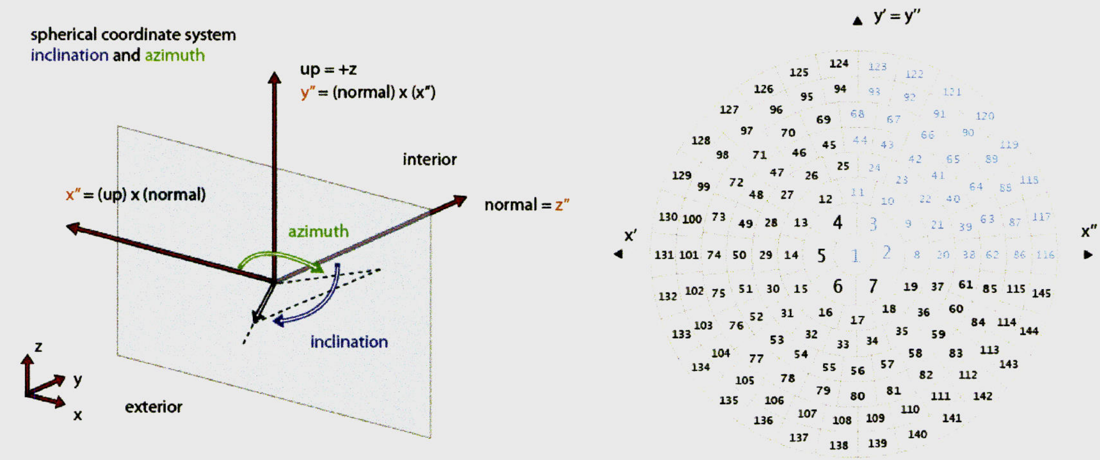

Figure 1: The coordinate system associated with the glazing used by default by mkillum (up=+Z) on the left-hand side, the numbering of the zones in the “EPFL/Tregenza Full” basis on the right-hand side (in blue the minimum of 42 zones for a complete set considering symmetries).

When defining a surface in RADIANCE to be represented by a BTDF, the user should define the vertex order to arrange for the normal of the surface to point inside the room. The *mkillum* routine then associates another reference frame to the surface: (x’’,y’’,z’’). The latter is defined by taking as default an “up” direction equals to the z-axis in the room’s Cartesian coordinate system (x,y,z): the vector product between “up” and the surface normal defines the x’’-axis, the vector product between the surface’s normal and x’’ defines y’’ and finally the normal itself defines the z’’-axis.

Remember that a fully transparent glazing represented by its BTDF matrix using the “EPFL/Tregenza Full” basis in input and output directions is diagonal.

Conversion of the IEA 21 BTDF file format to the *mkillum* XML file format

The programme *btdf2radiance* makes the link between the IEA 21 BTDF file format and the XML file format requested by *mkillum* after the previous modifications. The IEA 21 BTDF file format defines a separate file for each pair of incoming angles, each of which contains the BTDF values associated with a pairs of outgoing angles. Those angles (incoming and outgoing) are measured in a reference frame attached to the considered CFS sample (x',y'.z'), that is different from the one used by *mkillum* (see Figure 2).

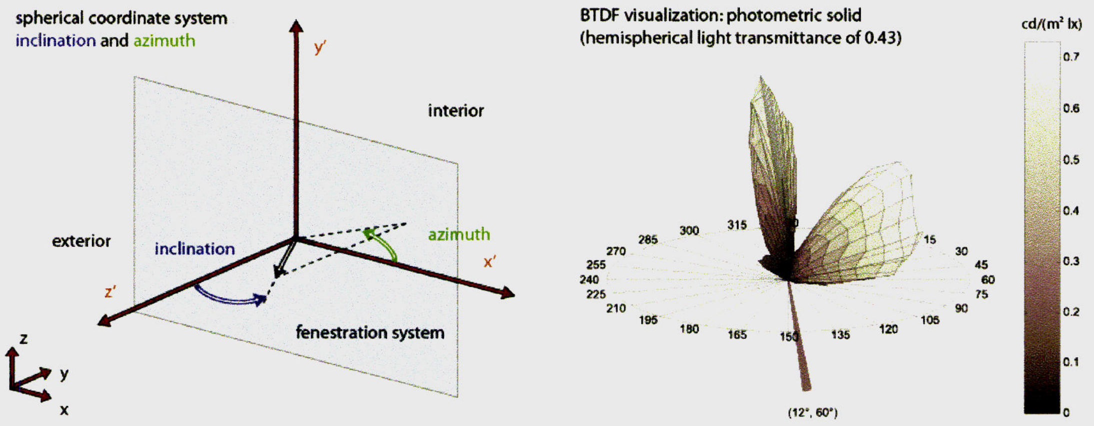

Figure 2: The coordinate system associated with the measured BTDF in the international standard IEA 21 and a visualization of the measured BTDF of Veglas Lumitop for impinging angles of 12° in inclination and 60° in azimuth (z'-axis goes downwards).

The transformation that goes from IEA 21 coordinate system (x',y',z') shown in Figure 2 to the *mkillum* coordinate system (x'',y'',z'') shown in Figure 1 can be written, in spherical coordinates, as:

$$\theta \mapsto \pi - \theta, \varphi \mapsto \pi - \varphi, \tag{4}$$

in which $\theta \in 0,\pi$ is the inclination angle and $\varphi \in 0,2\pi$ the azimuth angle in IEA 21 reference frame. The algorithm which produces an XML file usable by *mkillum* from IEA 21 BTDF files contains six steps: 1) transformation of the incoming angles in the *mkillum* reference frame, 2) identification of the incoming zone number (in the "EPFL/Tregenza Full" basis from 1 to 145), 3) transformation of all outgoing angles to the *mkillum* reference frame, 4) identification of the outgoing zone number (in the "EPFL/5deg Full" basis from 1 to 1297), 5) attribution of the BTDF values in the asymmetrical matrix (of size 145*1297) and 6) in case of symmetries defined, copy the values accordingly in the matrix. The final asymmetrical matrix is written in the form given by Table 1.

```
<?xml version="1.0" encoding="UTF-8"?>
<WindowElement>
 <Information Material="Lumitop" Source="btdf2radiance"/>
 <Optical>
  <Layer>
   <WavelengthData>
    <Wavelength>Visible</Wavelength>
    <WavelengthDataBlock>
     <WavelengthDataDirection>Transmission Front</WavelengthDataDirection>
     <ColumnAngleBasis>EPFL/Tregenza Full</ColumnAngleBasis>
     <RowAngleBasis>EPFL/5deg Full</RowAngleBasis>
     <ScatteringData>
      ... the asymmetrical BTDF data in 1297 rows of 145 columns ...
     </ScatteringData>
    </WavelengthDataBlock>
   </WavelengthData>
  </Layer>
 </Optical>
```

```
</WindowElement>
```

Table 1: The structure of the XML file for the simulation of BTDF data with mkillum.

As illustration of the matrix structure, the normal-hemispherical transmission of a monitored CFS sample can be computed using the first column of the matrix which corresponds to the incoming zone 1 (normal to the sample). Furthermore, the BTDF visualization in Figure 2 of Veglas Lumitop for incoming angles (12°,60°) corresponds to the incoming zone 4, in other words the 4th column of the matrix.

Usage of the resulting XML file with *mkillum*

The routine *mkillum* is used exactly in the same way as for any kind of glazing, except that one need to mention the name of the XML file to be used. Table 2 shows a RADIANCE file describing a surface that should behave in the same way as the XML file specified. For more details about RADIANCE simulations please refer to [2].

```
#@mkillum i=void c=d d=btdf2mkillum145x1297.xml s=40000 l+ u=+Z

void polygon upper_glazing
0
0
12
 0.1   0  2.7
 3.35  0  2.7
 3.35  0  2.1
 0.1   0  2.1
```

Table 2: The radiance description file (.rad) of a glazing with mention of the XML data file.

SIMULATION RESULTS

An office room in the LESO Solar Experimental Building located on the EPFL campus in Switzerland was chosen as virtual model for producing renderings (see Figure 3). The glazed facade faces south, with a standard double glazing in its lower part and a hypothetical installation of a Veglas Lumitop in its upper part. The device redirects the sun rays towards the ceiling in winter, spring and autumn; it blocks the sun rays in summer.

Figure 3: RADIANCE renderings of a virtual model of a simple room in LESO-PB office room (Switerland), from left to right: winter solstice, spring/autumn equinox and summer solstice at noon (local winter time).

These renderings give convincing results, which is not the case for the ones that can be realized with the *prism2* primitive in RADIANCE [8]. Indeed, the Lumitop has a diffuse directional redirection property (see Figure 2 for an illustration) that cannot be represented by two sharp directions.

CONCLUSION

The approximation of monitored BTDF data using the RADIANCE *prism2* primitive developed previously by the authors comes to a limit when considering CFS having a significant diffuse component. To overcome this and bring compatibility between the international standard IEA 21 for BTDF data storage and the recent improvement of the RADIANCE *mkillum* routine, a new C++ programme *btdf2radiance* was developed. The renderings are convincing so far; however a further verification procedure is foreseen for the next months.

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