MIXED-DIMENSIONALITY APPROACH FOR ADVANCED RAY TRACING OF LAMELLAR STRUCTURES FOR DAYLIGHTING AND THERMAL CONTROL

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ABSTRACT

The appropriate choice of the type of glazing and glazed area in a façade depends on many factors. They include amongst other criteria: location, orientation, climatic condition, energetic efficiency, usage of the building, required user comfort, and the architectural concept. All requirements cannot be fulfilled at all times and priorities have to be set to find a compromise between occupant comfort, design objective, cost and energetic efficiency. An innovative glazing system combining daylighting, glare protection, seasonal thermal control and clear view was developed [1] and patented by the authors. This design was developed using a novel ray tracing approach to obtain a strongly angular dependent transmission with a specific angular distribution. Taking advantage of the changing elevation of the sun between seasons, a seasonal variation is created by a strongly angular dependent transmittance.

In this paper we present the mixed dimensionality approach used to achieve a very fast and accurate ray tracing of any lamellar structure that has a two dimensional profile. The originality of the presented Monte Carlo algorithm is the separation of intersection and interaction. Intersections are computed using only the two dimensions of the profile thereby increasing significantly computational speed. Interactions are computed using vector calculus in three dimensions and provide accurate results with very little computational load.

With such optimizations, the user interface could be designed to give an instantaneous idea of the light path in the modelled system. The model also calculates an accurate bidirectional transmittance distribution function that is used in a Radiance simulation to obtain a rendering of the daylighting distribution in an office space. Hereby we can compare the daylighting performances of the novel design based on optical microstructures with those of other CFSs. Finally the combination of simulated angular dependent transmittance and Meteonorm data provides an estimate of transmitted energy over the year and proves the efficiency of the presented optical microstructures for dynamic thermal control. The proposed working principles of redirection and angular dependent transmittance are thereby demonstrated. The software provides all the mentioned results in the user interface where the performances of different designs can also be compared, making the optimization process of a profile with a defined objective very intuitive.

Keywords: Microstructures, Daylighting, Thermal Control, Smart Windows, Complex Fenestration System, Ray Tracing, Monte Carlo

INTRODUCTION

In Switzerland, electric lighting, heating and air conditioning account for about 71 % of total energy demand in private housing (dominated by heating : 67%) and 31% of the overall Swiss electricity usage (dominated by lighting :13%) [2]. The novel complex fenestration system (CFS) proposed by the authors combines several functions and can contribute to significantly reduce energy consumption in buildings with favourably oriented glass façades. In winter, solar gains are used to reduce heating energy requirements; in summer, the proposed device blocks direct radiation and thus limits air conditioning load as well as overheating risks. Judicious use of daylighting furthermore reduces energy needs for artificial lighting and improves the well-being of occupants. These principles are illustrated in figure 1.

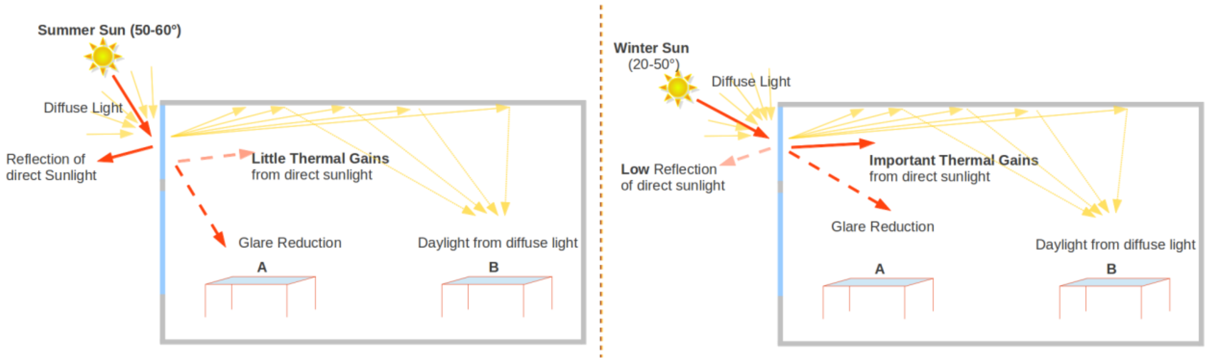

Figure 1 : Working principle of the CFS for daylighting, glare control and seasonal thermal control.

Ray tracing is a technique from geometrical optics to model the path taken by light in an environment by following rays of light. It may be use in the design of optical devices such as lenses and sets of lenses in microscopes, telescopes etc… Ray-tracing software is often used to calculate the Bidirectional Scattering Distribution Function (BSDF) of complex fenestration systems (CFS) [3, 4] but no dedicated tool was found for the modelling of CFSs combining geometry and material-dependent designs and integrating thin films. Also, existing commercial tools provide complete three dimensional characterisation but they are time consuming and the output is not adapted to the evaluation and comparison of CFS performances. For these reasons, a simple and efficient ray tracing tool for the study of laminar structures was developed with the possibility to directly compare glazing related performances and modulate designs. In this paper we describe the innovative concepts used in the algorithm, the user interface of the software and some of the CFS specific performance indicators provided.

Ray tracing is also used for graphical rendering in computer graphics and produces realistic illumination of virtual scenes. Amongst many, Radiance offers complete and flexible tools for the use of architects to render construction projects. More specifically and in relation to complex fenestration systems, rooms with different types of windows and electrical lighting sources can be modelled to study the illumination, be it natural or artificial, direct or indirect [5]. This however requires an accurate definition of the studied window. Such detailed description can be computed with the developed software.

Monte Carlo algorithms are stochastic and they are used to solve complex physical or mathematical problems. In a typical Monte Carlo algorithm, random draws define a chain of local events characterizing the global event and leading to a final state. Each draw follows a given distribution representative of the corresponding event. By repeating this iteration over random events numerous times, a probability distribution of the final states is obtained.

MIXED DIMENSIONALITY APPROACH

A two dimensional (2D) description of the designs is sufficient for most existing CFS products because they can be described as 2D extruded profiles. In a pure 2D ray-tracing of such a profile, with no scattering, transmittance is modelled accurately for zero degree azimuths because the rays are always in the same plane as the profile. For small deviations from this plane, the azimuth angle has little influence on the distribution of transmittance. However in some cases, for azimuth angles above 40°, using 2D only for reflection and refraction introduces errors above 20% in the angular distribution of transmittance. This is not acceptable for an evaluation of annual energetic transmittance that relies on three dimensional bidirectional Transmission and Reflection Distribution Functions (BTDF and BRDF). For an evaluation of daylighting using rendering software such as Radiance, complete and accurate BTDF are also required. For these reasons, the third dimension has to be considered.

In the proposed algorithm, all intersections are still computed in 2D. If a profile is defined in the x and y coordinates, the only loss of information is the z coordinate of the intersection. This information is of little use since we are interested mostly in the angular distribution of rays. Finding intersections between lines in two dimensions is very fast and can be efficiently done using a binary space partitioning tree [6]. For interactions however, all three dimensions are used. Reflection, refraction, scattering and absorption are precisely modelled using tree dimensional vector calculus and following physical rules. These principles are illustrated in figure 2.

Reflection and refraction probabilities are modelled following the Fresnel equations and Snell's law. Absorption follows the Behr Lambert law. The Fresnel equations for the calculation of reflectance and transmittance of thin films are derived from Maxwell's equations. Following the work of Macleod [7], a characteristic matrix can be used to compute these values. These behaviours all depend on the complex refraction indices of the implied materials. For accuracy, spectral values of these refraction indices are used.

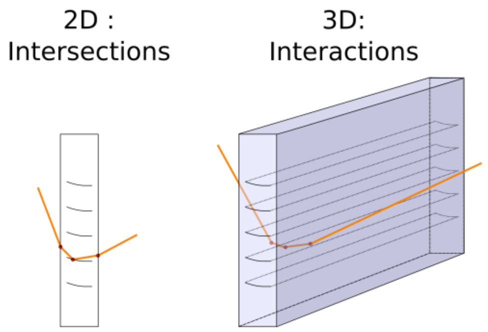

Figure 2: Illustration of the mixed dimensionality concept for ray tracing of profile defined geometries.

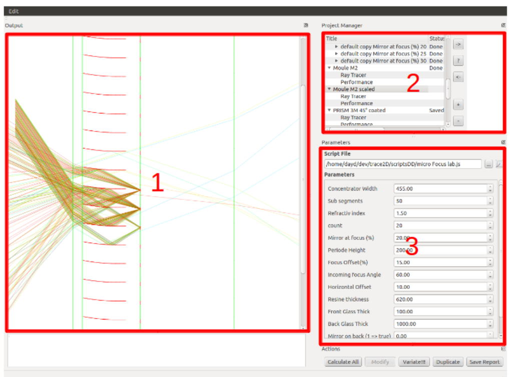

Figure 3: Graphical User Interface. Area 1 shows the output, in this case ray tracing. Area 2 shows the project list. Area 3 the parameters listed in the script.

OPTIMISATION OF GEOMETRY AND PARAMETERS

Besides accurate physical modelling and calculations, the developed software was also meant to be an intuitive and flexible design tool. For intuitive development, structures are parameterized and the parameters can be modified in the graphical user interface (GUI) with a direct rendering of the resulting rays distribution. The GUI can be used to change the angle of incidence of the beam and visualize the angular distribution of transmitted and reflected light. To provide flexibility, the projects are described by a file containing the geometrical description of the design and parameters to modify and optimise the design. For example, a script describing an integrated flat mirror contains a description of how to draw the interfaces between the bulk material and air and where to include mirrors of a given width, tilt and at a specified interval. The scripts can use basic javascript language such as *for* and *while* loops, *if then else* statements, mathematical operands as well as more advanced data structures such as arrays. In addition to the javscript language, ray tracing specific functions are implemented to add interfaces, define materials and light sources. Another set of instructions was defined to add parameters, these are directly included in the graphical interface. Hereby almost any structure can be defined, modified and visualized.

In the process of designing a solution, new concepts need to be tested and parameters optimized. To facilitate the study and optimisation of CFS complying with complex requirements, the graphical user interface of the software was built around a list of projects and their variations. As shown in part 2 of figure 3, this gives a rapid overview and history of designs. As mentioned above, the projects are described by a javascript containing both the geometry of the design and the list of parameters. Each parameter can then be modified individually in the GUI -area 3 in figure 3- and the resulting ray path visualised immediately-area 1 in figure 3- . The resulting performances can also be visualized in area 1 of the GUI for each design. For a meaningful comparison and optimisation, a design can be varied according to a single parameter. The different variations are sub projects that can then be varied again or discarded. By selecting several projects in area 2 of the GUI, their performances can be directly compared in area 1 regarding different criteria. These criteria include transmission distribution, transmittance depending on incident angle, energetic transmittance and daylight rendering. This approach proved to be very useful to understand how complex geometries affect ray paths depending on the angle of incidence and it was used to find and optimize an original design described in the next section.

RESULTS AND DISCUSSION

The engineered geometry shall provide elevated daylight levels by redirecting the incoming light towards the depth of the room. This redirection simultaneously protects occupants from direct sun light and reduces glare risk. For an optimized usage of available solar radiation, the direct sunlight is transmitted in winter and reflected in summer. This complex set of objectives needs to be reached to achieve daylighting, seasonal thermal control and transparency simultaneously. In this section we briefly re-introduce the novel design proposed and patented by the authors [1] along some new results.

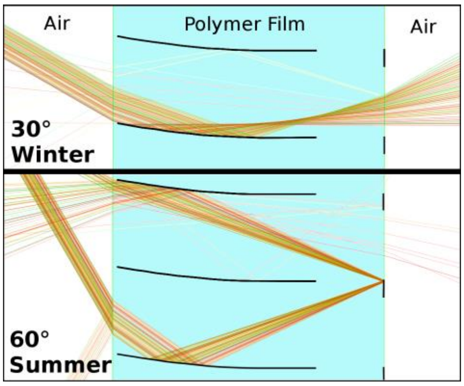

Figure 4: Structure as proposed with incoming beam at 60° and 30° elevation. Illustration of the focusing and resulting reflection in summer; and redirection for daylighting in winter.

The key of this new design is the focusing of light from a given angular interval by a first component onto a second component. To focus incoming light, the first component of the system should be a parabolic surface. The parabola has to be drawn in order to focus light incoming from a given range of incident angles on a second reflecting surface, which is located on the inner side of the system. This second mirror reflects lights from the selected range back through the system. The focus is achieved for angles corresponding to the summer elevation of the sun at the specified location (for example 60° in Lausanne). For this range the light is concentrated on the second surface and reflected. For angles out of the specified blocking range, the reflection on a parabolic shape distributes a parallel beam over a range of angles; this distribution is suited for daylighting. To achieve clear view, direct transmission without interaction for close to normal angles is maximized: the two elements have a minimal height and maximum overlap. The miniaturization of structures bellow a millimetre further reduces their impact on see-through property.

This principle is entirely based on a static structure and to be efficient, it has to be adapted to the geographical location where it will be installed. Depending on the latitude, the solar course changes and the two components have to be optimised to block radiation for the aestival elevations of the sun and transmit radiation from the winter sun.

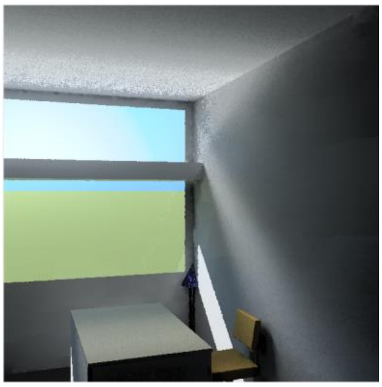

Figure 5: Radiance rendering of a scene with microstrucutred glassing following computed BTDF function using the bsdf primitive.

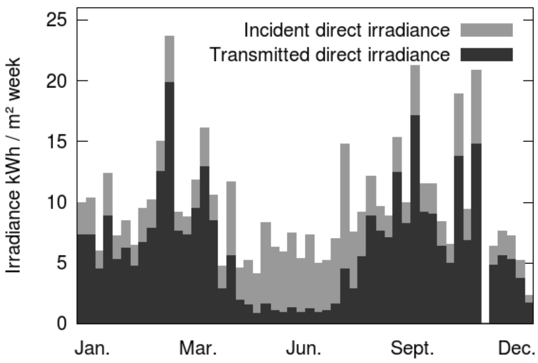

Figure 6: Simulated transmitted irradiance per surface area for a microstructured glass over the year compared to incident direct irradiance.

For seasonal thermal control, the defining value is the thermal gains. For each square meter of window, a portion of the incoming solar radiation is transmitted and this energy heats up the space behind the window. To calculate an estimate of this value, diffuse and direct transmission factors are calculated with the ray tracing simulation tool and used in combination with Meteonorm radiometric data. To combine these data, a common representation of space has to be used. For direct radiation the hourly solar position is used and for diffuse radiation, the hemisphere is divided into patches following Tregenza's subdivision of the sky. A Perez model of the sky is used to define the hourly radiation coming from each patch according to the corresponding climate file. The thermal gains due to direct and diffuse radiation were computed over the year and compared with other types of glazing. The designed glazing showed an energetic transmittance of direct sunlight lower than 20% during the summer period and higher than 70% during the winter period. Results are shown in figure 6.

Glare and illuminance on the work plane are the critical values for the evaluation of daylighting. Glare can be estimated using the Unified Glare Rating (UGR) or the Daylight Glare Index (GDI) and illuminance is measured in lux and should be between 300 and 1000 depending on the task. For common office work, values between 300 and 500 lux are required. To assess these values for the developed complex fenestration systems, the software is used to create the characteristic bidirectional transmittance distribution functions (BTDF). These BTDFs are then used to define a window in a Radiance scene and Radiance routines are used to render the scene, an example can be seen in figure 5. After careful alignment of the reference coordinates and of time, this radiance simulation was also used to compute hourly illuminance levels and glare indices on the defined workspaces over the course of a day, month or year in different sky conditions.

CONCLUSION

A simulation tool using a novel approach was developed for the modelling of CFSs. It was developed to find a new system that provides daylight, glare protection, seasonal thermal control and clear view. These aims were reached with the invention of a new design combining two reflective surfaces to achieve redirection of light and a strong seasonal dynamic in thermal gains. This design was characterised using Radiance simulations for the assessment of daylight and glare protection capabilities. An estimate of thermal gains for the evaluation of seasonal thermal controls was computed based on Meteonorm data. It was demonstrated that the simulated design reaches the set goals.

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