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LiDICS: A FMI-based light dynamics interface for the control evaluation of complex fenestration

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Abstract

This paper presents an interface for complex light dynamics coupled within a multi-domain simulation framework. The continuous model is derived from ray-tracing data by novel two-stage incidence operator regularization (ior). The tool-independant functional mock-up unit (FMU) is generated using the developed Modelica library. LiDICS is applied to switchable membrane cushion constructions featuring inhomogeneous and complementary printing patterns. Solar and visual raw data have been generated using LBNL and the three-phase method, respectively. The trained LiDICS model aligns with the raw data, achieving a median coefficient of determination ($r^2 = 99.4\%$). The model is validated against annual RADIANCE 3-phase method data. The time series closely align with each other ($r^2 = 98.4$). Finally, an application potential is presented.

Introduction

The Collaborative Research Centre 1244 at the University of Stuttgart is actively involved in addressing carbon reduction in the manufacturing and operation phases of façades and structures. Membrane cushion constructions made of ethylene-tetrafluoroethylene (ETFE) offer reduction potential due to their light weight, excellent recyclability, and other sustainable attributes. Customised dynamic shading effects can be achieved by incorporating complementary patterns. Numerous challenges confront the performance prediction of adaptive façades [1, 3]. Firstly, there is a growing need to model material and geometric properties transiently, which current Building Performance Simulation (BPS) tools struggle with. Secondly, adaptive façades exhibit pronounced angular dependencies in their properties concerning visual and solar light effects. The third challenge arises from the "strong mutual dependence between design and control aspects" [1]. Façade control must be comparative to reveal differences in design variations and multi-domain behaviour. Additionally, in the life cycle assessment of adaptive façades, high-tech components typically exhibit shorter lifecycles, while active control increases wear, leading to increased manufacturing and maintenance costs. Therefore, optimal control concepts are the focus of this interface which need twice continuous differentiable models.

Main Objectives

1. Establish an FMI model interface for any spectral light dynamics between ray-tracing of complex fenestration, control development and life cycle assessment.
2. Fulfill the requirements for nonlinear programming for twice continuous differentiability.

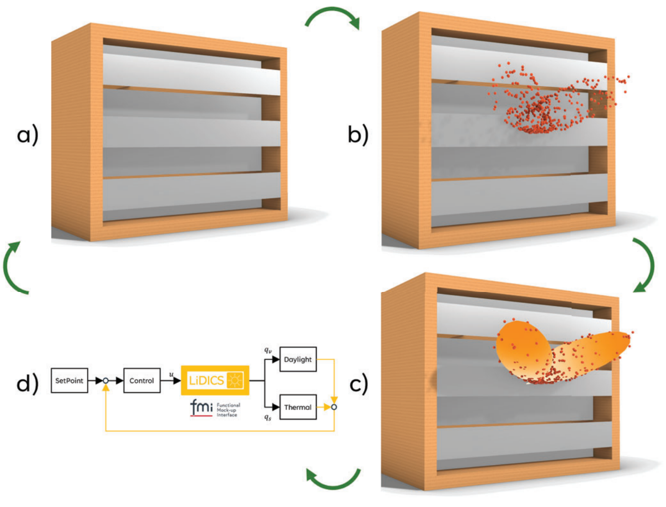

Figure 1: Steps of the LiDICS workflow: a) Parametric design, definition of quantities, facade inputs and geometrical discretization b) point-in-sky ray-tracing c) LiDICS model derivation d) coupling within multi-domain model.

Methods

The **Li**ght **D**ynamics **I**nterface for **C**oupled **S**imulation (LiDICS) is a model interface designed for the depiction of angle-dependent complex light dynamics, based on the Functional Mock-up Interface (FMI) standard. The standardisation facilitates a clear delineation of tasks and the interchange of models among architects, building physicists and control engineers. This delineation is depicted in Figure 1. In the first step considered, cmp. Figure 1a), the architect defines the parametric design and the spectral material properties of the facade the considered quantities and facade inputs. Then, by spectrum specific point-in-sky ray-tracing the quantities are simulated for predefined incidence angle pairs in step (b). In this work, the solar quantities are determined using the LBNL method (WINDOW) and visual quantitites by 3-phase-method (RADIANCE). In the third step, a continuous representation is created by novel two-stage incidence operator regularisation (ior) method. The approach in this work differs from the ground thesis [2] in that it is not focused on a specific L0-regularisation but open for highly parallel solvers like sklearn's routine linear_model.MultiTaskLassoCV. The quantity is calculated from its hemispherical integration, cmp. Equation 2 applying the Perez sky model. The matrix $\mathcal{P}$ and the taylor base $\vec{\mu}$ interpolate the expansion vector $\vec{s}$ with the continuous facade input u_{fac}, cmp. Equation 5.

$$\begin{aligned}
SIOP(u_{fac}, \theta_w, \phi_w) &= \vec{Y}^T(\theta_w, \phi_w)\vec{s}(u_{fac}) && \vec{s}, \vec{Y} \in \Re^{p_1} \quad (1)\\
q &= \int_{\phi_w=0}^{2\pi}\int_{\theta_w=0}^{\pi/2} L(\theta_w, \phi_w) SIOP(u_{fac}, \theta_w, \phi_w) d\Omega && (2)\\
&= \int_{\phi_w=0}^{2\pi}\int_{\theta_w=0}^{\pi/2} L(\theta_w, \phi_w)\vec{Y}^T(\theta_w, \phi_w) d\Omega \; \vec{s}(u_{fac}) && (3)\\
&= \vec{e}^T\vec{s} && (4)\\
&= \vec{e}^T\mathcal{P}\vec{\mu} && \mathcal{P} \in \Re^{p_1 \times p_2}, \vec{\mu} \in \Re^{p_2} \quad (5)
\end{aligned}$$

The calculation of the core matrix $\mathcal{P}$ is done for every 30 quantities considered. The FMU model is generated by extending a partial Modelica model with that matrices.

Results

In total 4 solar quantities and 26 visual quantities have been investigated for 5 discrete facade input states. The IOR model training achieves a median coefficient of determination of $r^2 = 99.4\%$. As an model validation, annual daylight simulations obtained through the 3-phase method and the LiDICS model are compared. The annual predictions of LiDICS model align with the 3-phase method by a coefficient of determination $r^2 = 98.4\%$ and a mean absolute deviation of 32 lux. Therefore, the matrix $\mathcal{P}$ can be trained using the results from the preliminary point-in-sky simulations and effectively transferred to real weather data and locations.

Additionally, Figure 2 shows the potentials of the LiDICS model. The operational strategy os_1 maintains the façade input constantly open at $u_{fac} = 100\%$. This leads to a disturbing glare level. The operational strategy os_2 controls the façade opening using a proportional controller, ensuring that the glare potential does not exceed a perceptible and mainly not disturbing value $DGPs = 0.4$ according to DIN EN 14501. This control is done by continuous control and without changing the transmission matrix / BSDF during simulation for different discrete facade input as it would be with operation strategy os_3.

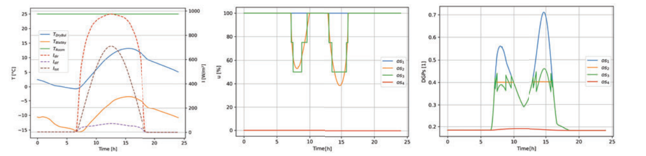

Figure 2: Time series of weather data (left) for four different operation strategies os (middle) and the simplified daylight glare potential (right).

Conclusions

- A new equation based model interface for complex light dynamics is presented.
- The training concept with two-stage IOR method closely aligns with presimulation data ($r^2 = 99.4$). The model validation with 3-phase method data achieves high accuracy $r^2 = 98.4$.
- A simple P-control ensures that the glare level remains perceptible and mainly not disturbing.

Forthcoming Research

In order to close the gap between architects and control engineers a grasshopper plugin should be generated to automatically generate the LiDICS interface model from parameteric design. With a multivariate facade input the second IOR stage becomes more and more complex. This could be managed by integrating differentiable machine learning techniques.

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