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Using a fuzzy black-box model to estimate the indoor illuminance in buildings

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ABSTRACT

Indoor lighting conditions and the efficient use of solar energy are becoming increasingly important, both in terms of overall living comfort and energy-efficient buildings. Thus, the methods of achieving adequate indoor lighting conditions, by making use of daylight to save energy, while still maintaining other indoor conditions at an acceptable level, and the corresponding control algorithms, have lately become the subject of considerable attention. For this reason, a fuzzy black-box model of indoor illuminance levels is proposed. The model is able to estimate the indoor illuminance levels as its outputs, by using real external conditions as its inputs. In general, the indoor illuminance is a combination of daylighting and electric lighting. Our study has shown that by using a fuzzy illuminance model, with the solar radiation, the external illuminance, the position of the blinds and the status of the lights as its inputs, an indoor illuminance estimation comparable to the measured data can be obtained. Furthermore, the sufficiently small error measures indicate that the presented modelling approach can be incorporated into larger test environments and used for studies on indoor living comfort, energy conservation, control design or even model-based control. Whenever needed, several fuzzy-illuminance models can be used in parallel in order to obtain the illuminance levels for more than one indoor position.

1. Introduction

Indoor lighting conditions and the efficient use of solar energy have become very important in recent decades, both in terms of overall living comfort [1,2] and energy-efficient buildings [3–6]. A summary of the research carried out to date in the area of buildings' energy efficiency, buildings' energy performance and buildings' processes modelling can be found in the excellent review paper by Foucquier et al. [7]. Furthermore, sufficient daylight conditions have been proven to have a beneficial effect on human health [8]. Numerous approaches to controlling indoor-illuminance conditions have been proposed, most of which attempt to either achieve constant indoor-illuminance levels, so as to provide sufficient living comfort, or to maximize the use of solar energy, while still providing acceptable lighting conditions [9–13]. Together with the modelling of light flux, indoor light intensities and surface illuminances, which usually represent the basis for control design techniques, have also been the subject of much attention. Furthermore, many methods exist that are able to provide approximate illuminance-level prediction in a certain position in a room, given its geometry, global orientation, the position of the sun, the surface characteristics and/or the weather conditions/measurements [14–16]. Moreover, a study performed by Lindelöf [17] proposes a fast daylight model, able to obtain indoor illuminances as a linear combination of the external global and diffuse radiations, validated using the Radiance model, which can be used as a replacement for the real system of embedded controllers. Similarly, available software tools, i.e., Radiance, Daysim, Skyvision [18–20] and many others, are also able to calculate more-or-less accurate illuminance levels for a given position in a room; however, significant knowledge of the modelled system (complete geometric and photometric characteristics of the room, inventory, windows, blinds, lights, etc.) and the software itself are needed, in order to ensure accurate results. A lot of the existing approaches rely on known mathematical daylighting concepts and thus try to describe the physical relations between the input and output variables. If the measurements of the real environmental conditions are available, a black-box approach to the calculation of the indoor illuminance can be introduced as one of the modelling possibilities. Black-box models have proved to be a useful tool for the modelling of processes whose characteristics, relations and dynamics are not exactly known or are harder to model with conventional approaches [21–24].

The objective of this study is to propose a black-box approach to indoor-illuminance estimation by using a fuzzy inference model. The proposed methodology results in the development of a model that describes the relations between its inputs: horizontal

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unobstructed illuminance (external illuminance), global and diffuse solar radiations, the positions of the blinds and the status of the lights; and its output: the estimated indoor illuminance. The method is, from the input/output point of view, similar to some existing methods, i.e., Lindelöf [17]; however, the methodological approach between the proposed and the existing methods is entirely different. One of the main advantages of the proposed method is the simple design and parameterization of the model, which does not require any knowledge about the modelled system, since the model's parameters, which define the input/output relations, inherit the room's characteristics, implicitly defined in the obtained measurements. Meaning that the room's characteristics, such as: geometry, indoor surfaces' reflectances, blinds' reflectances, quantity, sizes and positions of the windows, lights and furniture; and also the position of the indoor illuminance sensor, reflect in the measured indoor illuminance. Moreover, a change in either the room characteristics or the position of the sensor, if sufficiently large, also affects the measured value. After the model is parameterized (trained) and validated using the particular input/output measurements of interest, simulated or otherwise acquired input data can be used, replacing the actual measurements. The inputs defining the blinds' positions and the lights' status either need to be predetermined, adjusted manually or by means of the controller. Since the method uses measurements instead of physical characteristics in order to define the relations of the model, programming skills and the effort to manually design the room interior are not needed. The proposed structure of the fuzzy models is very simple (5 inputs, 1 output, 3 Gaussian membership functions per input and 3 fuzzy rules) and the fuzzification/defuzzification procedures are simple vector multiplications. The simplicity of the model is reflected in the fact that it is a fast model, with short evaluation times, which facilitates its inclusion in other applications or control algorithms. Finally, even though the model's structure is simple, the validation results have very accurate estimations in comparison with the measurements.

Although the proposed methodology has advantages, the fuzzy approach also has some drawbacks, which need to be considered when adopting the concept. In contrast to methods based on the physical modelling of the daylighting processes and preprogrammed algorithms, which normally require only the input part of the data in order to obtain the output, the fuzzy approach requires both the input and the output part of the data in order to parameterize the model using an automated training procedure. After the model is parameterized, only the input data is required. Moreover, since the model is based on measured data, which defines the room's characteristics, the calculation of the indoor illuminance under different conditions (e.g., different geometry, reflectances, sensor positions, etc.) needs a re-training of the model with new measurements. From this point of view, other tools like Radiance outperform the proposed method, since they are able to calculate a more-or-less accurate indoor illuminance for an arbitrarily positioned surface [25,26].

The purpose of the study is not to propose a specific model that would represent a general solution for all possible situations (like Radiance, for instance), but to propose a simple methodology for how to obtain a model for a particular environment, where the model is characterized as fast, accurate and easy to obtain, without excessive knowledge of the particular problem. Furthermore, since the in-depth studies on, e.g., building automation, control design, energy conservation, living comfort, etc., are practically impossible to perform on real systems, due to varying weather conditions and poor repeatability, the use of a relatively simple illuminance model of sufficient accuracy in combination with the simulation procedures allows fast and repeatable testing of the designed algorithms or the model-based control of real processes.

2. Indoor environment

The following section gives a description of the indoor environment, whose measurements are used as a basis for the fuzzy black-box model's development and the parameterization. The indoor environment consists of a room with dimensions of 7.49 m × 4.93 m × 3.88 m ($l \times w \times h$), a floor area of 38.80 m^2 and a volume of 163.40 m^3, with one outside wall that has a window, facing south–west (rotated approximately 30° counter clockwise from the east–west direction), where the outside wall is the longest wall. The room is located on the 4th of 5 floors in a building with no external obstacles that would obscure the light flow through the window (lat: 46.045737, lon: 14.494851). The area of the window is 11.4 m^2, with installed venetian blinds. The transmission of visible light through the window is 80%. The room characteristics in terms of the photometry are the following: grey floor (35% reflectance), white ceiling (80% reflectance), white walls and beige furniture (average 65% reflectance). Fig. 1 shows the floor plan of the particular room, with the marked positions of the sensors (indoor and external illuminance, global and diffuse solar radiation – placed on the roof of the building, blinds' position), the window and the blinds.

The studied indoor environment is equipped with an automation, supervisory control and data-acquisition system (SCADA), which is composed of three distinct parts: the sensor array, the process and supervision level, and the data-acquisition level. The system measures the necessary values, such as the global and diffuse solar radiation, the external illuminance, the position of the blinds (and other values not relevant to this study) and controls the indoor-illuminance levels (and other values not relevant to this study) using the motorized venetian blinds and the electric lighting. The sensor for external illuminance (Thermokon LI65 outdoor light sensor) is mounted vertically on the facade beside the window and is capable of measuring the illuminance in the range from 0 to 20,000 lux. The sensors for the global and diffuse solar radiation (Kipp & Zonen CM7B pyranometer and albedometer) are mounted 2 floors higher, horizontally on the roof of the building and are measuring the solar radiation in the range 305–1800 nm from 0 to 1400 W/m^2. The indoor illuminance sensor (Thermokon LI04) is placed horizontally on the workbench/desk (at a height of approximately 0.9 m) and is capable of measuring the illuminance in the range from 0 to 2000 lux. A complete description of the automation system and the applied control algorithms can be obtained from the paper by Košir et al. [13]. The global and diffuse solar radiation are measured in W/m^2, the external illuminance in lux, while the blinds' position can take values between 1 and 5 (1–0° slat angle (vertical), 2–30° slat angle, 3–60° slat angle, 4–90° slat angle (horizontal) or 5 – blinds completely retracted) and the lights' status can be either 0 (OFF) or 1 (ON).

3. Black-box illuminance model

3.1. Concept of the black-box approach

The concept of the black-box theory relies on understanding something entirely in terms of its function, without knowing the background or the mechanisms that enable this functionality. From this point of view, machine-learning techniques, among which are also fuzzy-inference systems, as one of the black-box approaches, can be considered as a mechanism of this black box for the input-to-output mapping of the data space. Meaning, if an appropriate structure of the system is designed, an arbitrary nonlinear function between the system's inputs and outputs can be described by the fuzzy mechanism. Since the black-box approach has no physical background to the particular process,