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MODELLING, IDENTIFICATION AND SIMULATION OF A LIGHTING CONTROL SYSTEM

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Abstract: This paper presents the results of the first phase in the design of a control system for closed-loop regulation of the light amount in office-building rooms. This project is a joint development of Ghent University and Niko Lighting Company. The final objective is to regulate the light amount in a room at a constant level, irrespective of the disturbances from outside such as weather conditions. The main benefits would be a higher level of comfort and a continuous saving of energy. The system will be made commercially available as a micro-controller-based intelligent light-switch. The first phase in the project, described in this paper, is the modelling of the lighting system and the identification of a dynamic model of the system. A simulator, based on the obtained model, is also presented and validated. The simulator will be used in the second phase of the project to design, tune and test the controller and to evaluate the closed-loop system performance under varying environmental conditions (robustness tests).The project is rather challenging because undesired interaction might occur between separately controlled zones in a big room.

Keywords: Lighting Control, Modelling, Simulation, Identification.

INTRODUCTION

The purpose of this paper is to present the results of a methodology to design a mathematical model and a software simulator for the lighting system of a 2-zone room. The simulator will be the platform to develop a real-life microcontroller-based system to regulate the light amount in a room (consisting of several zones) at a constant level, irrespective of the disturbances from outside, such as weather conditions. Any control system for lighting can be seen to consist of three main elements: i) a decision-making element (controller), ii) sensors to supply information to the controller, and iii) switches or variable controls in series with the supply to the luminaries and capable of being remotely controlled.

The potential for energy conservation of the automatic switching or dimming of electric lighting to take advantage of the daylight, using photoelectric sensors in closed-loop control, was already known earlier, yet from the ‘70s [1]. Although the necessary technology exists for this type of control, and prototypes have certainly been tried, it is only recently that lighting control systems (LCS) have been offered to the main public. Sufficient data exist to show that energy savings associated with lighting can be made by use of controls alternative to the

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wall-mounted switch panel [2], [3]. Also, a number of earlier studies have shown a subjective preference for daylight and some advantages and disadvantages are briefly presented in [4]. The location problem of the sensors is very important, due to the light amount and the disturbances from outside weather [5].

In this paper, the results of a modelling project considering a 2-zone room are described. Each of the zones in the room has its own light sensor and its own, separately controlled, bank of lamps. Standard fluorescent lamps including ballast, which are usually used in offices, were used in the experiments. To model and identify the lighting system, the supply voltage to the lamp dimmer circuits was varied step-wise and the resulting response, measured by the light sensors, was registered with a data-acquisition board. A nonlinear static characteristic in series with a linear 3rd-order dynamic characteristic was obtained from these data. This model was then used to implement and validate the light system simulator.

The paper is organized as follows. The 2nd section presents the experimental conditions and the real-life experiments themselves. The 3rd section is the main part, explaining the model building approach. The 4th section presents the structure of the resulting simulator and a validation of its performance. Finally a conclusion section summarizes the main outcome of this investigation and formulates some ideas concerning the future work regarding this lighting control project.

2. REAL-LIFE EXPERIMENTS

The MIMO (Multiple Input Multiple Output) configuration consists of 2 zones, as the lamps in the room are controlled separately in 2 groups.

2.1 Room layout and I/O scheme

In Fig.1 the room-layout is presented: the configuration consists of 2 lamp-banks (Zone 1 & Zone 2) and 2 sensor positions (S1 & S2).

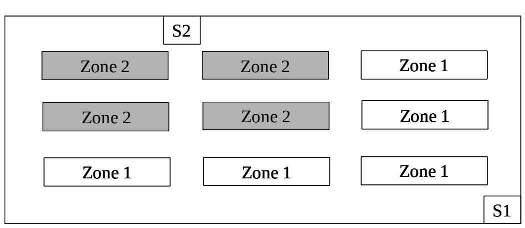

Fig. 1. Room Layout

In Fig.2 the input-output block scheme for one zone is presented, where a 12-bit AD/DA convertor (0:4095) has been used during the experiments.

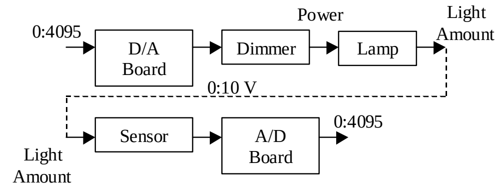

Fig. 2. I/O Block Scheme

2.2 Staircase experiment

The place of the sensors in the room is important, because the light coming from the 2 zones has a different effect on each of the sensors, according to their position. The experiments, which are illustrated in the following figures, consist of changing the light level in one zone while in the other zone the light level is kept zero.

Fig.3 shows the results when the dimmer of zone #1 is changed from 0% to 100% and back to 0% in steps of 10%, with a duration of about 5.5 seconds for each step (100 samples, with a 18Hz sampling frequency). Fig.4 shows the results of a similar experiment in zone #2. Both experiments are of fundamental importance, because their results contain important information for the modelling exercise (section 3).

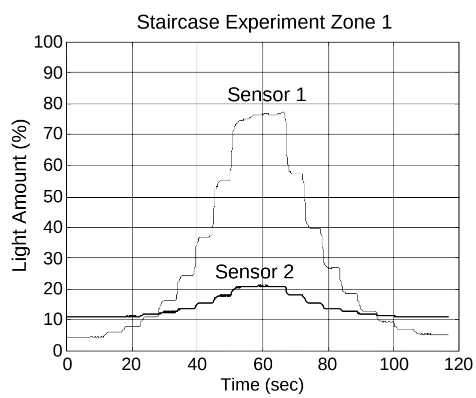

Fig. 3. Staircase Experiment in Zone #1

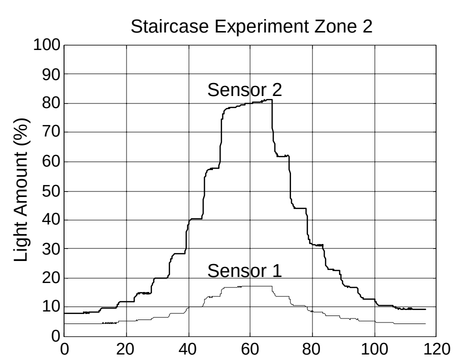

Fig. 4. Staircase Experiment in Zone #2

3. MODELLING

3.1 Structure of the mimo-model

From these experiments (Figs.3&4), and after rescaling them (Fig.5) according to the linear equation (*) - the effect of (*) being that all sensor outputs are at 0% during the 5^{th} step of the experiment and at 100% during the 9^{th} step - the conclusion is that all characteristics have about the same dynamics. This means that all input/output (dimmer/sensor) combinations react in a similar way, the difference being just a (linear!) scaling operation.

Scaling formula (*):

$$\text{new value} = \frac{\text{old value - first value}}{\text{last value - first value}} \cdot 100$$

where, 'first value' is the average of steady state at step 5 and 'last value' is the average at step 9.

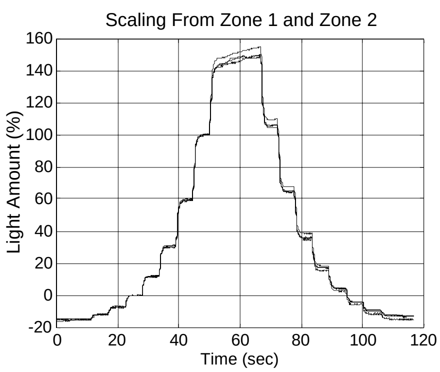

Fig. 5. Scaled Staircase Result (Zone #1 and #2)

Let us elaborate these conclusions now more in detail. Fig.6 illustrates the general structure of a 2X2 system. The sub-models indicate the direct (M_{11} and M_{22}) and the indirect (M_{12} and M_{21}) effect of the light in the 2 zones (D=Dimmer; S=Sensor).

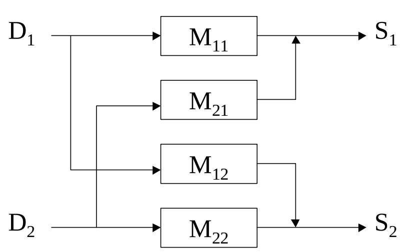

Fig. 6. General Structure of a 2X2 System

The conclusion from Fig.5 is: the responses of the 4 sub-models (both lamp-banks vs. both zone-sensors) are practically identical except for a linear transformation. Thanks to this observation, the general structure of Fig.6 can be simplified considerably to the structure of Fig.7. As a primary consequence, the four different sub-models M_{ij}, (i=1,2 and j=1,2) can be replaced by a single generic model followed by 4 sets of $\{a_{ij},b_{ij}\}$ parameters (where 'a' is called scaling gain and 'b' is called offset).

The generic model is the same for both zones, but the coefficients a_{ij} and b_{ij} are different for each zone/sensor.

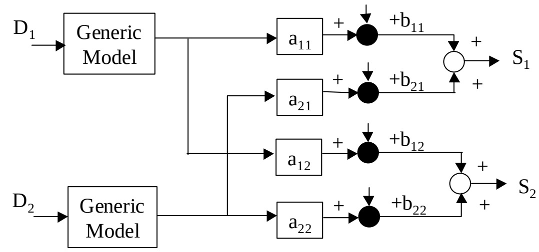

Fig. 7. Simplified 2X2 Structure

The generic structure reduces the 4 sub-models to only a single model, which does not depend on the room environment, nor on the sensor position nor on its covering. This is indeed an important result from practical point of view. Moreover the a_{ij} and b_{ij} parameters can be easily detected in a real-life situation (ref. Section 3.4).

3.2 Static characteristic

The generic model consists of a non-linear static part and a linear dynamic part (transfer function). The static characteristics presented in Fig.8 are obtained from the staircase measurements (Figs.3 & 4). The input is the constant dimmer input in percent (%) and the output is the light amount as measured by the sensors in steady state. If all 4 characteristics would be rescaled according to the linear transformation explained in section 3.1, they would practically be the same. So it is sufficient to construct a single generic static model, which generates a non-linear shape similar to Fig.8 and which starts at (0%,0%) and ends in (100%,100%).

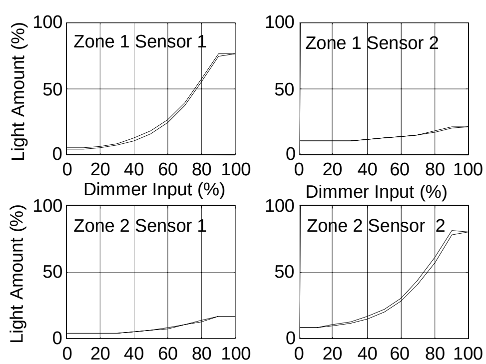

Figure 8: Static Characteristics

The static characteristic clearly reflects the hysteresis between dimming up and dimming down. The explanation is as follows: the dimmer's input is slightly filtered via the RC-components on the electronic board, such that a step-input is converted into an exponential input (very fast compared to the overall dynamics of the whole system).

The dead-zone, which is intentionally programmed in the dimmer-software in order to make it insensitive to ditter, then has the undesired side-effect of producing a hysteresis (Fig.9).

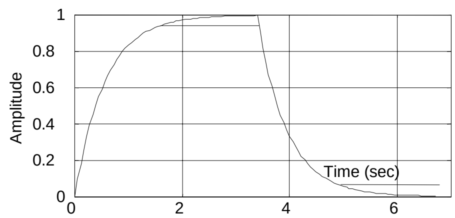

Fig. 9. Hysteresis from Anti-Ditter Dead-Zone

The several components of a generic static model, which produces a nonlinear characteristic with hysteresis, are given in Fig.10. The model consists of a (very fast) RC-filter block, an anti-ditter dead-zone block, a limiter block and a phase-cut-off block. Further details are given in section 4.

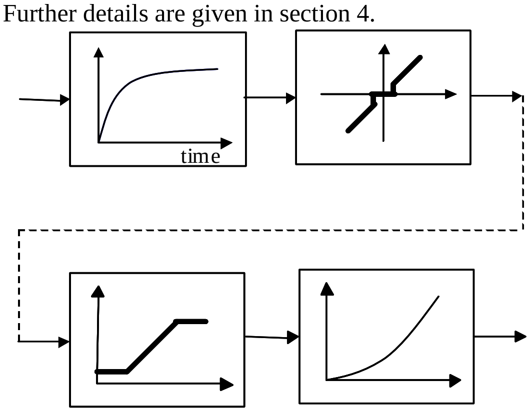

Fig. 10. Components of Generic Static Model

3.3 Dynamic characteristic

All step responses obtained in the staircase experiment (Figs.3 & 4) have the same dynamic transient, as can be seen in Fig.11a (after normalization to unit gain). After taking the average over all 21 steps of the whole staircase experiment (for each zone and each sensor, see Fig.11b), it is clear that all 4 responses are practically identical (notice that the responses of the cross-coupling Z1-S2 and Z2-S1 are more noisy, because they have been amplified more in order to obtain a normalized response). After final averaging of the 4 responses the generic dynamic characteristic of Fig.12 is obtained.

The transfer function of the generic dynamic model is obtained from the averaged step-response (Fig.12), using the 'least-squares identification method' [6].

Using shift-operator notation, the discrete-time version of the transfer function is given by:

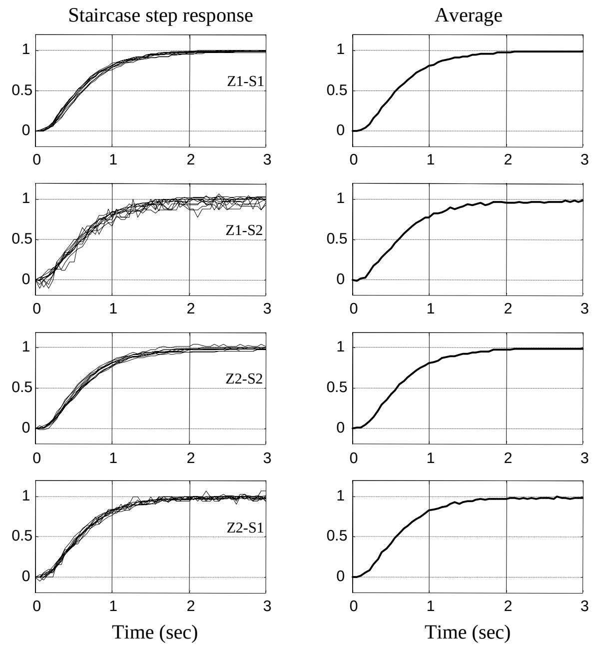

Fig. 11a,b. Dynamic & Averaged Characteristics

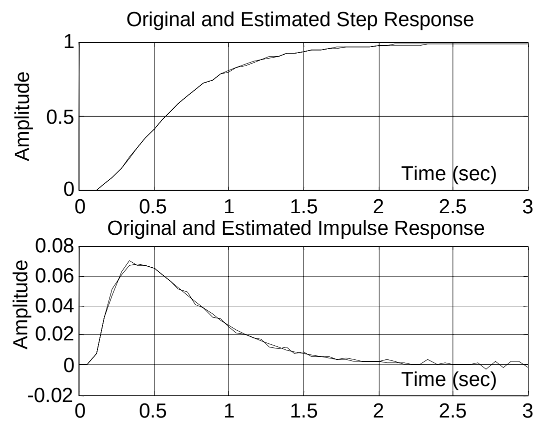

Fig. 12. Real & Estimated Step and Impulse Responses used in the Dynamic Model

$$y(k) = \frac{b_2 q^{-2} + b_3 q^{-3} + b_4 q^{-4}}{1 + a_1 q^{-1} + a_2 q^{-2} + a_3 q^{-3}} \cdot u(k)$$

with the identified parameters given in the Table.

Coefficients a	Coefficients b
-1.0769	0.0079
-0.2714	0.0243
0.3948	0.0136

The step-response of this 3rd-order discrete-time model is compared to the real one in Fig.12.

3.4 Model calibration

The single generic (static+dynamic) model is a common part of all 4 sub-models, which means that the differences between them is only in the values of the $\{a_{ij},b_{ij}\}$ parameters (Fig.7). These are thus the only parameters in the model which depend on the specific room-layout, sensor-position, sensor covering etc. Three simple experiments, which can be easily automated, are sufficient to identify these 'a' and 'b' parameters in any specific situation (ref. Fig.7):

1. Put $\{ D_1=0\%,\ D_2=0\% \}$ and measure the corresponding values $\{S_1^{00}, S_2^{00}\}$.
2. Put $\{ D_1=100\%,\ D_2=0\%\}$ and measure the corresponding values $\{S_1^{10}, S_2^{10}\}$.
3. Put $\{ D_1=0\%,\ D_2=100\% \}$ and measure the corresponding values $\{S_1^{01}, S_2^{01}\}$.

Taking into account that the generic model goes through the points {0%, 0%} and {100%, 100%}, Fig.7 then leads to the following result:

- $b_1=S_1^{00}$ and $b_2=S_2^{00}$

($b_1=b_{11}+b_{21}$ and $b_2=b_{22}+b_{12}$; only the sum is needed)

- $a_{11}=0.01*(S_1^{10}-S_1^{00})$ and $a_{21}=0.01*(S_1^{01}-S_1^{00})$
- $a_{12}=0.01*(S_2^{10}-S_2^{00})$ and $a_{22}=0.01*(S_2^{01}-S_2^{00})$

Based on the real-life experiments of Figs.3&4, the following numerical values are found:

$$\{a_{11}=0.72 \quad a_{21}=0.13 \quad a_{12}=0.10 \quad a_{22}=0.70 \quad b_1=5 \quad b_2=10\}.$$

4. SIMULATOR

4.1 Simulator structure

The simulator is based on the model-structure developed in section 3.1 (Fig.7) and the models derived in sections 3.2, 3.3 & 3.4; its layout is given in detail in Figs.13&14. Based on these block-schemes, it is rather straightforward to understand the functioning of the simulator. Notice that the supplementary inputs W_1 & W_2 (Fig.13) can be used to introduce light disturbances due to outside weather, which will be important in the next project phase.

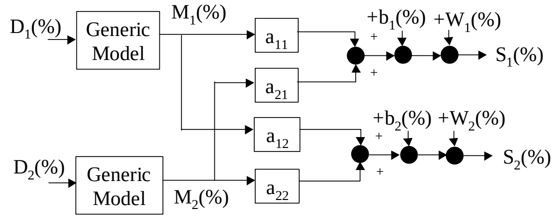

Fig. 13. Simulator Structure

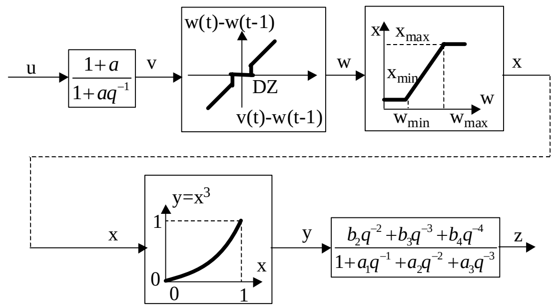

Fig. 14. Internal Structure of the Generic Model

4.2 Simulator validation

The staircase experiment as described in section 2.2 for the real-life room has been repeated on the simulator (Figs.15&16; they have to be compared to Figs.3&4).

From these data, the static and dynamic characteristics of the simulator have been identified again as has been done before in sections 3.2 & 3.3 for the real-life data. The results are shown in Figs.17&18 (to be compared to the results of Figs.8&12).

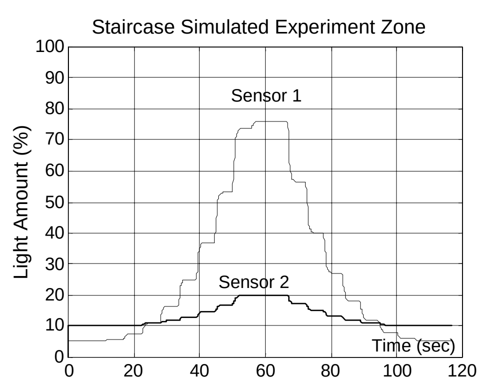

Figure 15: Simulated Staircase Experiment Zone #1

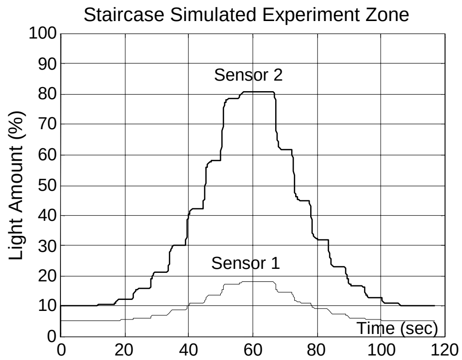

Fig. 16. Simulated Staircase Experiment Zone #2

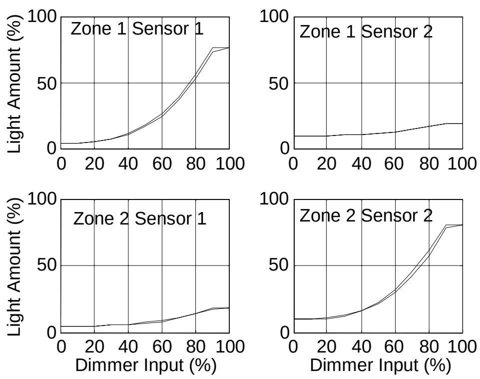

Fig. 17. Simulated Static Characteristics

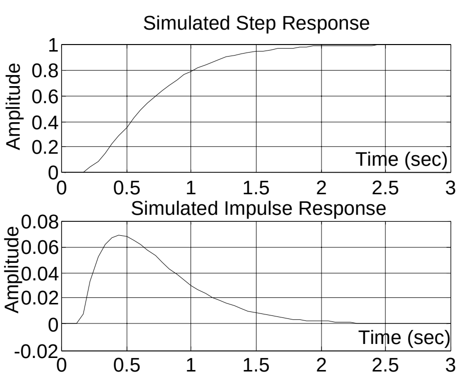

Fig. 18. Simulated Dynamic Characteristics

4.3 Simulator use

The next step will be the design and comparison of several candidate-controllers for the lighting system. The simulator for the lighting system, resulting from the modelling exercise described in this paper, will then be the basis to:

- tune the controller parameters;
- compare different control strategies;
- obtain insight in the behaviour of the feedback loop;
- detect the stability limits of the system;
- assess the performance characteristics of such a lighting control system;
- evaluate the closed-loop control system in the presence of various weather disturbances;
- evaluate the robustness of the control system for other room configurations.

5. CONCLUSIONS

Based on a modelling and identification exercise, a simulator for a real-life 2-zone lighting control system has been developed. The model and the simulator can be easily extended to more zones.

The simulator response is remarkably close to the observed real-life response of the test-room. This means that the model-building exercise was very successful.

The simulator will now be used to design, tune, test and evaluate lighting-controllers for both zones. After having obtained good results with the control system on the simulator, the next step will be to run the same software in the real-life test-room for evaluation and fine-tuning.

The final step will then be to implement the controller software in the target micro-controller system as a commercial product.

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