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An Analysis of Dynamic Lighting Control in Landscape Offices

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Abstract: This paper makes a discussion on the control of light in landscape offices. This is a feature of modern office buildings, with increasing incidence as the number of employees increase while individual space allocation decreases. This can have already an impact on the efficiency and versatility of coping with stress situations of the employees. Apart from the stress induced by the lack of space and privacy, the light level is yet another important factor. Poor light or extreme illumination, or even more relevant: periodic shadow disturbance (i.e. windmills) are all increasing factors of stress levels. Control of illumination in a closed environment seem to be a feasible solution, but perhaps not very useful for the overall mood of the employee. Windows and possibility to see green patches, sunlight, have significant positive influence on the overall working conditions. Although easy to implement and broadly available in industrial lighting components, PID control has some limitations which we discuss here.

Keywords: light control systems, robustness, stability, multi-agent system, PID control.

1. INTRODUCTION

Over the last decade, energy conservation of any form and any use has become a striving target (EC Report (2005); Ochoa et al. (2012)). The potential for energy saving by using automatic dimming of electric lighting - in order to take advantage of the daylight - was already investigated in the seventies (Crisp (1977)) Although the necessary technology exists for this type of control, it is only in the last decades that light control systems (LCS) have been offered to the main public and only in specific applications (Chang and Mahdavi (2001); Sweitzer (1993)). Both experimental and commercial data indicate that important energy savings associated with lighting can be made, by use of smart controls alternatives to the classical on-off manual wall-mounted switch panel (Ure and Crisp (1981)). The changes in light technology itself has also brought significant cost reduction further on. In landscape offices, the trend by all means nowadays, a constant/variable light level seems to be important in altering the work efficiency and comfort of employees (Dounis and Caraiscos (2009)). A number of earlier studies have shown a subjective preference for daylight and some advantages and disadvantages are briefly presented in (Ure and Crisp (1980)). From a control perspective, the location of the light sensors is a very important aspect, mainly related to potential disturbances (De Keyser and Ionescu (2010)). These may origin from windows and outside weather conditions, or vicinity of renewable sources of energy, i.e. periodic shadowing from windmills. Continuous changes in daylight - usually fast and big changes - are quite normal in our regions (Belgium, Western Europe). Mornings can be sunny and then suddenly the weather may change to rainy; or vice versa, mornings can be foggy and gradually the sun breaks through. During a large part of the year, average daylight is very low when people start their job in the morning, but it might increase substantially during the day. All these are examples of rather gradual light changes. But usually more challenging light variations occur (challenging from the control point-of-view): clouds are continuously passing-by in the presence of a background sun and these clouds cover the direct sunlight. Without any active control system, people then usually push on the light switch, and then have the habit to forget and leave the lighting on. In the community, the opinion that PID control suffice to solve this kind of problems from control performance point of view is not broadly shared (Cao et al. (2010)). It remains to see whether optimal solutions are required from more advanced control strategies (e.g. model based predictive control) mainly when disturbance rejection is necessary. Filtering techniques combined with predictive control may prove suitable if the disturbances have main energy spectrum located in bandlimit intervals of frequency as such, prediction of their dynamics may improve drastically the closed loop performance (De Keyser and Ionescu (2003)). In this paper we present a simulation of a laboratory system for investigating the interactions of light in a landscape office in various circumstances. The control used in this paper is PID-based as to analyse its potential and limitations. The paper is structured as follows. The process is described in the second section, followed by the control

strategy. The fourth section gives the results and points to some perspectives.

2. STUDY CASE: LANDSCAPE OFFICE

2.1 Office Setup

The MIMO (Multiple Input Multiple Output) configuration of the lighting system consists of eight zones, in two circumstances: i) full interaction and ii) partial interaction between them. The amount of interaction is determined by the presence of full-way or half-way delimiter walls between the work cubicles. In this way, the reflection of light on the working area is altered.

It is assumed that each of the 8 zones in the room has its own light sensor and its own - separately controlled - bank of lamps (Wen and Agogino (2011)). Standard fluorescent lamps including ballast, which are usually used in offices, are assumed to be controllable by dimmer voltage. Figure 1 provides a schematic of the landscape office as simulated in Matlab/Simulink platform and some photos of authentic Belgian landscape.
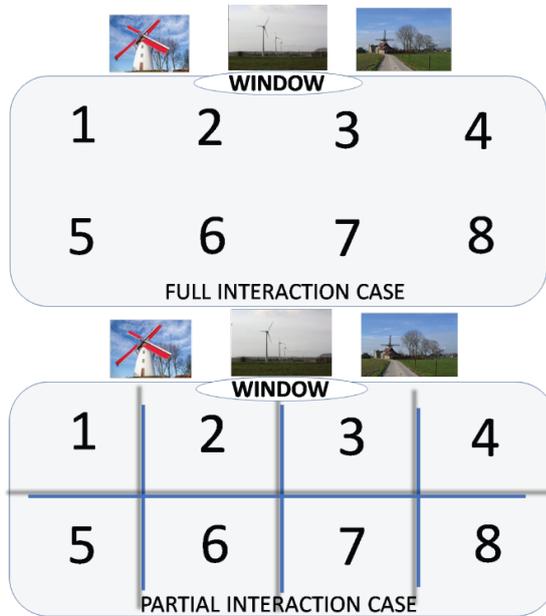

Fig. 1. Schematic of the landscape office in the two situations of full and partial interaction among the controlled zones.

The setup consists of a cupboard box with eight incandescent lights that are steered by dSPACE™ DS1104 R&D controller board. A TIP120 IC acts as a buffer between the controller board and the lights. The eight light sensors are Light Dependent Resistors (LDRs) of the Cadmium-Sulfide type. The LDR is part of a voltage divider: one side of the LDR is connected to a constant voltage source V_{cc} and the other port is connected to a constant resistor with a known value ($1k\Omega$). The voltage V_{Sens} over the known resistor depends on the resistance of the LDR. The voltage V_{Sens} is measured with the controller board and is sent to the computer. An extra light is added to the side of the box to simulate external disturbances as discussed above. The setup is shown in Figure 2.
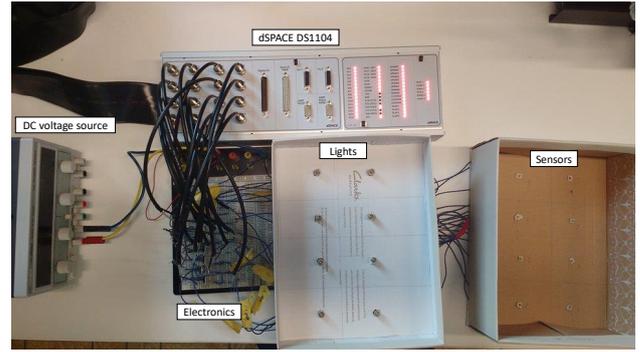

Fig. 2. The different hardware modules used for the measurements are depicted: Power source, dSPACE™DS1104, the signal processing circuits and the test setup with eight light bulbs and sensors.

2.2 A simple model for one zone

Every zone is modelled as a linear second-order system with a non-linear static gain that is given by the static characteristic that is found with a staircase experiment, as depicted in Figure 3. The non-linearities in the dynamics are negligible. In Figure 4 the generic model is shown.
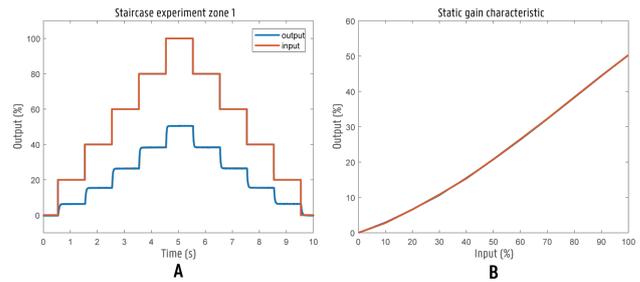

Fig. 3. The staircase experiment for zone 1; (A) The input and output signal of the experiment; (B) the static characteristic derived from the staircase experiment
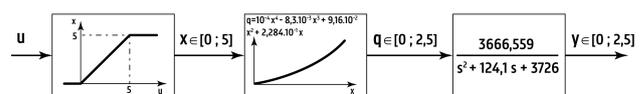

Fig. 4. The process depicted as a series connection of different building blocks.

The static characteristic can be approximated by the function

$$q(x) = 10^{-4}x^4 - 8 \cdot 10^{-3}x^3 + 9 \cdot 10^{-2}x^2 + 2.284x \quad (1)$$

The model of one zone as from dimmer voltage to the light meter in the centre of the room, assuming window closed (black) and other possible disturbances absent, is given by the following transfer function:

$$y(s) = \frac{3666.559}{s^2 + 124.1s + 3726} \cdot q(s) \quad (2)$$

with y(s) the system output (illumination level measured by the sensor, 0-2.5V); q(s) the system input (dimmer action for the lamp-banks, 0-2.5V); and s being the Laplace operator.

Every zone is calibrated to be able to work with the same transfer function. Every light bulb will influence the sensors of the other zones. By introducing a step to one light bulb the interaction can be found by monitoring the sensors of the different zones. The effect on the dynamics is rather limited, so without loss of generality, it is assumed that the coupling can be modelled as the process as described in (2) multiplied with a constant, depending on the interaction level. This constant introduces a change in the static gain of the original transfer function, which can be confirmed intuitively. After all, the light intensity drops proportionally to one over the squared distance.

The coefficients C_{ij}, the factor that determines the effect of lamp i on sensor j, is found by comparing the the static gain for a step on lamp i from 0% to 60% of sensor i with the static gain of sensor j. For full-interaction the coupling matrix looks as follows:

$$[C_{ij}] = \begin{bmatrix} 1.00 & 0.67 & 0.34 & 0.23 & 0.61 & 0.47 & 0.31 & 0.23 \\ 0.70 & 0.80 & 0.62 & 0.39 & 0.53 & 0.54 & 0.44 & 0.32 \\ 0.56 & 0.59 & 0.81 & 0.66 & 0.32 & 0.41 & 0.58 & 0.34 \\ 0.19 & 0.27 & 0.56 & 1.05 & 0.23 & 0.26 & 0.46 & 0.73 \\ 0.57 & 0.41 & 0.26 & 0.20 & 0.98 & 0.67 & 0.33 & 0.22 \\ 0.49 & 0.40 & 0.39 & 0.30 & 0.63 & 0.83 & 0.61 & 0.36 \\ 0.30 & 0.44 & 0.56 & 0.50 & 0.41 & 0.64 & 0.83 & 0.59 \\ 0.21 & 0.23 & 0.44 & 0.66 & 0.24 & 0.31 & 0.60 & 0.97 \end{bmatrix}$$

For partial interaction the coefficients are:

$$[C_{ij}] = \begin{bmatrix} 1.28 & 0.84 & 0.16 & 0.09 & 0.30 & 0.23 & 0.12 & 0.08 \\ 0.35 & 1.13 & 0.39 & 0.10 & 0.15 & 0.24 & 0.18 & 0.07 \\ 0.11 & 0.41 & 1.14 & 0.45 & 0.08 & 0.17 & 0.29 & 0.20 \\ 0.05 & 0.12 & 0.33 & 1.35 & 0.04 & 0.09 & 0.19 & 0.31 \\ 0.60 & 0.47 & 0.11 & 0.07 & 1.18 & 0.69 & 0.14 & 0.07 \\ 0.22 & 0.59 & 0.19 & 0.07 & 0.41 & 1.10 & 0.38 & 0.09 \\ 0.09 & 0.23 & 0.62 & 0.25 & 0.13 & 0.74 & 1.09 & 0.40 \\ 0.05 & 0.09 & 0.27 & 0.77 & 0.05 & 0.12 & 0.37 & 1.24 \end{bmatrix}$$

An interesting fact about the coupling matrix is that the coupling parameters show to be dependent on physical parameters. The d^{-2} correlation, as mentioned above, can be seen for the parameters C_{1j} in Figure 5.
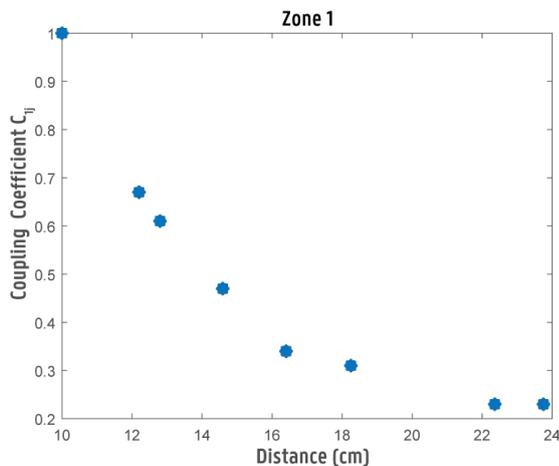

Fig. 5. The coefficients C_{1j} are plotted versus the distance between lamp one and sensor j. The coefficients obey the physical law of intensity drop due to distance.

Some symmetry in the coefficients was expected, but this was only the case for the order of magnitude. It would not be beneficial to assume $C_{ij} = C_{ji}$. Also, notice that some parameters are larger than 1. This is due to reflection of the light on nearby walls. The original process model (2) is obtained without lights so the only direct light paths are taken into account in this model.

2.3 Control Design

The dynamics of the system indicate that the process is first-order dominant. In that case it is very easy to design an efficient PI-controller:

$$C(s) = K_p(1 + \frac{1}{T_i s}) \tag{3}$$

The transfer function of a first order system is

$$P(s) = \frac{a}{\tau s + 1} \tag{4}$$

where τ is the time constant of the process P(s). The transfer function of the closed loop with $C(s)$ and $P(s)$ is:

$$T(s) = \frac{C(s) \cdot P(s)}{1 + C(s) \cdot P(s)} \tag{5}$$

$$= \frac{K_p a(T_i s + 1)}{T_i s(\tau s + 1) + K_p a(T_i s + 1)} \tag{6}$$

If $T_i = \tau$ the transfer function reduces to

$$L(s) = \frac{1}{\frac{T_i s}{K_p a} + 1} \tag{7}$$

Notice that the static gain of the loop function $T(s)$ equals one. The proportional gain coefficient K_p will affect the time constant of the closed loop process. By increasing K_p the time constant decreases and the control effort will increase as the system will go more aggressively towards its setpoint. By increasing K_p the controller will act less aggressively, which results in a smaller control effort, but in a slower system. In this case the parameters are chosen as follows:

$$K_p = 1$$
$$T_i = 0.035ms$$

3. RESULTS

In this section the PI-controller is included in the closed loop. The process with the controller is simulated in Simulink^{TM} and the model is compared with measurements on the setup. The controller is evaluated in the case of high coupling between the zones (no walls) and with partial coupling (intermediate walls). For this experiment all light intensities per zone are maintained on a constant value except for zone 1 and zone 5. Zone 1 introduces a step to the system at 0.5 seconds from 323% to 34% and zone 5 sees a step from 32% to 36% at second 2.5. Zone 2, 3, and 6 are maintained on 34%. Zone 4, and 8 are maintained on 30%. Zone 7 sees an input of 32%.

3.1 Full coupling

For this experiment the walls between the zones are removed. The coupling is the largest. The sensor output
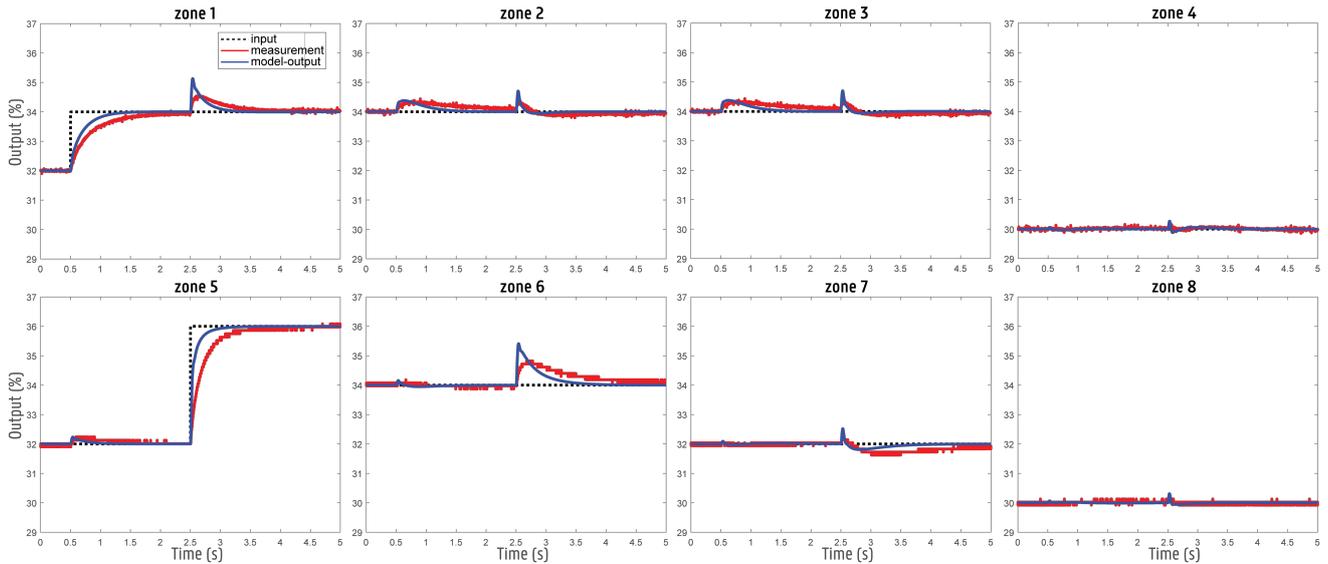
Fig. 6. The simulated and measured output of the eight zones for full coupling (no walls). The reference is given as well.
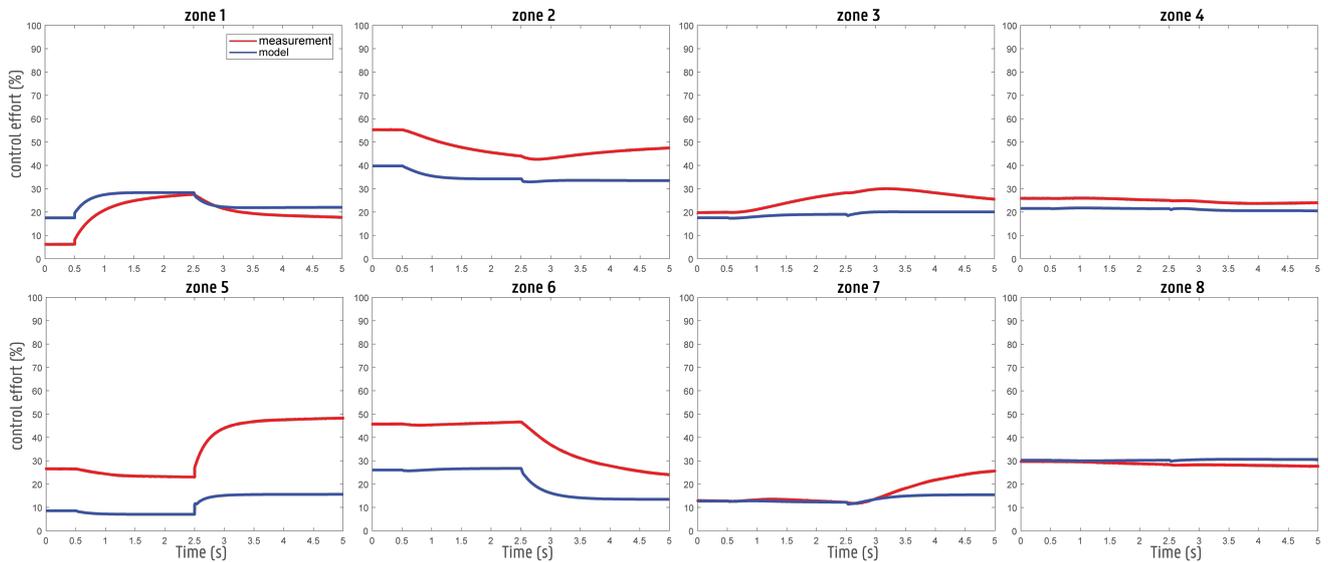

Fig. 7. The simulated and measured control effort of the eight zones for full coupling (no walls).

for every zone is given in Figure 6. The control effort for every zone is given in Figure 7.

In Figure 6, the reference is given by the dotted line. The model's solution is given by the blue line and the red line is the measured output. In general, the model is a good representation of the measured data. For the simulation, the overshoot is a bigger and the peaks are sharper. The settling time for the measured data is a larger. It can be concluded that the dynamics of the model differ a little bit from these of the real setup. For the control effort, in Figure 7, the difference is more significant. The blue line again represents the model and the red line shows the measured data. The further away from the zones where the step occurs the better the control effort of the simulation compares to the control effort of the setup. The dynamics of the simulated setup are comparable to these of the real setup. The values are not comparable and the model underestimates the real control effort.

3.2 Partial coupling

For this experiment intermediate walls are placed in between the different zones. The wall height compared to the total height is 0.5. In Figure 8 and 9, the output and control effort respectively are given.

The observations for the partial coupling are quiet similar to the observations of the full coupling case. It can be seen that the coupling is significantly smaller between the different zones.

3.3 Effect of Periodical Disturbance

A window close to zone 1 introduces a disturbance to this zone. A periodic disturbance creates an unwanted effect in all zones. The simulation of the output and the control effort of this situation is given in Figure 10 and 11. To keep the figures clear only zone 1, 2, and 5 are given. The simulation takes place in the case with full interaction
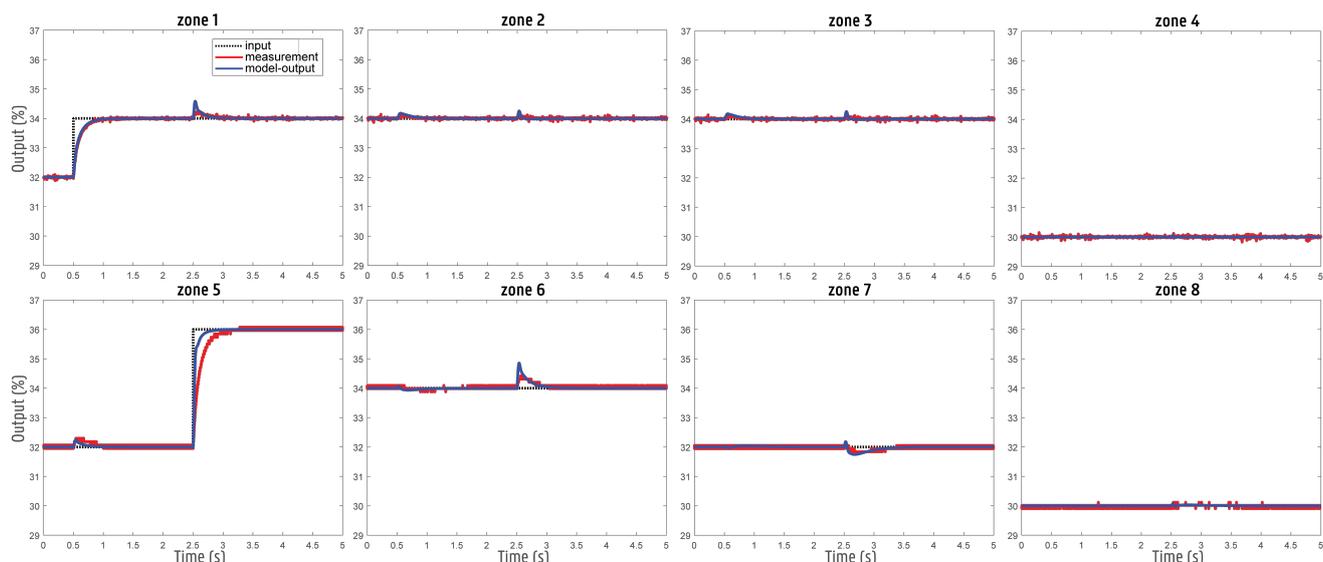
Fig. 8. The simulated and measured output of the eight zones for partial coupling (the wall height is 50% of the total height). The reference is given as well.
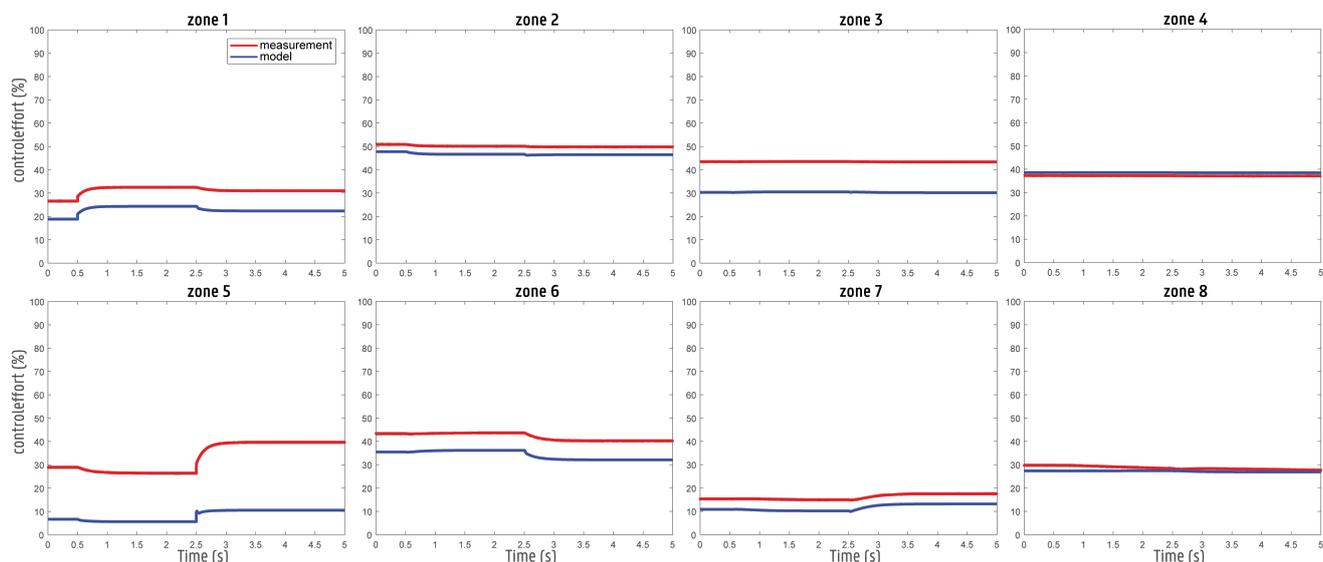

Fig. 9. The simulated and measured control effort of the eight zones for partial coupling (the wall height is 50% of the total height).

(no walls). The periodic disturbance is a sine with an amplitude of 5% of the end value of the step in zone 1. The frequency is $1Hz$.

4. DISCUSSION

From this simple example, it is clear that the presence of disturbance in such a landscape office setting conditions is of paramount importance for the dynamic of the closed loop. One can easily imagine more complex situations where the interactions among the neighbouring zones will require some sort of optimization in terms of inputs (Koroglu and Passino (2014)). For instance, the results here suggest that at times, mostly one zone will be more active than another zone. This implies that some zones will actively degrade with time due to wear and tear of instrumentation, while others will have longer lifetimes. Other aspects as resolution, dither and rate limiters may also influence the output dynamics.

One may argue that simple PID-type controllers may do the job properly, in combination with decoupling blocks, anti-reset windup elements and perhaps adaptive gain tuning for different situations. Indeed, this may be the case. However, if economic objective is to reduce consumption, while taking into account balanced distribution of the control effort, a more accurate or faster (milliseconds) response, then advanced control strategies are needed.

Known or detectable, measurable hence predictable disturbances are important factors in designing advanced control strategies. Several possibilities exist: internal model control (De Keyser et al. (2017)), predictive control (De Keyser and Ionescu (2003)), distributed control (Scherpen (2015)) and game theory control (Quijano et al. (2017)).
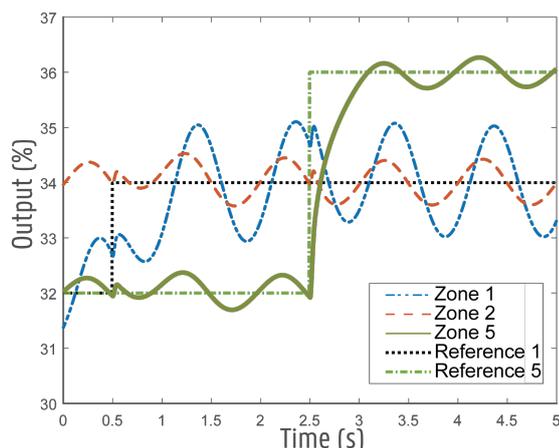
Fig. 10. Near zone 1 a window is introducing a sinusoidal disturbance to the system with full interaction (no walls). The output is simulated here.
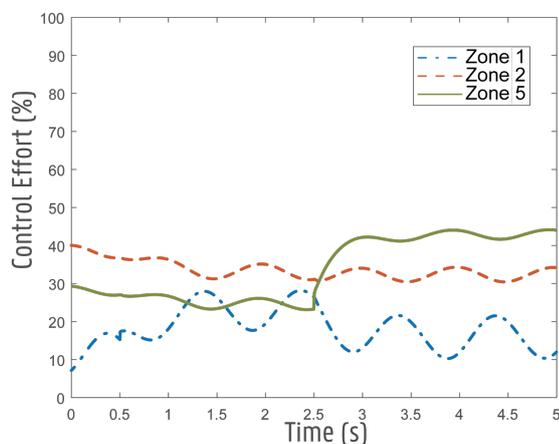

Fig. 11. Near zone 1 a window is introducing a sinusoidal disturbance to the system with full interaction (no walls). The simulation of the control effort is given.

The control of light level in offices may also be considered as a part of a larger energy optimization problem, namely HVAC systems (Heating, Ventilation and Air Conditioning) control. In the context of renewable energy combined with fossil energy, all energy related controls must be unified within a modern building architecture. Hence, inclusion of the light control system within HVACs, is here motivated.

The implementation of successful control strategies in larger systems, such as office buildings, requires the division of the environment. This implies the introduction of local controllers, of various zones, communicating over a network. As the number of actuators and sensors increases, centralized techniques become inefficient and distributed strategies become interesting. Distributed architectures are robust with relative low computational cost for the control algorithm. The resource allocation limitations and topology of such a network will then become important to investigate its effects on the overall system dynamics, say energy saving per year/building. Other applications of such interconnected systems include: smart grids, connected water reservoirs and multi-agent systems.

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