Model-based daylight-dependent light control using KNX

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1 Abstract

Energy consumption for lighting accounts for 14% of overall European energy consumption. The savings potential is estimated to be about 40%. A major contribution to these savings is expected from daylight- and presence-dependent light control. Artificial light from luminaires with dimmable electronic control gears is added to the natural daylight in the room as required. Using one or more illuminance sensors groups of lamps are controlled according to their position in the room so that a predefined illuminance level is maintained in the whole working area.

Although a broad spectrum of products for daylight- and presence-dependent light control is available on the market, there seems to be quite a potential for improvements with respect to control performance and cost effectiveness.

The present study discusses several concepts of constant light control, especially focussing on rooms with several groups of lamps. The concepts are classified from a control systems point of view and inherent limitations regarding control performance or cost effectiveness are pointed out. Some of these concepts were implemented and tested within a KNX network in a seminar room and a laboratory at Bremen University of Applied Sciences.

In addition, a new model-based control strategy is presented which uses only one sensor to control several groups of lamps. The control concept is described in detail and results of a test-implementation in a laboratory are given.

2 Daylight usage in buildings

Lighting in buildings, especially in working areas, is generally subject to regulations, such as [2], that require minimum illuminance levels which depend on the type of usage of the buildings. Energy savings can be realised by using energy efficient equipment, e. g. efficient luminaries with electronic ballasts, and by making use of daylight as much as possible.

Making use of daylight is first and foremost a matter of architecture. Rooms should have windows on more than one side, e. g. additional windows to an inside courtyard or to an atrium (see e. g. [1]). To achieve this, best possible use of daylight must become a leading issue already in the first steps of the planning of a building.

However, this is not yet common practice. The majority of new buildings as well as of existing ones consists of rooms with only one window front. Therefore, the present study focuses on this type of rooms which can be characterized as follows:

- one window front,
- depth of the room ranging from 4m to 10m and more,
- one to five and more groups of luminaires in parallel to the window front.

The artificial light necessary to comply with the lighting requirements in this type of room depends on the distance from the windows and on the daylight. Therefore, some sort of control system during daily operation is needed. A rough classification of types of light control in this context can be given as follows:

- manual control of artificial light by switching and dimming, done by users,
- use of inside sunblinds as a glare shield, also typically done manually,
- use of outside blinds as a glare shield in addition to their function to prevent excessive room heating, done manually or by automatic control,
- automatic switched light control based on time schedules or illuminance thresholds,
- automatic daylight dependent constant light control.

In practice more than one of these strategies will be used, combining different manual control actions and/or manual and automatic control. Automatic daylight dependent light control can be achieved by different strategies which are detailed in the next section.

3 Different types of daylight dependent light control

3.1 Light control with outside illuminance sensor

Using an outside illuminance sensor in combination with knowledge about the distribution of outside light in the room groups of lamps can be set to suitable predefined dimm-levels according to their position in the room. Also information about sun position – time of day, day of the year – can be included into this approach.

This strategy is a pure feedforward control scheme. The quantity to be controlled is the illuminance inside the room in the user's work space, e. g. on the desktop. This is not measured. Therefore, this strategy is very sensitive to changes in the room, especially to operation of blinds.

An important advantage of this control strategy is that several rooms on the same side of a building can be controlled by only one sensor.

3.2 Control of one group of lamps with one illuminance sensor inside

Using an inside illuminance sensor the dimm-level of a dimmable group of lamps can be adjusted to achieve and maintain a prescribed illuminance measurement value. This is a typical setup for office rooms with luminaires above the working area.

It should be noted that the sensors, mounted at the ceiling, don't really measure illuminance but luminous density of the area below. Therefore the measured value is typically rather sensitive to the characteristics of this area (texture, colour, distance from sensor). Suitable placement of the sensor, that takes this issue into account, is crucial for all control schemes using inside illuminance measurements.

The setup of sensor, dimming actuator, lamp and surface of the working area builds up a feedback control loop (fig. 1). In practice, measurement, setpoint and control are typically all incorporated in the sensor device.

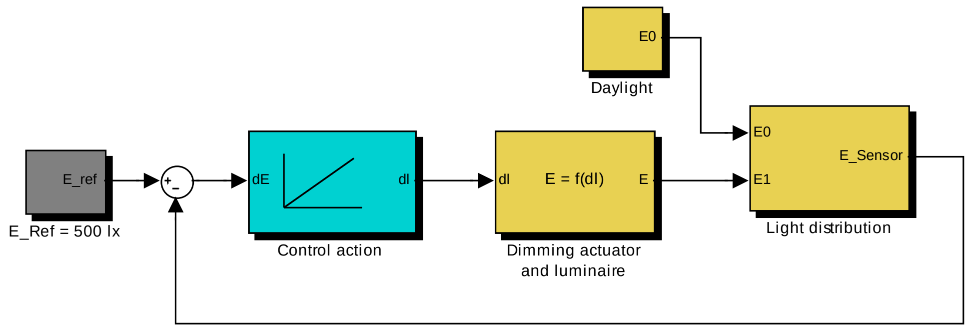

Fig. 1: Constant light level control loop

If the sensor uses cyclic dimming this control system performs an integral type of control action. A constant deviation of measured illuminance from the setpoint value will result in dimm-levels that follow a ramp function. If the sensor sends dimming values (0 – 100%) the control algorithm is part of the sensor application program and more sophisticated control designs can be employed.

Pure integral control action is typically rather slow. This is no severe drawback in this case because of ergonomic requirements that have to be considered. Humans are very sensitive to rapid changes in light conditions. Even though daylight may change rapidly the control design should not aim at following these changes very fast. At work and even more in classrooms this would have a very disturbing effect.

Therefore, the setting of the speed of the light control is always a compromise between achieving minimal deviations from the setpoint illuminance (or achieving maximum energy savings) and minimizing disturbing effects on users. In practice, several parameters of both the sensor and the dimming actuator may have to be adjusted to set the control speed, e. g. cycle interval, dimm-level step size, dimming speed of the actuator. This makes optimal parametrisation difficult. Considering in addition the complex issue of sensor placement it becomes clear that daylight dependent light control is a demanding task even in this simple case.

3.3 Control of several groups of lamps with dedicated illuminance sensors

Large rooms are lighted by more than one group of luminaires. In this case the concept of the previous section can be applied to each group of lamps. This appears to be quite straightforward at first sight. However, the issue of sensor placement becomes even more complex especially when the illuminated areas of the groups of lamps overlap. Control problems may arise from mutual influences of adjacent groups.

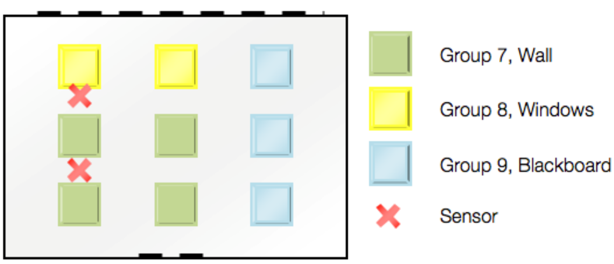

Fig. 2: Lamps and sensor location in a classroom

This concept was realised in a classroom at Bremen University of Applied Sciences (see fig. 2) and resulted in substantial electrical energy savings ([3], [4]).

Figure 3 shows electric energy consumption of this classroom compared to an identical one without automatic light control. Energy savings are about 20%. Since the standby losses of the dimming actuators account for a substantial part of the consumption the savings potential is even larger.

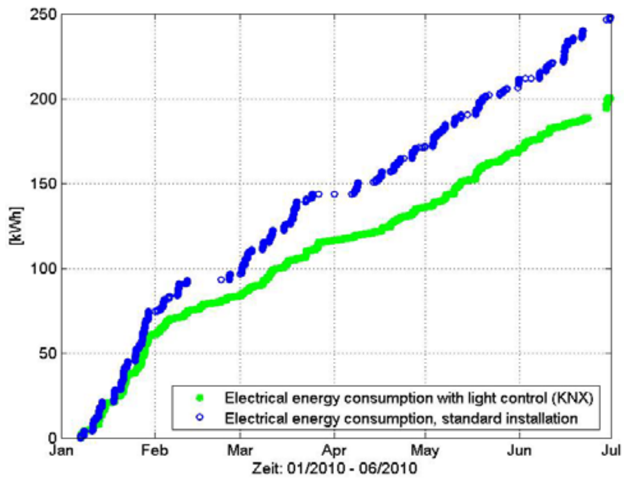

Fig. 3: Electric energy consumption with and without daylight dependent control

An obvious drawback of this concept is, however, that the sensors account for a major part of the investment costs of a light control system. So this is a rather expensive solution.

3.4 Control of several groups of lamps with one sensor – master/slave

The illuminance coming from daylight is obviously highest near the window front and decreases towards the opposite wall. This is described by the daylight factor D which is the ratio of illuminance at a certain point in the room to the illuminance outside (measured at cloud overcast weather conditions):

$$D = \frac{E_P}{E_0}$$

The daylight factor at a point in the room can be described as a function of the distance from the window front. We will call this the "daylight factor characterstic". It mainly depends on window area, window height and room interior.

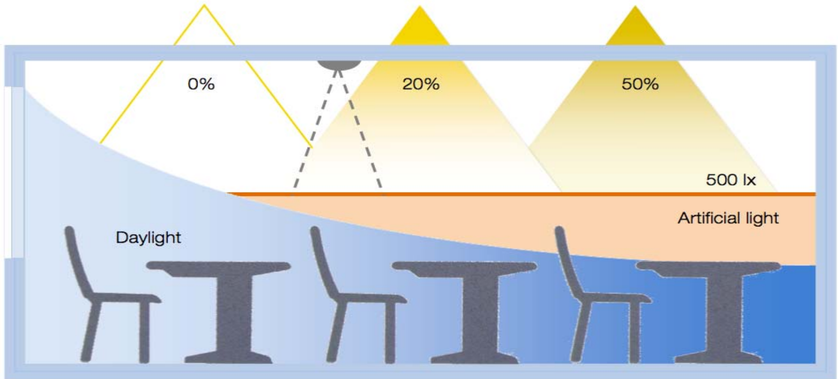

Fig. 4: Daylight factor characteristic and corresponding demand of artificial light

If groups of lamps are arranged in lines parallel to the window front the dimm-level near the windows will be lower and near the opposite wall will be higher as compared to a group in the middle. This leads to a master/slave concept with a sensor that performs constant light control with two or up to five groups of lamps, where one acts as a master (comparable to the setup of section 3.2) and the other groups are dimmed to levels that differ from the master by certain offsets. These offsets are typically chosen in a more or less heuristic manner without knowing the daylight factor characteristic in detail.

In a laboratory at Bremen University of Applied Sciences this concept has been implemented and tested using a master/slave sensor that allows for up to 4 slave groups. In the room three groups of lamps are arranged in lines parallel to the window front (see fig. 5).

Fig. 5: Laboratory with automatic light control

The center group was chosen as the master, with the sensor placed at the ceiling near the middle of the room. Experiments with different offsets for the two other groups of lamps under different daylight conditions were carried out. Fig. 6 shows illuminance results measured with a luxmeter on the desks on a rainy day at noon and towards the evening. Offsets were chosen symmetrically: -20%/-40%/-60% for the lamps near the window and +20%/+40%/+60% for the lamps near the opposite wall.

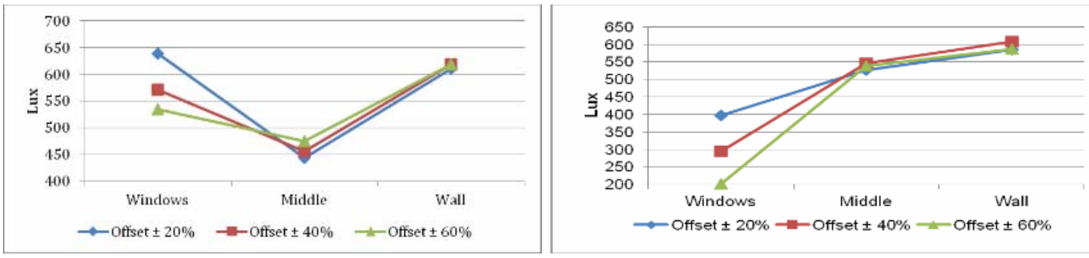

Fig. 6: Measured Illuminance with master/slave light control at noon (left) / in the evening (right)

With each of these settings the dimm-level of the master group is controlled so that the resulting illuminance in the middle of the room matches the setpoint of 500 lx reasonably good. The lamps at the wall are fully turned on even with the lowest offset of +20%. At the windows the required illuminance at noon is maintained even with an offset of -60%. Lower offsets of -20% or -40% would not yield optimal energy savings. However, in the evening the dimm-levels of the lamps near the window remain too low to provide the required illuminance and with an offset of -60% only 200 lx were measured [5].

On the other hand, when there is sufficient daylight at the location of the sensor, the sensor will switch off the master group. As a consequence all the slaves are turned off, too, which may result in insufficient lighting at the wall opposite the windows.

Both effects are due to the fact, that regarding the slaves this concept is no feedback control. No information about the illuminance at the location of the slaves is available within the control system. This leads to unfavourable behaviour under certain daylight conditions. However, with only two lines of lamps to be controlled (master + 1 slave) negative effects can possibly be avoided by placing the sensor between these lines. For such a setting the concept is a very cost-effective solution.

4 Model based control of several groups of lamps

Using only one sensor in the middle of the room means lacking information about the illuminance at the window and the opposite wall. Instead of installing additional sensors the new concept developed here takes a model based approach to estimate the illuminance in the whole room and adjust the dimm-levels of all groups of lamps accordingly.

The required model consists of the illuminance distribution of all relevant light sources, which can be derived from luminaire data sheets and a few illuminance measurements. The quantities needed are

- the daylight factor characteristic,
- a similar characteristic for the illuminance distribution of each group of lamps,
- the relation between dimm-levels and illuminance below the lamps,
- the measurement value of the sensor.

The resulting control structure is shown in figure 7.

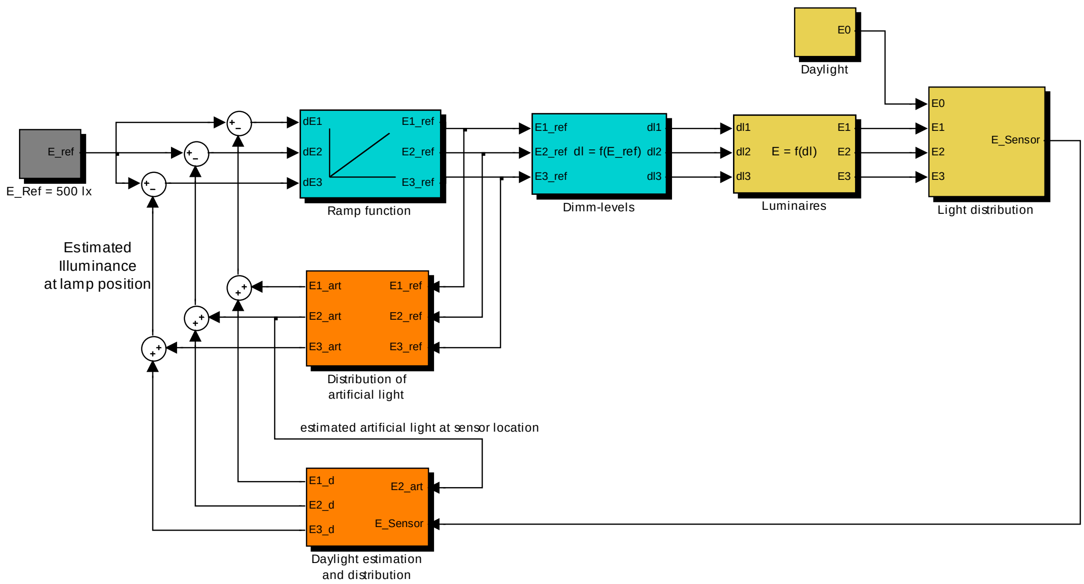

Fig. 7: Structure of daylight dependent light control of 3 groups of lamps with a single sensor and illuminance estimation

The estimator (lower part of the structure) calculates the daylight fraction of illuminance at the sensor position as the difference between the measurement value and the estimated contribution of all the groups of lamps. From this the daylight fraction and the total sum of the actual illuminance below each group of lamps can be estimated. The deviation of each illuminance from the setpoint (500 lx) is controlled via a ramp function. From a control systems point of view this is an integral controller with disturbance estimation (where daylight is the "disturbance").

The control speed is defined by the ramp function and has to be chosen carefully taking ergonomic aspects into account. Especially small daylight changes should not lead to noticeable changes of dimm-levels. On the other hand a faster reaction may be desired for example when large sudden changes occur, e. g. when the blinds are shut. This can be realised by a variable steepness of the ramp function depending on the actual setpoint deviation.

The concept was implemented in the laboratory in 2009 using an ELVIS server [6]. It maintains the required illuminance level in the whole room under all daylight conditions and thus solves the problems arising from fixed dimm-level offsets in the master/slave concept. The system performs with good ergonomic quality and does not attract attention or disturb students.

5 Conclusion

A new concept for daylight dependent constant light level control for large rooms with several groups of lamps has been developed and tested. It uses only one illuminance sensor inside and estimates actual daylight level and illuminance in the whole room from a light distribution model. The applicability of such a concept depends on the effort required during commissioning of such a system. To reduce complexity and installation time the modelling task must be condensed into a few parameters that can easily be determined. Therefore further work will focus on simplifying the representation of the information that is needed in the estimator.

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