Static Scalar Swarm Algorithms for Lighting

Andreas Rumsch, Lukas Kaufmann, Aliaksei Andrushevich, Martin Weber*, Rainer Kyburz, Alexander Klapproth

**iHomeLab, Lucerne University of Applied Sciences and Arts,
CH-6048 Horw, Switzerland.**

***now with Zühlke Engineering AG,
CH-8952 Schlieren, Switzerland.**

Abstract

Since a sizeable amount of electrical power is consumed by lighting, saving energy in this field is important to reach the goals of the energy transition. Using LED lamps contributes an essential amount of savings. Even more energy can be saved by illuminating only when, where and as much as necessary.

Lighting systems consist of an array of lamps. An on-demand and good-enough lighting at each working place can be realized by equipping each lamp with light and presence sensors, by adding intelligence and communication abilities to them and by using suitable control algorithms. Since the proposed setup has similarities with a swarm, swarm optimization algorithms are potentially good candidates. Further a decentralized swarm setup has the advantage of low hardware requirements and no central controller is needed.

We evaluated swarm algorithms regarding energy savings and user comfort. Based on the rules for swarm algorithms we designed various swarm algorithms and simulated their illumination control. We compared these swarm algorithms with conventional approaches. The results of the simulations were evaluated regarding the energy consumption and how accurate and constant the illumination is.

The linear optimization algorithm showed the best results concerning energy consumption and stability. The investigated swarm algorithms tended to be less stable and predictable. Linear optimization requires a central processing unit with considerable computational power however, which might make the retrofit of existing installation impractical. Therefore further work is necessary to improve the stability of the swarm algorithms and to verify the simulation results in a test setup.

Introduction

The amount of electrical power consumed for lighting is not negligible. The total electrical energy consumption in Switzerland is about 59.9 TWh/a (2010). 14% (8.3 TWh/a) thereof is consumed by lighting where public, industrial and commercial buildings contribute with 10% (5.9 TWh/a) and private buildings with 4% (2.4 TWh/a) [1].

In [1], it is estimated that the consumption will increase until 2035 up to 71.8 TWh/a. Then the percentage of lighting will be 13% (9.2 TWh/a) with public, industrial and commercial buildings contributing 9% (6.5 TWh/a) and private buildings 4% (2.7 TWh/a). This extrapolation is based on the population development and the increasing needs of consumers.

With respect to technological developments, the author of [1] predicts a potential for electrical energy saving for lighting of 40% in public, industrial and commercial buildings whereas the potential is 60% in private buildings. Main reason for this saving is due to the technological development, particularly the change from incandescent lamps to LED – technology. Further potential offers the use of intelligent control of lighting: light only when and where and in the amount it is needed.

Currently, there are two types of products on market that make first step into the direction of intelligent control of lighting. The simpler systems are stand-alone products that often combine an occupancy sensor with an illuminance sensor and an actor to control a light. Thereby, one occupancy sensor is mostly used to control a number of lights, e.g. all the lamps in a room. A setup with one such occupancy sensor per light is rarely used on one hand for cost reasons and on the other hand because each occupancy sensor works independently from the others which can be uncomfortable because the surrounding of the person will be dark. Particularly when walking, it’s like walking against a dark wall.

The currently available complex lighting systems, so called lighting control systems, consist of a network of connected devices like sensors (occupancy) and actors (switches). The connection can be hardwired or wireless and is based on a uniform communication protocol such as. KNX, DMX, DALI. Hardwired communication systems need cables that have to be installed on top of power cables. That could be eliminated by the use of wireless technology like for example ZigBee, Bluetooth, WLAN or 6LoWPAN. Both cases are however realized with a central managing unit. The information of the sensors is processed by the central unit which then controls the lights using the actors. With such systems the comfort can be augmented by not only switching on the lights where people are present but also to dim the surrounding lights a little bit.

In this paper we will look at a system where the sensors for occupancy and illumination are integrated into the lamp. Additionally a microprocessor is built in to control the light depending on the sensor signals. The lamp is equipped with means for wireless communication. Therefore a lamp can control the light also dependent on other lamps. There is no need to install cables or to have a central unit. Such a lamp can be seen as an individual of a swarm and using swarm optimization algorithms allows the use of microprocessors with low power and low resources. The behaviour of a swarm can be more complex than the behaviour of its individuals. With the approach of swarm optimization we pursued mainly two goals: 1. lower the energy consumption of a lighting system and 2. an accepted comfort for the users. As the sensors and the processor are integrated into the lamp there is no need for further installations. This solution helps in retrofit situations: only the lamps have to be exchanged.

In the next chapter, the investigated swarm algorithms are described in detail. We also introduce the simulation tool that was used to assess the various algorithms. The corresponding results and discussion are provided in the following chapter.

They show that the best results concerning energy consumption and stability are obtained by linear optimization that was used as a baseline. Swarm optimization algorithms are still promising with regards to energy consumption but lack in stability and predictability. Further work needs to be done to improve the swarm optimization algorithms and to verify the obtained simulation results in a test setup. A motivation for the additional work is that solutions with a central processing unit are impractical for retrofitting.

Swarm algorithms: a new approach for lighting control

To address energy consumption, user comfort and easy retrofitting the idea of using swarm algorithms for lighting control was pursued. We look at every lamp being a single individual of a swarm. There is no central management unit like a building automation system or a server that controls the lighting. But every lamp communicates with the neighbours to optimize the illuminance and energy consumption. This approach doesn’t need high performance computers in each individual.

Goals

For a lighting system – particularly in public, industrial and commercial buildings – we prosecute two main goals:

- Energy saving
- Accepted comfort (minimal illuminance of 500 lux for office work places, low variation in illuminance)

Energy saving

Energy saving in lighting system can be achieved by change of technology of the illuminant. Changing to LED results in a potential in energy savings from 60% (compared to fluorescent tubes) up to 90% (compared to incandescent lamp).

Further savings can be realized by controlling the lighting. Many a time in a room every lamp is switched on although it’s not necessary because at certain places there is no person. Therefore the system shall only illuminate when it is needed (not sufficient natural light) and where it is needed (presence of people). It is aimed to save up to 50% energy by controlling the lamps dependent on illuminance and presence compared to a lighting system without a controlling system.

Comfort

The illumination at a person's location must have a value according to the appropriate standards. For an office work place the illumination shall reach at least 500 lux.

If lighting is controlled only considering existing illuminance and presence of people this can lead to uncomfortable situations: the place where people is located is illuminated according to the requirements but the surrounding areas are dark. Particularly if a person is walking along a corridor this feels like walking against a dark wall.
Therefore the controlling system has to illuminate the neighbouring areas of the location of people as well but with less luminosity.

Another aspect of comfort is the variance in luminosity. As described in [2] constant light and slowly varying light (period more than 5 min) is accepted well. This is also valid if the frequency of variation is higher than 30 Hz. Light variations between 0.67 and 18 Hz are perceived as most distracting. Therefore a lighting system has to regulate the light in a way that it doesn't produce varying light with periods shorter than 5 min, except when conditions change like a person entering a room.

Swarm Algorithms

Generally spoken an individual in a swarm acts depending on what it perceives from the environment. The environment can be both: a dangerous situation like an obstacle or a predator where the individual has to pass around or the behaviour of neighbouring individuals which influences the own behaviour. Two approaches to swarm algorithms that seem suitable for lighting control are particle swarm optimization and boids, see e.g. [3][4][5][6] and references within.

Particle Swarm Optimization

Particle Swarms are used to solve optimization problems. The lighting system can be seen as an optimization problem with the goal to reach the lowest possible energy consumption with an illumination considering the comfort of the users. Particle swarms realize the optimization by comparing the value to optimize at current location against the individuals and the global best solution already computed. Therefore the lamps illuminance is controlled in a way that the energy consumption is as low as possible but also respects the before mentioned conditions of minimal illumination and comfort.

Particle swarms consist of particles moving around the search space. For a lighting system we have two kinds of space: 1. the spatial distribution of the luminaires and 2. the value (in our case the energy consumption) to search an optimum for. Neighbours are defined through the spatial distribution not through proximity in search space. The particles (luminaires) that are spatial close are neighbours.

In our further investigation we use as the fitness function the energy consumption that shall be minimized. For simplicity we assume that energy consumption is proportional to the brightness of the light and that the brightness is controlled by a dim factor df. The fitness function becomes a scalar function:

$$(1) \qquad fitness = f(df)$$

Each particle calculates its dim factor df as

$$(2) \qquad df(t+1) = df(t) + dr(t+1)$$

where dr represents the velocity. The velocity in this case is the rate at which the dim factor is changed and we call it dim rate. The dim rate is calculated as

$$(3) \qquad dr(t+1) = dr(t) + c_1 * r_1(t)[df_{best}(t) - df(t)] + c_2 * r_2(t)\left[\widehat{df}_{best}(t) - df(t)\right]$$

Here df_{best} is the best dim factor the particle has found since the first time step and $\widehat{df}_{best}$ is the best dim factor the particles neighbours have found since the first time step, c_1 and c_2 are acceleration constants that define the contribution of the cognitive and social components, and $r_1(t)$, $r_2(t)$ are random values to introduce a stochastic behaviour. The dim rate is set to fixed values when a light detects presence or absence respectively. This is necessary to get the particle accelerated to find a new optimum for the new conditions.

For stability reasons we damp the two acceleration constants with a factor d over time when the conditions are static. This is the case when people don't move around. The accelerations constants are reset to the initial values if conditions change, e.g. when people start moving.

$$(4) \qquad c_i(t+1) = c_i(t) * d$$

Using these equation leads to dim factors with value 0 what is equivalent to the lowest possible energy consumption. But then the condition of having enough illuminance at the place where a person stays is not fulfilled. Therefore a penalty function is introduced:

$$(5) \qquad penalty = f(illuminance, presence, df)$$

If presence is detected the penalty is higher the less illuminance we have. We also get a higher penalty if the illuminance is higher than the desired value of 500 lux.

Boids

Boids have been developed by Reynolds [6] and can explain the behaviour of bird flocks or fish schools. Boids base on three simple rules: Cohesion (move with the same speed as the others), Adhesion (move towards the centre of the others) and Separation (avoid collision with others). These three rules lead to a swarm that seems to be a single organism. For a lighting system the boids concept can be adapted so that lamps brightness depends on the brightness of the neighbours (Adhesion). The dim factor then is calculated according to (6) where df_{avg} is the average dim factor of the neighbouring luminaires that detected presence of people.

$$(6) \qquad df(t+1) = \begin{cases} df(t) + dr(t); & if\ df(t) < df_{avg}(t) \\ df(t) - dr(t); & if\ df(t) \geq df_{avg}(t) \end{cases}$$

The speed of change in brightness represented by the dim rate dr can be directed towards the average dim rate of the neighbours (Cohesion):

$$(7) \qquad dr(t+1) = \frac{1}{n} \sum_{i=1}^{n} dr_i(t)$$

We have not implemented the rule for separation. It's no problem when two individuals have the same dim factor. But we have introduced an additional rule that respects presence of people. In this case the minimal required illuminance must be reached and therefore the algorithm has to increase the dim factor with a higher dim rate dr:

$$(8) \qquad dr(t+1) = 2 * dr(t)$$

Simple Swarm

We also implemented a very simple algorithm where the dim factor of an individual is calculated depending on the illuminance and the presence of people. Only when no presence is detected the dim factor will depend on the neighbouring individuals that have detected presence.

$$(9) \qquad df(t+1) = \begin{cases} f(illuminance); & if\ presence\ detected \\ df_{avg}(t); & if\ no\ presence\ detected \end{cases}$$

Linear Optimization

To compare the results of the swarm optimization we use linear optimization. We search the minimum for the sum of dim factors of all luminaires:

$$(10) \qquad min\{c^T df \mid A * df \geq b, 0 \leq df \leq 1\}$$

where df represents a vector with the dim factors of each luminaire (to be determined), A is a vector of a conversion factor between dim factor and resulting illuminance of the luminaire and b is a vector of the constraints. For each luminaire b is determined in dependence of the presence of a person; it is 500 lux in case of presence, 0 else. c is a vector where each element has the value 1.

Simulation

For the simulation of a lighting system a room with 24 lamps was chosen. The layout of the room is shown in Figure 1. Here also the path a person is walking through the room can be seen.

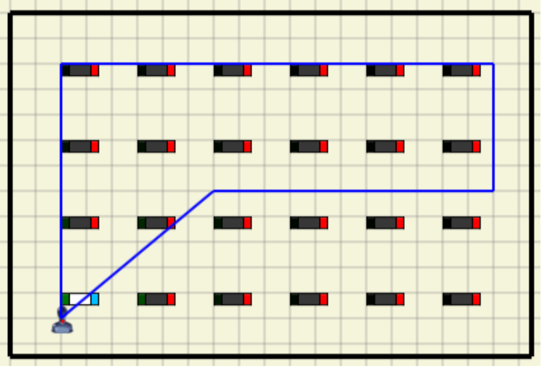

Figure 1: The layout of the simulated room with the path of a moving person

During a simulation that covers 55 seconds the person walks along the defined path. The dim factor of each lamp is calculated according to the chosen algorithm described in the previous chapter. The results of the simulation are the overall energy consumption and the illuminance at the location of the person walking through the room. The algorithms are then compared using these criteria:

1) energy consumption of all luminaires in the room
2) illuminance at the person's location
3) illuminance variability at the person's location

Concerning the energy consumption the best algorithm is that with the lowest energy consumption. We also compare it to a situation when all the luminaires are switched on all over the time. This comparison indicates the potential of energy savings compared to switch the luminaires manually. The luminaires have a standby power of 8 W with dim factor 0 and a maximum power of 146 W with the dim factor 1. In the case all luminaires are switched on the power consumption is

$$(11) \qquad P_{total,manual} = n_{luminaires} * P_{luminaire} = 24 * 146W = 3504\ W$$

The energy consumption during one simulation period of 55 seconds therefore is

$$(12) \qquad E_{total,manual} = P_{total,manual} * t_{simulationperiod} = 3504\ W * 55\ s = 192720\ Ws$$

The simulated illuminance is compared to the minimal required illuminance for an office work place of 500 lux. For the illuminance variability we look at the standard deviation of illuminance.

Results

The results of using swarm algorithms for a lighting controlling system have been compared to conventional algorithms. As relevant results with respect to the formulated goals, the energy consumption, the brightness at the persons location and the variation of brightness have been calculated in the simulation.

The results in Table 1 show the energy consumption, the illuminance and the variation of illuminance for the investigated lighting control algorithms.

Table 1: Energy consumption, illuminance and illuminance variability for the investigated lighting algorithms

Algorithm	Energy consumption [Ws]	Mean illuminance [lux]	Standard deviation of illuminance [lux]
Particle Swarm Optimization	40391	531	185
Boids	70857	530	126

Simple Swarm	60584	497	70
Linear optimization	39257	500	5

The swarm algorithms reach the nominal brightness quite good with the highest energy consumption and variation in brightness. The energy consumption can be explained by the fact that the lamps in the neighbourhood tend to have higher illuminance due to the algorithm.

The best result is obtained using a linear programming approach. This algorithm reaches the nominal brightness with the lowest energy consumption and the lowest variation of brightness.
Figure 2 gives an impression of the brightness over time for the algorithms. It clearly comes out that not all algorithms show a reasonable value of the variation of brightness. The illuminance obtained with linear optimization (LinOpt in Figure 2) shows the lowest variability whereas the particle swarm optimization (PSO in Figure 2) shows the highest variability regarding at the amplitude of the deviation from the nominal value.

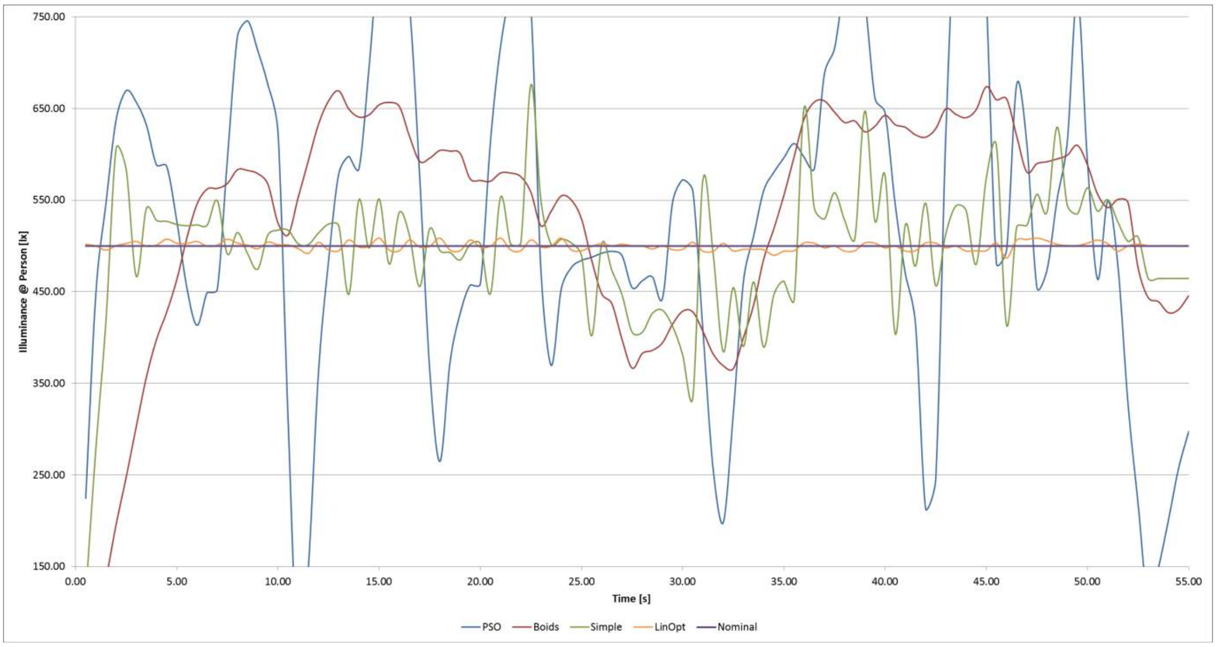

Figure 2: Comparison of the different algorithms where the illuminance at the person's location is shown over time

In Table 2 the energy consumption of the investigated algorithms is compared to the energy consumption a full illuminance (all luminaires permanent on) has, see equation (11). The potential of energy saving using intelligent algorithms for lighting control can reach 80%.

Table 2: Energy consumption and potential of energy saving for the investigated lighting algorithms.

Algorithm	**Energy consumption [Ws]**	**Energy saving [%]**
Particle Swarm Optimization	40391	79
Boids	70857	63
Simple Swarm	60584	69
Linear optimization	39257	80

Conclusion

Swarm algorithms seem ideal candidates for lighting control due to the low system complexity compared to centrally controlled systems. In this work, various such algorithms have been assessed through simulation the main criteria being energy efficiency. Results indicate that the energy consumption of the investigated swarm algorithms is from equal up to 75% higher compared to the optimization approach using linear programming that was used as a benchmark. Brightness variations are likewise significantly higher for swarm algorithms. The average variation of the swarm algorithms is about 30 times higher than the variation of the linear optimization algorithm.

Outlook

The approach of using swarm algorithms for lighting systems seems promising due to the mentioned advantages. But as has been shown, further work is required to optimize their energy consumption and reduce the variation in brightness. More algorithms and the parameters of them will therefore be examined.

Till now we have worked with simulation data. In a next step the simulation results have to be verified in a real world installation of a lighting system. In such a setup, comfort aspects of the lighting algorithms should also be assessed. In particular, the local distribution of illuminance in a room should be looked at because it is expected that the feeling of comfort of a person can differ significantly depending on this distribution. The comfort feeling probably also is dependent on the activity of the person, like sitting at the table or walking along a corridor.

References

[1] Nipkow Jürg, S.A.F.E. Factsheet, Tabelle Strom-Sparpotenziale, 2011. http://www.energieeffizienz.ch/dam/studien/2011_factsheet_stromverbrauch_2035_2050_dfi/pdf_de/SAFE_FS_Stromeffizienz_Tabelle_d.pdf

[2] Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg als Vorsitzland der Bund/Länder-Arbeitsgemeinschaft für Immissionsschutz (LAI), Hinweise zur Messung, Beurteilung und Minderung von Lichtimmissionen, 2012.

[3] Bonabeau Eric, Dorigo Marco, Theraulaz Guy, Swarm Intelligence From Natural to Artificial Systems, Oxford University Press, 1999.

[4] Engelbrecht Andries P., Fundamentals of Computational Swarm Intelligence, John Wiley & Sons, 2005.

[5] Kennedy James, Eberhart Russel C., Swarm Intelligence, Academic Press, 2001.

[6] Reynolds Craig W., Flocks, Herds and Schools: A Distributed Behavioural Model, Computer Graphics, 21(4), July 1987, pp. 25-34 (ACM SIGGRAPH '87 Conference Proceedings, Anaheim, California, July 1987.).