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DEVELOPMENT AND RESEARCH OF A MODEL FOR OPTIMAL CONTROL OF SMART HOUSE LIGHTING USING MATLAB

Pekh P., Geledchak V., Miskevych O. Development and research of a model for optimal lighting control of a smart home using Matlab. The article considers issues related to the development and research of a model for optimal lighting control of a smart home using Matlab. The lighting control system of a smart home consists of a number of interconnected elements that provide automatic, remote or intelligent control of light sources. In the work, however, the emphasis is placed on building a mathematical model of the functioning of the lighting control system of a smart home, assuming that the composition of its elements is well known to specialists. The objective function of the mathematical model is the loss function that needs to be minimized. This function consists of two parts. The first part takes into account losses from a lack of light, and the second takes into account losses from excessive use of artificial light (energy consumption). The program developed using Matlab uses the fmincon optimization method with the sqp algorithm (sequential quadratic programming) to find the best distribution of the desired value of artificial lighting. As a result of modeling the process of the lighting control system, optimal values of artificial lighting were obtained for each hour of the day. The corresponding graph is presented and analyzed. In our opinion, the proposed mathematical model and BrightLight program solve the problem of energy-saving optimization of smart home lighting.
Keywords: smart home, smart home lighting system, Matlab, Matlab Simulink, mathematical model

Пех П.А., Геледчак В., Міскевич О.І. Розробка та дослідження моделі оптимального управління освітленням розумного будинку засобами Matlab. У статті розглянуто питання, які стосуються розробки та дослідження моделі оптимального управління освітленням розумного будинку засобами Matlab. Система управління освітленням розумного будинку складається з низки взаємопов'язаних елементів, які забезпечують автоматичне, дистанційне або інтелектуальне керування джерелами світла. У роботі, однак, наголос зроблено на побудові математичної моделі функціонування системи управлінням освітлення розумного дому, вважаючи, що склад її елементів для фахівців добре відомий. Цільовою функцією математичної моделі вибрано функцію втрат, яку потрібно мінімізувати. Ця функція складається з двох частин. Перша частина враховує втрати від від нестачі світла, а друга враховує втрати від від надмірного використання штучного світла (енерговитрати). У програмі, розробленою засобами Matlab, застосовується метод оптимізації fmincon з алгоритмом sqp (послідовне квадратичне програмування) для знаходження найкращого розподілу шуканого значення штучного освітленняі. В результаті моделювання процесу роботи системи управління освітленням отримали оптимальні значення штучної освітленості впродовж кожної години доби. Відповідний графік наводиться та аналізується. На наш погляд, запропонована математична модель та програма BrightLight вирішує задачу енергозберігаючої оптимізації освітленням розумного будинку.
Ключові слова: розумний дім, система освітлення розумним будинком, Matlab, Matlab Simulink, математчна модель

Problem statement. A smart home (Fig. 1) is a residential space equipped with an automation system that controls engineering devices (lighting, heating, security, household appliances, etc.) in order to increase the comfort, energy efficiency, and safety of residents. In other words, a smart home is a system where all devices are combined into a single network and can interact with each other and with the user via a smartphone, tablet, voice commands, or automatic scenarios [1,2,3,7]. The main characteristics of a smart home are: automatic or remote control of systems (light, climate, security, multimedia); use of sensors (motion, temperature, humidity, smoke, etc.); ability to learn the system and adapt to user habits; integration with the Internet (IoT - Internet of Things). The lighting control system of a smart home is a component subsystem of a smart home [4,5,6]. An overview of various smart home lighting control systems is given in Table 1. One such system is the optimal lighting control system, which is investigated in this paper.

The level of natural light changes throughout the day. To constantly maintain the required level of lighting in a smart home room, for example, 500 lux, it is necessary to dynamically adjust the brightness of artificial lighting. But it is important not to simply add a certain amount of artificial light to achieve the desired level, for example, 500 lux. It is necessary to do this energy-efficiently - not to waste unnecessary electricity where there is already enough natural light. To solve this problem, we have developed and studied a mathematical optimization model.

The purpose of the study is to develop and study a mathematical model of smart home lighting control.

The novelty of the study. Mathematical models of lighting control make it possible to analyze system behavior, optimize energy consumption, and improve lighting comfort. There are known linear and nonlinear mathematical models, optimization models, feedback models, and stochastic models of lighting control. Each of the listed types of models uses an appropriate mathematical framework [1-3].

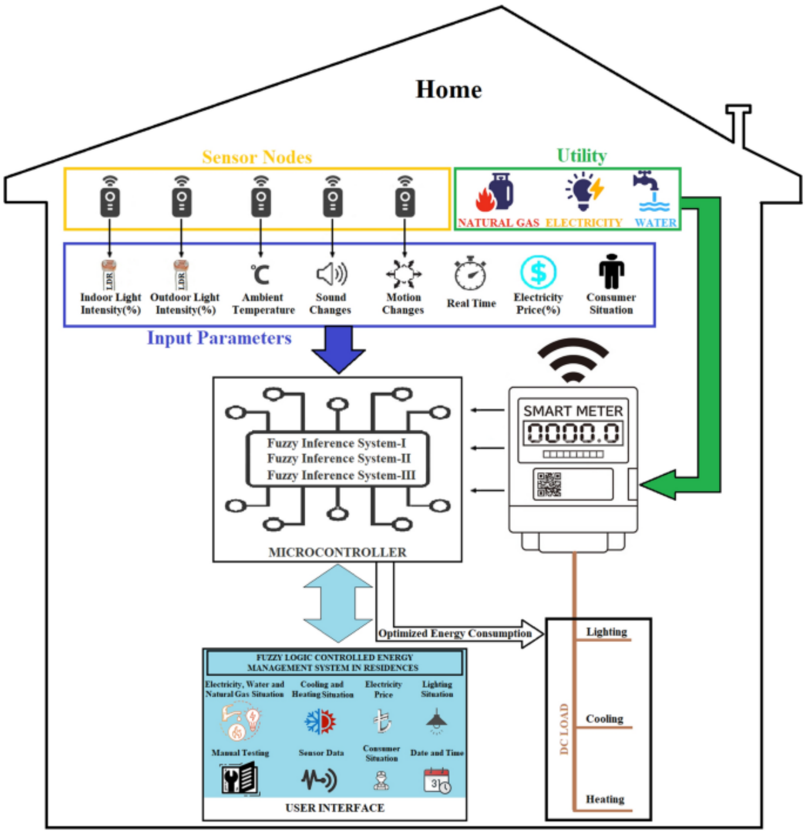

Fig.1 – Lighting control system as a component of the Smart Home system [1]

Modern systems often combine optimization, nonlinear, and feedback models to achieve maximum efficiency and accuracy [4,6]. The novelty of this research lies in the use of quadratic programming methods to construct a mathematical optimization model for controlling the lighting of a smart home and in the use of modern software tools for its implementation.

Smart lighting is to use sensors and network technologies to control light sources. The system consists of several key components.

Illumination sensors. Light sensors measure the level of natural light and transmit this data to controllers. This allows the system to automatically adjust the brightness of artificial lighting depending on external conditions.

Smart lamps. LED lamps with the ability to change the brightness and color of light are equipped with built-in modules for communication with controllers via Wi-Fi, Zigbee, Z-Wave or other protocols. Smart lamps can be integrated into various lighting devices, including lamps, chandeliers, wall and ceiling lamps.

Controllers and software. Controllers collect data from sensors and transmit commands to smart lamps. They can be separate devices or integrated into other components of the system. The software allows you to configure lighting scenarios, plan schedules, and control the system using mobile applications or voice assistants (for example, Google Assistant, Amazon Alexa).

The main part.

Building a mathematical model. The objective function of the model should minimize deviations from the set level of illumination with minimal use of artificial light.

Let us denote the input data and the desired variable of the optimization model:

L_t – target lighting level (500 lux).

L_n – list of natural lighting values during the day (for example, 24 hours).

L_s – value of artificial lighting for each hour (these are the values that needs to be found).

Table 1 – Overview of smart home lighting control systems

System name	Purpose / function	Implementation type	Sensor examples	Actuators	Difficulty level
On/off lighting when a person is present	Automatically turn on the light when a person appears	MATLAB script + Simulink model	PIR sensor (motion, presence)	Relay, LED lamp	Low
Daylight dimming	Brightness adjustment depending on the level of daylight	Code + Simulink block diagram	LDR / photodiode / light sensor	PWM-controlled LED driver	Medium
Cinema scene	Dim light plus colored LED scene	MATLAB script + Simulink model	—	RGB LED strip / dimmable lamp	Low
Timer scenario "turn off at 23:00" Timer scenario "turn off at 23:00"	Timed light switch-off	MATLAB script	—	Relay, lamps	Low
Distributed control (rooms plus controller)	Multiple zone control via central hub	Code (network modules)	PIR sensors, LDR sensors in rooms	Relay, dimmers, LED lamps	Medium - High
Intelligent presence prediction	Motion/activity prediction and lighting preparation	MATLAB algorithm / Simulink	PIR, ultrasonic, historical data	LED lamps, dimmers	High
Remote control via cloud (IoT)	Light control via internet/app	MATLAB + Simulink + IoT blocks	Combination of sensors (PIR, LDR)	IoT relay, smart LED	High
Integration with security (motion sensor)	Light switch-on in case of alarm or movement	Code / Simulink	Motion sensor, door sensor	LED spotlight, relay	Medium
Optimization of energy consumption	Minimum light taking into account daylight	MATLAB / Simulink algorithm	PIR + LDR / brightness sensors	Dimmers, LED lamps	High
Visualization in MATLAB GUI	Light and room status control interface	MATLAB GUI	(receives data from other systems)	Virtual buttons, control panels	Medium

Then the objective function, i.e. the loss function, of the mathematical model takes the following form:

$$\sum_{t=1}^{24}\left(max\left(0, L_t-(L_n+L_s)\right)^2+0.01L_s^2\right) \rightarrow min. \quad (1)$$

The first part of the expression takes into account losses from lack of light. The second part takes into account losses from excessive use of artificial light (energy consumption).

Let us transform the objective function so that quadratic programming methods can be applied to find the optimal values of artificial lighting. For this purpose, we introduce an auxiliary variable

$$d_t = \max\left(0, L_t-(L_n+L_s)\right), \quad (2)$$

which means the deficiency of illumination at time t.

Then the mathematical model of the problem takes the form

$$\begin{cases} \sum_{t=1}^{24}(d_t^2 + 0.01L_s^2) \to min; \\ d_t \geq L_t - (L_n + L_s); \\ d_t \geq 0; \\ L_s \geq 0. \end{cases} \quad (3)$$

We have obtained a quadratic programming problem to which standard library solution methods can be applied. The quadratic programming problem has the following standard form:

$$\frac{1}{2} * \|X^T\| * \|Q\| * \|X\| + \|C^T\| * \|X\| \to min, \quad (4)$$

where the solution matrix ‖X‖ for our problem of size 48*1 has the form

$$= \begin{pmatrix} L_s(1) \\ \dots \\ L_s(24) \\ d_1 \\ \dots \\ d_{24} \end{pmatrix}; \quad (5)$$

the auxiliary diagonal matrix ‖Q‖ of size 48*48 has the form:

$$\|Q\| = diag(0.01 \dots 0{,}01\ 1\ \dots\ 1); \quad (6)$$

the values 0.01 are written on the diagonal of the first 24 lines of the matrix ‖Q‖, and units are written on the diagonal of the remaining 24 liness; all other elements of the matrix ‖Q‖ are equal to zero;

the matrix ‖C‖ takes into account the linear part of the model, which is absent in this case, therefore the transposed matrix-line $\|C^T\|$ contains only zero elements.

Implementation of the mathematical model using Matlab. The model is implemented using Matlab in the form of the BrightLight program, the main code blocks of which are given below.

Setting the target illumination level (500 lux) and forming the values of natural illumination.

```
% BrightLight.m
% Optimal lighting control in a smart home
% Single file: model formulation, solution, and plot with gray background
clear; clc; close all;
%  Target illuminance and natural light
Lt = 500 * ones(24,1);     % Target indoor illuminance (lux)
hours = (1:24)';           % Hours of the day
% Realistic indoor natural light model
% Peak at noon (~1200 lx), smooth decay, almost zero at night
Ln = max(0, 1200 * exp(-((hours - 12).^2)/20));
n = length(Lt);            % Number of time intervals (24 hours)
```

Formation of the matrix ‖Q‖ of the quadratic objective function and the matrix ‖C‖, which takes into account the linear part of the model

```
%  Quadratic cost matrix Q
Q = zeros(2*n, 2*n);
Q(1:n, 1:n) = 0.01 * eye(n);       % Penalty for artificial light usage
Q(n+1:2*n, n+1:2*n) = eye(n);      % Penalty for illuminance deficit
%  Linear term of the objective function C
C = zeros(2*n, 1);  % No linear terms in this case
```

Formation of matrices ‖A‖ and ‖b‖ of the main constraints of the problem

```
%  Constraints: -(Ls + d) ≤ Ln - Lt  <=> d + Ls ≥ Lt - Ln
```

```
A = zeros(n, 2*n);
b = zeros(n, 1);
for t = 1:n
    A(t, t) = -1;        % Coefficient for -Ls(t)
    A(t, n+t) = -1;      % Coefficient for -d(t)
    b(t) = Ln(t) - Lt(t);% Right-hand side
end
%  Variable bounds: Ls ≥ 0, d ≥ 0
lb = zeros(2*n, 1);  % Lower bounds
ub = [];             % No upper bounds
```

Solving a quadratic programming problem

```
%  Solve the quadratic programming problem
options = optimoptions('quadprog','Display','none');
[X_opt, fval] = quadprog(Q, C, A, b, [], [], lb, ub, [], options);
```

Formation of solution vectors for the problem

```
%  Extract solution
%% -----------------------------------------------------
Ls = X_opt(1:n);         % Optimal artificial light
d  = X_opt(n+1:2*n);     % Illuminance deficit
totalLight = Ln + Ls;    % Total indoor illuminance
```

Output of numerical values of solution results

```
%  Display results
disp('Optimal artificial light L_s:');
disp(Ls);
disp('Illuminance deficit d:');
disp(d);
disp('Minimum value of the objective function:');
disp(fval);
```

Construction of daily schedules of natural, artificial and total lighting

```
%  Plot results with gray background
figure;
ax = axes;
ax.Color = [0.9 0.9 0.9];   % Light gray background
plot(hours, Ln, '-o', 'LineWidth', 2); hold on;
plot(hours, Ls, '-o', 'LineWidth', 2);
plot(hours, totalLight, '-o', 'LineWidth', 2);
plot(hours, Lt, '--k', 'LineWidth', 2);
xlabel('Hour of day');
ylabel('Illuminance (lux)');
title('Lighting Optimization in a Smart Home');
legend('Natural light L_n', 'Artificial light L_s', 'Total light', 'Target L_t');
grid on;
```

The program uses the quadprog optimization method to find the best distribution of the desired L_s values. As a result, we obtained the optimal values of artificial lighting for each hour of the day. The graph of this dependence is shown in Figure 2. The program will calculate the most economical lighting option for each hour to reduce electricity consumption, but not reduce user comfort.

Practical significance of the study. The results obtained can be implemented as part of an IoT system for managing office or home lighting, since:

- natural light, which is simulated realistically throughout the day (night → day → night), can be easily replaced with values obtained from light sensors;
- artificial light is turned on only when natural light is insufficient;
- the deficit is minimized due to the optimal distribution of artificial light.

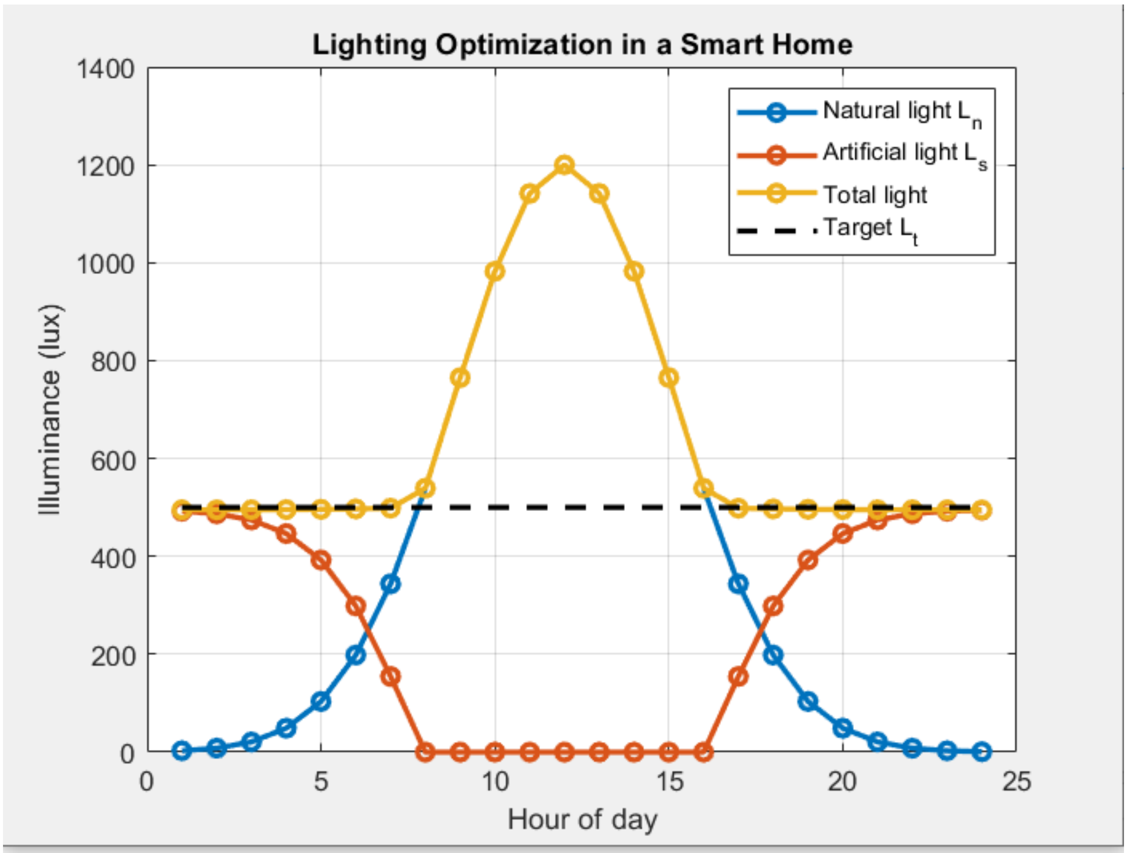

Figure 2 – Hourly schedule of natural, artificial and general lighting during the day

Conclusions.

The proposed mathematical model and BrightLight program solves the problem of energy-saving optimization of indoor lighting by automatically determining how much artificial light needs to be added at each moment in time to achieve the desired level of illumination, while minimizing energy consumption.

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