# Adaptive Smart Lighting Control based on Genetic Algorithm

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*Abstract*

**Smart lighting system plays an important role in smart homes because of its convenience comparing with boring and tedious on/off switches. With conventional smart lighting systems, users can easily change the lighting level of a room with a smart phone or voice control device. However, design an automated lighting system with energy saving is still a challenge.**

**In this paper, we propose an adaptive smart lighting system using a control algorithm based on Genetic Algorithm (GA). Our system turns on and off lights that match the user's desire brightness and utilizes nature illuminance efficiently to save as much electric energy as possible. The control algorithm based on GA provides the optimized light turning pattern to the system and can adapt with the change of lighting environment and user requirement. Our evaluation results showed that the execution time of our algorithm is short enough to be used in real environment.**

*Keywords— Smart lighting, Genetic algorithm, MQTT, Home Gateway, API Server, natural illuminance, power consumption.*

## I. INTRODUCTION

With the high-speed development of computer and network technologies, a new paradigm of Internet of Things (IoT) that things around us such as RFID, sensors, electrical devices, etc. can connect to the Internet, which gradually becomes a reality. Smart homes are among widespread IoT applications because they can bring to users a comfortable living environment. Smart lighting system is one of the most basic and essential systems for smart homes. In a smart lighting system, a user can easily turn on or turn off each light in a room via a smartphone application to achieve his desired brightness level. However, it is a tedious task for him when the number of smart home services increase. Further, lights are energy-consumed since it is used for a long time every day. We can effectively reduce electrical energy consumption by utilizing natural illuminance and optimizing the light turning pattern. Thus, an automated smart lighting system consuming less energy with or without user control is essential. Two problems need to be considered when we design such a system. The first problem is how to determine the illuminance at a position when turning a light on or off and the second one is how to select the best light turning pattern.

A number of conventional researches on smart lighting control have been done recently. For the first problem, one approach is to use a lighting model such as ray tracing or light's propagation model to calculate the distribution of light illuminance or natural illuminance in a room [1, 2-4]. Local search or exhaustive search is then used to calculate optimized light turning pattern to satisfy users' desired brightness. This approach, however, requires precise information of room structure and light position, which are not easy to obtain, for lighting model building. Recently, with the strong development of AI, researchers have integrated AI into smart lighting systems so that the system itself will be able to make predictions from which control lights meet user expectations [5,6]. AI model can be used to represent the complex relationship between measured illuminance on the table and dimming levels of luminaires. However, these researches do not consider the use of natural illuminance, which changes dynamically over time.

In this paper, we focus on the realization of an adaptive smart lighting system, which can optimize light turning pattern to meet user desired brightness and save energy usage to the maximum by utilizing natural illuminance efficiently. Furthermore, since natural illuminance may change over time and so are the user demand, our system monitors and adapts with the dynamic change of the light environment and user requirement. Furthermore, our system is easy to implement since it does not require detail information about room structure, nor light positions.

Our lighting control algorithm is built based on Genetic Algorithm (GA). The algorithm calculates the optimal light turning patern based on nature illuminance, light illuminance and user desired brightness level. The utilization of GA-based optimization algorithm can not only reduce the running time of the optimization algorithm to meet the requirement of real-time control but also give high accurate results.

We have designed and developed a prototype smart lighting system, which can be easily integrated and installed into residential homes. The experimental results showed the effectiveness of our proposed system. We also evaluated the performance of our GA-based optimization algorithm by simulation. The simulation results showed that our algorithm
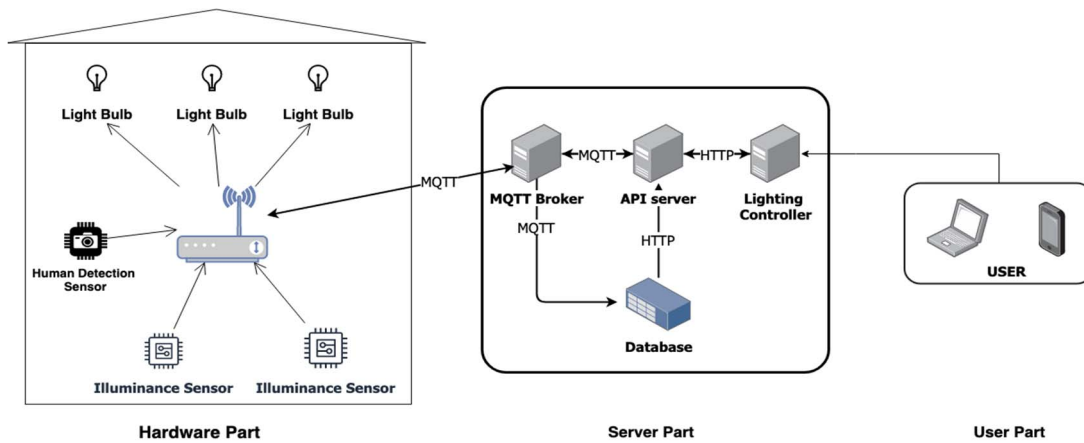
Figure 1: System overview

can achieve adequate accurate results but need small running time comparing with the case of exhaustive search.

The structure of the paper is as follows. In the next section, we will describe the related works and their limitations. We then describe our proposed adaptive smart lighting system using Genetic Algorithm in Section 3. In Section 4, we describe our prototype system and its performance. We also evaluate the performance of our GA-based light turning algorithm. The last section concludes the paper.

## II.   RELATED WORK

There are many conventional works focusing on optimizing light turning pattern to satisfy user desired brightness and save lighting energy.

The authors in the paper [1] proposed a method, which utilizes a lighting model built based on a combination of Octree and Ray Tracing. To be specific, Octree is used to divide rooms into multiple cubes and Ray Tracing is used to analyze light rays. They also used Local Search algorithm to optimize the light turning pattern. However, the authors did not consider the energy saving problem in the paper.

There are several studies that take advantage of natural illuminance to put forth lighting control scenarios as well as energy saving [2-4]. In the paper [2], the authors proposed a lighting control method which divides room into multiple regions, each of which is affected by natural illuminance differently. The pattern of controlling lights is given for each region and is optimized for energy savings. Kontadakis el. al. proposed the utilization of movable mirrors installed on a light shelf, which are able to track the sun. Natural illuminance is diverted into the core of the building to replace electric light. In the paper [4], Pandharipande el. al. proposed an energy-efficient illumination control method for LED based lighting systems in office spaces. User locations are detected by ultrasound array sensors. Natural illuminance and illuminance of lights are measured by photosensor in real-time. Information about light illuminance and user locations is used to optimize turning light pattern to minimize the energy consumption of the system. These methods can save lighting energy by the use of natural illuminance, but they all require accurate information of the structure of the room and light positions to calculate the distribution of natural illuminance and light illuminance. This information is not easy to obtain by normal residents of smart homes.

Besides, smart light systems are being developed towards integration with artificial intelligence [5,6]. Paulauskaite-Taraseviciene el. al. [5] have used ANN based intelligent lighting control with online learning for smart home systems, which has the capability to adapt to the resident behavioral patterns in various environmental conditions. An algorithm based on data similarity threshold was proposed in order to produce decisions for a more accurate and adaptive lighting control. However, the algorithm cannot be applied for residents with conflicting behavior which prohibits its application to office spaces. In the paper [6], the authors proposed a lighting energy optimization algorithm based on a development model, which represents the complex relationship between measured illuminance on the table and dimming levels of luminaires. The utilize the model to optimize the illumination level of the distributed luminaires to minimize the energy consumption of the system and meet the individual lighting preferences of each office user on their table. However, this research does not consider the use of natural illuminance for energy savings.

A number of researches offer hardware and software design solution for smart lighting systems to control lights and save energy [7,8]. In the paper [7], the authors proposed a light control system using wireless sensor network for user location identification. Each light has a wireless power transmitter, which transmits energy to the sensors. From the user's location and a lighting model, the system calculates the optimized pattern to control the lights and save power consumption of the smart light system. However, in order to be able to calculate the illuminance of the lights in a room, detailed information such as light position, room size, which is not always available, is needed. In the paper [8], T. P. Huynh el. al. have used a wireless sensor network with a star topology. The data collected from the sensor network is processed at a computer, which sends control signals via DALI (i.e. digital addressable lighting interface) to control lights.

## III.  PROPOSED SOLUTION

### 3.1. System Overview

We propose a lighting control system which can automatically turn on/off lights in a room in order to not only satisfy the demanding brightness level of residents, but also save the energy of the whole system. Our smart lighting control algorithm use Genetic Algorithm to optimize the light turning pattern.
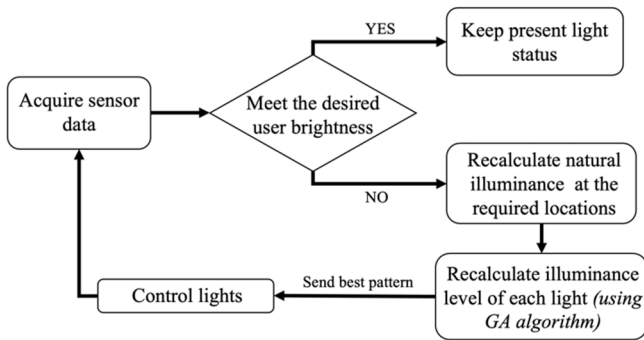
Figure 2. Lighting control to adapt with the change of natural illuminance and user desired brightness level



Figure 3. Modelling a room with a number of lighting areas

Our proposed system contains 3 main components: The hardware part inside the home, the server part and the user part (Fig. 1).

The hardware part in the home includes light devices, human detection sensors and illuminance sensors. These devices communicate with a special device called Home Gateway by a network protocol such as Zigbee or Echonet Lite [9]. The Home Gateway is responsible for collecting data from illuminance sensors and human detection sensors and sending the data to the server part via MQTT protocol [10], a well-known IoT protocol for data collection, to MQTT Broker. The home gateway also receives on/off commands from server part and send them to light devices.

The server part, which is responsible for data storage and data processing, include following elements.

- MQTT broker: A server for MQTT clients to publish or subscribe for device information and control commands
- Database server: Responsible for saving information, such as users' information, device information, light illuminance information, ...
- API server: Allow lighting controller to communicate and send control commands to a home gateway
- Lighting controller: Using Genetic Algorithm to generate optimal light turning patterns based on current natural illuminances and demanding illuminance level at a specific location.

These server elements can be located on cloud servers and shared with other smart home services.

The last component is the user part, which is a mobile app to monitor and control the smart lighting system inside their house. Sometimes, the desired brightness level calculated by the lighting controller based on use activity does not meet a user's desire. In that case, users can use Mobile App to adjust the desired illuminance level at their desire locations. The Mobile App also directly connects to the server part to receive information about smart lighting system.

Locations and behaviors of users will be detected by human detection sensors. User desired brightness level is then calculated based on the use activity. The detection methods of user location and activity are studied in many researches such as the ones in the paper [11], [12]. Therefore, we assume that human detection sensors can detect user location and activity and the solution for human detection problem is out of the scope of this paper.

In fact, the illuminance level at user's location does not remains stable over time. For instance, when a user opens a curtain or the sky turns dark in the evening, the natural illuminance will affectively change the current illuminance
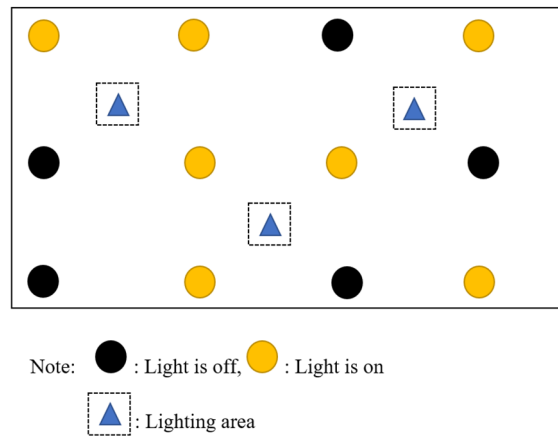
level at user's location. With that said, the light turning pattern needs to adapt to those changes. Besides, if the user's behavior or location changes, for example, a user may change his state from watching TV into reading book, the smart lighting system has to re-generate the light turning pattern that match the user's current state.

In order to adapt with the change of desired illuminance at user's location, the lighting controller gathers sensing data provided by illuminance sensors and human detection sensors, and then compares the present illuminance with user desired illuminance level. In each control period, if the illuminance level at user's location gathered from illuminance sensors fit to what the user expects, the light turning pattern still remains the same. However, if the illuminance level at user location exceeds or is less than a threshold, the lighting controller will re-calculate the natural illuminance at required locations (Fig. 2). The lighting controller then re-calculates the illuminance level of each light, using Genetic Algorithm to adapt with the change.

After sending light control pattern from the lighting controller, API Server will execute that pattern to send on/off request with different lighting illuminance level to Home Gateway. Home Gateway then sends those command into each individual Echonet Lite device via MQTT. The controlling result will be sent back to the users via Mobile app by API.

3.2. Control Algorithm

We propose a lighting control algorithm to provide a turning pattern which not only saves the energy, but also satisfies the demanding illuminance of users in a smart home. Our algorithm is built based on Genetic Algorithm which is suitable for solving metaheuristic problem with a very reasonable amount of running time.

We consider there are $M$ lights which have $C$ different illuminance levels in a room. We choose N lighting areas in the room, which are used frequently such as sofa area or television area. An illuminance sensor and a human detection sensor are placed at each lighting area in order to measure the illuminance and determine users' action in that area respectively. When users are detected in a lighting area, the system will supply illumination to them appropriately.

In order to control lights, we utilize 4 types of data.

- $Ln[j]$: natural illuminance of the $j^{th}$ area with $j = 0...N-1$. Natural illuminance is

- $L[i, j]$: illuminance of the ith light to the jth area with $i = 0...M-1, j = 0...N-1$.
- E[i]: energy consumption of the ith light *with $i = 0...M-1$*.
- D[i]: demanding illuminance of the jth area *with $j = 0...N-1$*. If there is no lighting demand in the jth area, *D[j] = -1*.

Natural illuminance at a lighting area and the illuminance of a light affecting to a lighting area are calculated based on the illuminance measured by illuminance sensors. We define *Ls[j]* as the illuminance measured by the illuminance sensor at the jth lighting area.

We divide the running process of the system into two periods, pre-optimization period and optimization period. At the beginning, when the system just starts, the illuminance of a light affecting to a lighting area is undetermined. Thus, in the pre-optimization period, the lights in a room are turned on/off in a simple control mechanism. When a user is detected at a lighting area and the user desired brightness is not satisfied, the system turns on each light in the room until the sensing illuminance reaches the user desired brightness.

During the pre-optimization period, the illuminance of a light affecting to each area is calculated based on the sensing illuminance values before and after the light is turned on. Concretely, if the illuminance of the jth area before turning on the ith light is *Ls' [j]* and the one after turning on the light is *Ls [j]*, then the illuminance of the ith light affecting to the jth area *L[i,j]* is calculated as follows.

$$L[i, j] = Ls[j] - Ls'[j] \ (1) \tag{1}$$

This calculation is repeated until all values *L[i,j], i = 0...M-1, j = 0...N-1* are calculated and stored into the database. At this moment, the pre-optimization period is finished and the system moves to the optimization period.

In the optimization period, the natural illuminance of the jth lighting area *Ln[j]* is calculated from the sensing illuminance *Ls [j]* at the jth lighting area and the illuminance of on-lights affecting to each area as follow:

$$Ln[j] = Ls[j] - \sum_{i=0}^{N_{on}-1} L[i, j] \tag{2}$$

Here, $N_{on}$ is the number of lights which are in on status in the room.

Furthermore, the lighting controller gets information about energy consumption of lights from light specification and estimate user demanding illuminance based on user position and user activity.

After collecting necessary data, the lighting controller find a light turning pattern $X = [x_0, x_1, ..., x_{M-1}]$ with $x_i$ is the illuminance level of the ith light. The light turning pattern X must ensure the demanding illuminance of users in a specific threshold and save the consumed energy to the maximum. To be specific, we have:

$$X = argmin_{x \in X} \sum_{i=0}^{M-1} E[i] * x[i] \tag{3}$$

*subject to*

$$\sum_{k=0}^{M-1} (L[k, j] * x[k]) + Ln[j] \geq D[j]$$

Our system analyzes illuminance sensor data to figure out natural illuminance and light illuminance at desired lighting area. It does not require the information of room structure, nor light position. Therefore, our system can be easily deployed in any smart home without complicated setup process.

In order to find an optimized light turning pattern, we can apply exhaustive search algorithm, but it has a complexity of $O(C^M * N)$. If the M is large, it takes a huge amount of time to run. Therefore, we choose genetic algorithm to solve our problem. The next subsection shows our proposed algorithm.

### 3.3 GA-based optimization algorithm

In general, genetic algorithm reflects the process of natural selection where the fittest light turning patterns are selected for reproduction in order to produce offspring of the next generation. At first, we propose the objective function in order to evaluate candidate light turning patterns in the population. The objective function is shown by equation F. The less the equation F is the better the candidate light turning pattern is.

In order to build objective function, we define $\Delta_j$ is the difference between the user desired illuminance and the actual illuminance achieved in the jth area:

$$\Delta j = D[j] - \sum_{i=0}^{M-1} (L[i, j] * x[i]) - Ln[j] \tag{4}$$

We define illuminance penalty *Pen[j]* is an exponential function to score the difference between the user desired illuminance and the actual illuminance achieved in the jth area in two cases:

$$Pen[j] = \begin{cases} \alpha^{\frac{\Delta j}{\beta}} & if \ \Delta j >= 0 \\ 0 & if \ \Delta j < 0 \end{cases} \tag{5}$$

With $\alpha$ and $\beta$ are constants which indicate illuminance threshold.

Objective function is built based on the total energy consumption of lights in the room and the penalty function:

$$F = \sum_{i=0}^{M-1} E[i] * x[i] + \sum_{j=0}^{N-1} Pen[j] \tag{6}$$

To be specific, $\sum_{i=0}^{M-1} E[i] * x[i]$ operand shows the energy consumption of the system when turning on the ith light at level *x[i]*. If the amount of illuminance measured in the jth area $\sum_{i=0}^{M-1}(L[i, j] * x[i]) + Ln[j]$ is smaller than the demanding illuminance *D[j]*, objective function will penalize *Pen[j]*. In contrast, if the amount of illuminance measured in the jth area $\sum_{k=0}^{M-1}(L[k, j] * x[k]) + Ln[j]$ is bigger than the demanding illuminance *D[j]*, the objective function will not need to add an amount of illuminance because redundant illuminance is illustrated in the increase of $\sum_{i=0}^{M-1} E[i] * x[i]$ operand.

We use exponential function to express the illuminance penalty while using linear function to express electricity consumption because we want to give priority to ensure the illuminance for users. For example, the system will choose a light turning pattern which provides enough illuminance to users instead of the one which consume less electricity but do not satisfy demanding illuminance.

We find that our control light problem and "Multi Knapsack"- a NP problem have many features in common. Therefore, the control light we proposed is based on a metaheuristic method - Genetic Algorithm. To be specific, a light turning pattern for our problem is considered as a chromosome which contains m genes. The ith gene is the illuminance level of the ith light. The fitness of a candidate
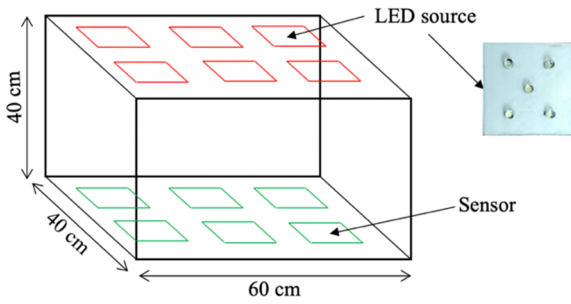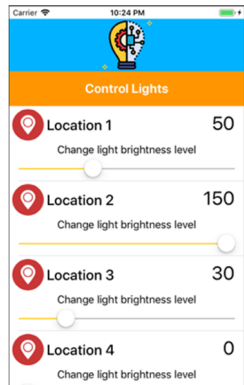
Figure 4. Prototype house design model



Figure 5. The UI of mobile app

light turning pattern (chromosome) is estimated by objective function F. All candidate light turning pattern is managed in a population and the light turning pattern with lower fitness will be removed from the population after a loop of selection process. To be clear, the process contains 5 steps: Initialization, Fitness Evaluation, Crossover, Mutation and Termination.

Step 1: Initialization: We create chromosomes in the population by a greedy algorithm. First, we choose randomly an area in which customers' demands illuminance. Next, we turn randomly some lights on which are near the chosen area until the real illuminance in the chosen area is bigger than demanding one. Each random turn contributes to the population a chromosome. We loop the random creation process until the number of chromosome reaches the limit K.

Step 2: Fitness Evaluation: We evaluate all chromosomes in the population by the objective function F.

Step 3: Crossover: We choose all pair of chromosome in sequence. With each pair, we choose randomly a point to divide each chromosome into 2 parts. Next, we create 2 new chromosomes by combining the first part of the first chromosome and the second part of the second chromosome and vice versa. Finally, we add 2 new chromosomes to the population.

Step 4: Mutation: At this step, we start to optimize locally chromosomes in the population. With each chromosome, we choose randomly a gene and change the value of the gene from 0 to C-1. We will add the new chromosome to the population if its fitness is on top of best fitness of the population.

Step 5: Termination: We save K best chromosomes and remove the rest of the population. Next, we return step 2. The process will end if the best chromosome in the population remains. The complexity of the control algorithm is

O($M*N*C*K$) with K is the maximum number of chromosomes maintained in the population.

## IV. EXPERIMENTS AND RESULTS

### 4.1. Experimental environment

We have built a prototype smart lighting system and installed the system within a plastic model house (Fig. 4). The model house has 6 smart lighting kits and 6 illuminance sensors which are controlled by 6 ESP8266 Wi-Fi module (Fig. 4). Smart lighting kits are installed on the roof of the model house and each of which contains 5 white LEDs, which represent 5 different brightness levels of a light. We use a BH1750 illuminance sensor to measure illuminance value at each lighting area. Besides, a Raspberry Pi board is installed within the model house as a Home Gateway.

We didn't install a human detection sensor inside the house because the human detection problem is out of the scope of this paper. Instead we implement a mobile app which allows a user to set his/her desired brightness level and send the level to Lighting Controller (Fig. 5).

We performed a number of experiences on our testbed environment to verify the operation of our system. We evaluate the difference between user desired brightness level and sensing illuminance controlled by our smart lighting system. The experimental results of 5 testcases are shown in Table 1. The value -1 of a lighting area means that there is no request at that lighting area.

In these testcases, the light turning pattern provided by the system almost satisfies illuminance demands of users. In first 4 testcases, we increased the number of requested lighting positions from 1 to 4. As shown in Table 1, the difference between requested illuminance and actual brightness at each position in each case is small (within 14.4%). In testcase 5, the system had to handle a massive difference amongst lighting requests from users. For example, a user who is reading a book requests more illuminance than the user who is sleeping. In that case, the system cannot handle those requests perfectly.

### 4.2. Convergence speed and solution quality

Because the number of lights in our prototype smart lighting system is small, we cannot sufficiently evaluate the performance of our GA-based optimization algorithm. So, we perform simulation to compare the performance of our algorithm with an algorithm using exhaustive search. We change simulation parameters including the number of lights M, the number of lighting area N and the level of lights C for each simulation. We evaluate two algorithms in two aspects, the runtime of a algorithm and the total energy consumption of the lighting system. Here, we define an energy unit as the energy consumption of a LED light.

| Testcase | No. of requested position | Requested illuminance value at each position (lux) | Actual brightness at each position (lux) |
|---|---|---|---|
| 1 | 1 | 100, -1, -1, -1, -1, -1 | 112, 24, 23, 24, 4, 4 |
| 2 | 2 | 120, 150, -1, -1, -1, -1 | 137, 144, 49, 49, 9, 9 |
| 3 | 3 | 50, 80, 100, -1, -1, -1 | 50, 72, 106, 34, 15, 15 |
| 4 | 4 | 50, 80, 100, -1, 85, -1 | 57, 72, 92, 68, 81, 27 |
| 5 | 5 | 20, 120, -1, 30, 150, 10 | 30, 125, 50, 55, 165, 35 |

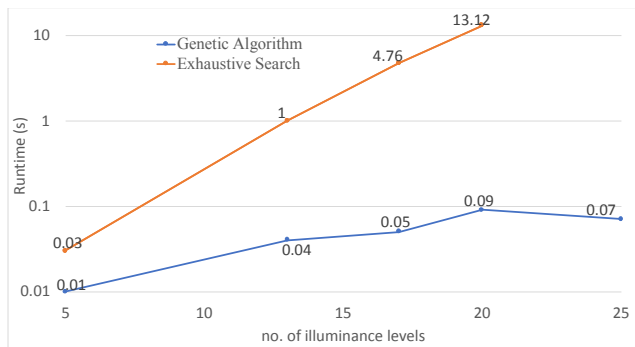Table 1. Results when system runs in real cases

Figure 6. Runtime of GA-based optimization algorithm and Exhaustive Search with different number of illuminance levels of a light
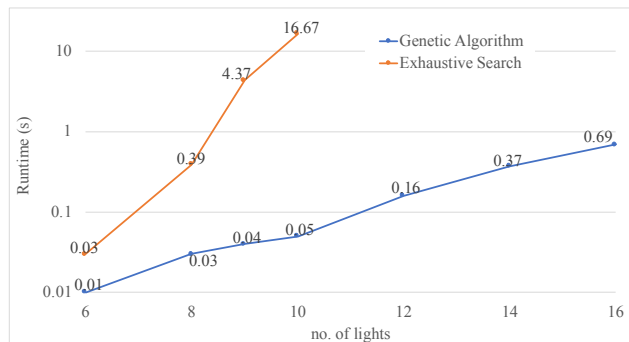


Figure 7. Runtime of GA-based optimization algorithm and Exhaustive Search with different number of lights in a room

We performed 5 testcases in which M and N is kept unchanged and C is change from 5 to 25, and 5 testcases in which N and C is kept unchanged and M is change from 6 to 16. Data about natural lighting illuminance in those test cases was randomly generated based on the data obtained from the model house.

In Fig. 6 and Fig. 7, the comparative results of our algorithms and exhaustive search can be seen. From the results of Fig. 6, when the number of illuminance level changes, our algorithm has a quite small runtime (i.e. under 0.1 seconds) while exhaustive search has a very large runtime. When the number of lights in a room increases (Fig. 7), our GA-based optimization algorithm still gives us a very impressive runtime (i.e. under 0.7 seconds).

Further, we compare energy consumption of light turning patterns which are generated from our algorithm and exhaustive search algorithm in Fig. 8. To be clear, we consider a turn-on led in a smart lighting kit consumes a power unit. Our algorithm can give a solution of light turning pattern which can satisfy user desired brightness level but as small consume electric energy as the solution given by exhaustive search-based algorithm while the runtime is much faster (Fig. 8).

## V. CONCLUSIONS

In this research, we have proposed a smart lighting system for smart homes, which utilizes an optimization algorithm based on Genetic Algorithm to calculate the pattern of turning lights on or off based on natural illuminance, light illuminance and user desired brightness, which can meet the desired user brightness while still minimizes electric energy consumption. Further, our system can adapt with the dynamic change of natural illuminance and user desired brightness level. We verified the effectiveness of our proposal by experiments on a
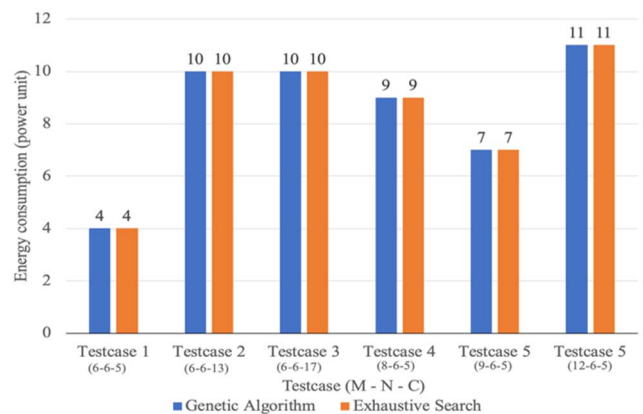


Figure 8. Comparing results of GA-based optimization algorithm and Exhaustive Search-based optimization algorithm

prototype system and performed simulations to evaluate the running time and the energy consumption of our GA-based optimization algorithm.

In the future works, we will integrate user location and activity recognition part to the system and work on various kinds of user demanding on lighting.

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