The Illumination Balancing Algorithm for Smart Lights

A Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

M. Taha Köroğlu, B.S.E.E.

Graduate Program in Department of Electrical & Computer Engineering

The Ohio State University

2012

Master’s Examination Committee:

Prof. Kevin M. Passino, Advisor

Prof. Andrea Serrani
Abstract

In this thesis, we present two decentralized algorithms that aim to achieve uniform lighting across the floor of an experimental testbed under a variety of challenges including cross-illumination effects and external light disturbances. These challenges cause over-illuminations in the environment that result in a waste of energy and discomfort to the occupants. First, a decentralized integral control approach that does not have any communication between the lights is developed and applied to the system. Due to its failure in achieving uniform lighting when the cross-illumination effects are maximized, a new decentralized method called the illumination balancing algorithm (IBA) is developed that takes the local light levels into account in adjusting the light voltages. The stability analysis of the IBA for the full height partitions case of the testbed is shown as well as the regulation problem results where the algorithm successfully balances the illuminations and hence achieves uniform lighting. In order to track a desired light level across the zones, the IBA is augmented with an integral control at an arbitrarily selected control loop. This combined algorithm achieved successful control even in a case where the decentralized integral control failed.
to Muaz and Emre...
Acknowledgments

First of all, I would like to thank my advisor Prof. Passino for his patience and guidance which made this work possible. He is an exceptional researcher and advisor. I am very fortunate to complete my MS studies under his supervision. I am also grateful to Prof. Serrani for accepting to be a member of my master’s examination committee. I am lucky that I had the opportunity to benefit from him.

I thank Faruk Sezgin and Ahmed Şimşek for all their precious time they allocated to me. I thank İbrahim Aydoğan for his sincere friendship. I thank Orhan and Fuat Kansu for all the things they supplied me unrequitedly since I was a little boy. Verily, I wouldn’t have reached this far without their helps.

I thank Coşku Kasnakoğlu and Ünver Kaynak for their support. I genuinely thank Esat Kondakçı and Enes Yılmaz for their guidance in my application to OSU. I wish the very best for them in their lives.

In Columbus city, I have been assisted by Mücahid Kutlu, Talip Gönülal, Öğuz Kurt, Ali Adah, Fatih Akyol, A. Erdem Sarıyüce, Hüseyin Acan, Mehmet Tomaç, Ahmet Çakanel, Serkan Biçici and Fatih Ölmez. I thank them all for their helps. I genuinely thank Savaş Pamuk for the effects he provided me. I thank Hayrettin Odabaşı for guiding me in my application to ECE graduate program. I thank Abhijit Bansal, Kishore Sai and Jaeyong Park for their helps and friendship. I appreciate
the assistance of Ted Pavlic and Zhongkui Wang in \LaTeX{}. Finally, I thank Sary, Mohammed Alsolami, Ketan, Pratik, Yazan and Saranya for their various helps.
Vita

March 6, 1986 .......................... Born - Bursa, TURKEY

2008 .................................B.S.E.E. - Ankara, TURKEY

Fields of Study

Major Field: Electrical Engineering
## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Dedication</td>
<td>iii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>iv</td>
</tr>
<tr>
<td>Vita</td>
<td>vi</td>
</tr>
<tr>
<td>List of Figures</td>
<td>ix</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Overview</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Thesis Outline</td>
<td>4</td>
</tr>
<tr>
<td>2. Smart Lights Experimental Testbed</td>
<td>5</td>
</tr>
<tr>
<td>2.1 Experimental Testbed</td>
<td>5</td>
</tr>
<tr>
<td>2.1.1 A Model Building and Light-Sensor Layout</td>
<td>5</td>
</tr>
<tr>
<td>2.1.2 Photosensors and Interface Circuity</td>
<td>7</td>
</tr>
<tr>
<td>2.1.3 Microcontroller and Data Acquisition</td>
<td>8</td>
</tr>
<tr>
<td>2.1.4 Bulbs and Interface Circuity</td>
<td>10</td>
</tr>
<tr>
<td>2.1.5 Overall System</td>
<td>12</td>
</tr>
<tr>
<td>2.2 Sensor Calibration</td>
<td>13</td>
</tr>
<tr>
<td>2.2.1 Why Sensor Calibration Is Required?</td>
<td>13</td>
</tr>
<tr>
<td>2.2.2 Calibrating the Raw Sensor Outputs</td>
<td>16</td>
</tr>
<tr>
<td>2.2.3 Testbed Dynamics</td>
<td>18</td>
</tr>
</tbody>
</table>
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The testbed and zone layout</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>Light dependent resistor (LDR)</td>
<td>7</td>
</tr>
<tr>
<td>2.3</td>
<td>Voltage divider circuit that is used as interface circuitry to DS1104 hardware and the raw sensor output according to given circuit.</td>
<td>8</td>
</tr>
<tr>
<td>2.4</td>
<td>DS1104 R&amp;D controller board</td>
<td>9</td>
</tr>
<tr>
<td>2.5</td>
<td>A screenshot from the ControlDesk® user interface</td>
<td>10</td>
</tr>
<tr>
<td>2.6</td>
<td>Simulink® real-time model</td>
<td>11</td>
</tr>
<tr>
<td>2.7</td>
<td>TIP120 Integral Circuit</td>
<td>12</td>
</tr>
<tr>
<td>2.8</td>
<td>Pictorial representation of the overall smart lighting system</td>
<td>13</td>
</tr>
<tr>
<td>2.9</td>
<td>A picture of the overall system</td>
<td>14</td>
</tr>
<tr>
<td>2.10</td>
<td>Raw sensor data when the zones are excited with a voltage sweep in the applicable range</td>
<td>15</td>
</tr>
<tr>
<td>2.11</td>
<td>Calculating the slope of the linear region of the raw sensor output</td>
<td>16</td>
</tr>
<tr>
<td>2.12</td>
<td>Input-output characteristics after sensor</td>
<td>17</td>
</tr>
<tr>
<td>2.13</td>
<td>Calibrated sensor outputs</td>
<td>18</td>
</tr>
<tr>
<td>2.14</td>
<td>Dynamics of the smart lighting testbed</td>
<td>19</td>
</tr>
</tbody>
</table>
3.1 Intuitively designed algorithm in the $i^{th}$ control loop .......... 22
3.2 Convergence to desired light level with heuristic design .......... 23
3.3 Actual light levels (full height partitions case) ................. 25
3.4 Voltage signals applied to bulbs (full height partitions case) ...... 26
3.5 Actual light levels (half height partitions case) ................. 27
3.6 Voltage signals applied to bulbs (half height partitions case) ...... 27
3.7 External light disturbance generated in order to test for daylighting . 28
3.8 Actual light levels (daylighting) ..................................... 29
3.9 Voltage signals applied to bulbs (daylighting) ..................... 30
3.10 Energy consumption of the bulbs in daylighting test ............. 30
3.11 Actual light levels (no partitions case) ............................ 32
3.12 Voltage signals applied to bulbs (no partitions case) ............. 32
3.13 All actual light levels together for the first five seconds of the experiment 33
3.14 Increment in the cross-illumination effects when half height partitions are removed ........................................... 35
4.1 A network of processors for executing tasks ....................... 37
4.2 Topology used in the illumination balancing algorithm ............ 38
4.3 Block diagram of the zone 1 closed loop in the regulation problem .. 47
4.4 Actual light levels (regulation problem, full height partitions) .... 47
4.5 Voltage signals applied to bulbs (regulation problem, full height partitions) ........................................... 48
4.6 Actual light levels (regulation problem, full height partitions) .... 48
4.7 Voltage signals applied to bulbs (regulation problem, full height partitions) ........................................... 49
4.8 Actual light levels (regulation problem, half height partitions) . . . . 50
4.9 Voltage signals applied to bulbs (regulation problem, half height partitions) ........................................... 51
4.10 Actual light levels (regulation problem, half height partitions) . . . . 51
4.11 Voltage signals applied to bulbs (regulation problem, half height partitions) ........................................... 52
4.12 Actual light levels (regulation problem, no partitions) . . . . . . . 53
4.13 Voltage signals applied to bulbs (regulation problem, no partitions) . 53
4.14 Actual light levels (regulation problem, no partitions) . . . . . . . 54
4.15 Voltage signals applied to bulbs (regulation problem, no partitions) . 54
4.16 Block diagram of the zone 1 closed loop control system in the tracking problem ........................................... 56
4.17 Actual light levels (tracking problem, full height partitions) . . . . . 57
4.18 Voltage signals applied to bulbs (tracking problem, full height partitions) . 58
4.19 Actual light levels (tracking problem, half height partitions) . . . . . 59
4.20 Voltage signals applied to bulbs (tracking problem, half height partitions) . 59
4.21 Actual light levels (tracking problem, half height partitions, daylighting) 60
4.22 Voltage signals applied to bulbs (tracking problem, half height partitions, daylighting) ........................................... 61
4.23 Actual light levels (tracking problem, no partitions) . . . . . . . 62
4.24 Voltage signals applied to bulbs (tracking problem, no partitions) . . 62
Chapter 1

INTRODUCTION

1.1 Overview

Energy conservation has become a crucial research topic due to the increasing demand for energy by today’s developing world. Exhaustion of energy resources and considerable environmental issues (e.g., ozone depletion, global warming) point to the necessity of research that aims to avoid energy waste. Among various components of overall energy consumption, lighting represents a major one. It consumes close to 15% and 35% of the electricity used in residential and commercial buildings, respectively in the U.S. [1, 2]. Along with the energy usage of 11% in industry [3], lighting uses about 18% of the electricity. Commercial buildings account for close to 71% of this 18% overall lighting electricity use. For this reason, the smart lighting applications mostly focus on commercial buildings.

Automatic lighting controls can reduce lighting energy consumption by 50% in existing buildings [4, 5]. These lighting control systems gained popularity in recent years as they pay for themselves quickly due to considerable reduction in energy usage. The energy savings is provided by avoiding redundant illumination (i.e., over-illumination). Over-illuminations occur due to multiple artificial lights in the ceiling
and/or daylight penetrating the room. In a shared-space office, a light illuminates not only the cubicle under it but also rest of the cubicles at different levels depending on the distance. The contribution of a light to the light level of the other cubicles is the “cross-illumination effect” of the particular light. When these cross-coupling effects arise, lighting control starts to require communication between the lights in order to obtain a desired light level across the room.

Wireless sensor networks (WSN) are used in some lighting applications. They provide a global communication between the lights. The nodes send the data to a central controller (i.e., centralized approach) in a WSN. A smart lighting problem in a shared-space office is formulated into a linear programming problem under the assumption that the light level at a particular point in the environment is the summation of light from each luminaire in [6, 7]. The problem is solved with a centralized control strategy by using a WSN.

In addition to cross-illuminations, external daylight is another challenge in lighting control. The lights take advantage of natural light in order to use the least amount of energy necessary to uniformly light a room. The concept of utilizing sunlight for illumination is called “daylighting” or “daylight harvesting.” When integrated with photosensors, the system saves considerable energy by attenuating artificial lights in response to daylight. The centralized control strategy developed in [8] adapts to the presence of natural light and provides a significant reduction in electric light usage. The authors investigate how a WSN can be used to adjust the lights to illuminate only the spaces receiving inadequate natural light in [9].
Some lighting control systems take occupant preferences into account and hence provide maximum comfort to users. The research in [10] focuses on occupant satisfaction and acceptance in office buildings with different structures. All offices have daylight responsive systems and daylighting is studied in terms of user reactions and energy savings. User preferences are considered as constraints in the linear programming approach in [6, 7].

The smart lighting systems that have the ability to tune the light levels focus on avoiding over-illumination to save energy. These systems can also detect under-illuminations that might occur when the daylight intensity decreases during the day (e.g., disappearance of the sun when the weather is cloudy), and tune the artificial lights. Moreover, some of the systems are equipped with sensors (e.g., ultrasonic sensors, passive infrared sensors, cameras) that can detect if a part of the room is not occupied for some time [11]. The system can shut down the lights which are responsible for the illumination of the unoccupied areas. The combination of these two functionalities (i.e., tuning the light levels and turning the lights on/off) results in the highest energy savings in buildings.

In addition to energy savings, some evidence indicates that exposure to daylight reduces stress [12]. A study of the effect of daylighting on sales performance is given in [13]. Results have shown that there is an important relationship between daylight availability in buildings and human factors that affect sales performance. Benefits of daylighting are studied in [14].
1.2 Thesis Outline

This thesis is organized as follows. Chapter 2 describes the experimental testbed. It shows the zone-layout, photosensors, and the interface circuitry. The microcontroller is shown along with the algorithm development environment associated with it. The sensor calibration is described. Also, a quick look at the dynamics of the smart lighting system is given which results in an important assumption that is going to be used in algorithm development later on. Chapter 3 describes an intuitive approach to the lighting system and shows how this method analytically coincides with a well known control scheme. The designed controller is applied to the testbed with a decentralized approach for all partition height cases. In the half height partitions case (where commercial buildings are emulated), the experiment for daylighting is shown as well. Chapter 4 describes the load balancing in processor networks problem, and shows the transition from this problem to the “illumination balancing algorithm” (IBA). Stability analysis of the algorithm for the full height partitions is given. The regulation problem is explained and experimental results are shown for this case. In order to track a desired light level in the testbed, a new algorithm that combines the IBA and integral control is developed. Tracking problem results are shown at the end of this chapter. Chapter 5 provides the conclusions and future directions for this research.
Chapter 2

SMART LIGHTS EXPERIMENTAL TESTBED

Smart light control requires a well equipped testbed in which the cross-illumination and external light disturbance challenges can be observed. A testbed with multiple lights and sensors will be described here. In addition, algorithm development environments are presented in order to explain the overall feedback system. The calibration process is portrayed explicitly. A brief look at the system dynamics is given at the end of the chapter.

2.1 Experimental Testbed

2.1.1 A Model Building and Light-Sensor Layout

A small box is used as the testbed as shown in Figure 2.1. This testbed is a physical model of residential, commercial and industrial environments; by using cardboard partitions at different heights, the effects of multiple rooms in a building are emulated (e.g., cubicles in an office building). Eight miniature incandescent bulbs (#1847) are placed in the top of the box as shown in Figure 2.1 (a) and (c). To sense the illumination levels in each zone, eight Cadmium-Sulfide photocells (#276-1657) are fixed directly under the lights on the bottom of the box. In this way, eight zones are defined; each zone consists of a bulb and the sensor under it. A pictorial representation
Figure 2.1: (a) The box viewed with its lid closed. The yellow wires are the outputs of TIP120 Darlington transistors and the black wires are common ground. (b) Zone layout from top view. (c) Interior of the box. A photocell is placed at the bottom of each zone. Half height cardboard partitions are shown in this picture which partially isolate the zones from each other. At the left side, a bulb is used to emulate daylighting effects.

of the testbed and how the bulb-sensor pairs are numbered can be seen in Figure 2.1 (b). In Figure 2.1 (c), note that, all the zones do not have an identical size (e.g., zones 7 and 8 are larger than zones 5 and 6).

One of the major challenges in smart light control is to overcome the effects of external lights by adjusting the voltages on artificial lights. If the illumination in the environment increases due to external lights such as daylight, then the lights should be dimmed to converge back to desired light level in the environment. This is called as
“daylighting.” To test the designed algorithms under this challenge, an incandescent bulb is placed at the left side of the box that can be seen in Figure 2.1 (c). Note that the external light will most significantly impact zones 1 and 2 as they are closest to the external light.

2.1.2 Photosensors and Interface Circuity

Light dependent resistors (LDR) are utilized to sense the light levels at the bottom of the box (see Figure 2.1 (c)). As its name implies, the resistance of an LDR varies when the light intensity falling on it changes. If there is no light on an LDR, its resistance is infinite; it behaves as an open circuit. When the light intensity falling on it increases, the resistance of the LDR decreases. By using this principle, the light level can be converted to a voltage signal with a voltage divider circuit. Hence, the light level will be measured in Volts in the experiments although the unit for light intensity is lux. The divider circuit along with its simulation can be seen in Figure 2.3. In the figure, the raw sensor output, $y_{\text{raw}}(t)$, grows when the illumination on the LDR increases. Eventually, the light levels will be proportional to the applied light voltages in the testbed.

![Light dependent resistor (LDR)](image)

Figure 2.2: Light dependent resistor (LDR).
2.1.3 Microcontroller and Data Acquisition

A microcontroller is required to take the raw light levels in, to calibrate them, and then to produce voltage signals to be applied to bulbs according to the calibrated light levels. dSPACE DS1104 R&D hardware is used as the microcontroller in the experiments. This board is mounted on a free PCI slot of a PC; it has microprocessors, timers, memory and an interrupt control unit embedded in it to process the data. It provides comprehensive I/O ports; analog to digital converter (ADC) channels, digital to analog converter (DAC) channels, serial interfaces (RS232, RS485 & RS 422), incremental encoders, PWM channels, and digital input-output ports to interact with the outside world. A picture of the DS1104 hardware is shown in Figure 2.4.

The DS1104 is installed with the software ControlDesk®, which provides several types of visualization methods for real-time data. This software is associated with MATLAB®; the captured data can be saved as a data file that MATLAB® supports.
In this way, data are transferred to MATLAB® for illustrations and post-processing. A screenshot from ControlDesk® software is shown in Figure 2.5.

The DS1104 and ControlDesk® are used in many university laboratories in conjunction with MATLAB-Simulink®. MATLAB-Simulink® is used for implementing the design that is going to run on the microcontroller. The user can graphically configure all I/O ports provided by the Real Time Interface (RTI), insert the supported blocks from the Simulink® Library Browser into the model file to accomplish the algebraic operations required in the design, and generate the code via Real Time Workshop®. The real-time model is compiled, downloaded and executed automatically. If more complicated mappings are required in the designed algorithms, the DS1104 supports the use of MATLAB® Embedded Function blocks in which the design can be implemented with code (e.g., MATLAB® code). Furthermore, in case
very efficient coding is needed (e.g., real-time image processing), S-Function blocks are supported in which the programming language C is used to implement the designed algorithms. A picture of the Simulink® real time model is shown in Figure 2.6.

2.1.4 Bulbs and Interface Circuitry

The miniature bulbs need current to illuminate the environment and the required amount cannot be supplied by the microcontroller. Moreover, the microcontroller
Figure 2.6: A screenshot from the Simulink® file that shows the operations running on the DS1104 hardware.

could be harmed if voltage signals at the DAC channels are directly applied to the bulbs. Therefore buffer circuits (see Figure 2.7) are utilized between the DAC channels of the microcontroller and the bulbs in order to provide the sufficient current to bulbs and to protect the DS1104 hardware. Buffers provide the required amount of current to the load (i.e., bulbs) from the power supply instead of the microcontroller while maintaining the voltage signal applied to it.

In the following experiments, the voltage signals from the DAC channels will be referred to when the bulb voltages are mentioned due to the fact that the gain of the buffer circuits is unity in theory. In practice, this gain could be slightly different from one. However, this fact will be neglected due to lack of ADC channels in the microcontroller; eight more channels are required to observe the bulb voltages.
Figure 2.7: TIP120 IC and its schematic diagram. TIP120 functions as a buffer between the microcontroller and the bulbs.

2.1.5 Overall System

The actual light levels should be converted to digital signals in order to process them in the microcontroller; therefore, ADC channels of DS1104 board are used in this operation. DS1104 provides 4 channels with 12 bit precision and 4 channels with 16 bit precision which are quite sufficient in this application. After sensor calibration (see below) and generating the voltage signals to be applied to bulbs, the output data are converted to continuous time signals via 16 bit DAC channels. Except ADC and DAC channels of DS1104 hardware, one of the digital output channels is used in generating repeatable identical external light disturbance to the testbed. An overall representation of the closed loop system is depicted in Figure 2.8. Note that the sensed light levels shape the voltage signals generated by the algorithm with feedback. When the experiment is running, the goal is to find the voltage signals on bulbs that
Figure 2.8: Pictorial representation of the overall smart lighting system. Here, $u_i$ denotes the applied voltage signal to the $i^{th}$ bulb, $y_{raw}^i$ and $y_i$ denote the raw sensor output and light level in the $i^{th}$ zone respectively, for $i \in \{1, 2, \ldots, 8\}$. The notation defined here will be used in algorithm development.

result in uniform illumination across the entire floor of the box even though there are cross-illumination effects and external light disturbances. In addition to pictorial representation, a picture of the overall set-up is shown in Figure 2.9.

2.2 Sensor Calibration

2.2.1 Why Sensor Calibration Is Required?

There is a trade-off between the quality of a sensor and its cost. Due to the cheap price of the LDRs, this trade-off is experienced in the testbed. Differences in sensor
ControlDesk Screen DS1104 is connected to a free 32-bit PCI slot in the PC test-bed Interface circuitry
DS1104 ADC channels
DAC channels
I/O board

Figure 2.9: A picture of the overall smart lighting system.
readings occurred when a voltage sweep is implemented at each zone. All the bulbs are excited with a ramp signal in the feasible range (0V-10V) in 10 seconds and the raw sensor readings are shown in Figure 2.10.

Figure 2.10: Applied input vs. raw sensor outputs (voltage sweep).

Photosensors have shown different characteristics under the same excitation signal. As an example, if the responses of zones 3 and 6 are compared, the light level of zone 3 is always higher than zone 6 except the dead zone observed at the beginning of the sweep (the dead zones are due to the threshold voltages of the transistors used in the buffer circuits and all the threshold voltages are in the 2V-3V region as can be seen in Figure 2.10). This voltage sweep experiment indicates that the calibration of the raw sensor data is essential in order to observe the same outputs under the same input signals.
2.2.2 Calibrating the Raw Sensor Outputs

It is observed in Figure 2.10 that all the zones behave approximately linearly in 4V-7V range. In this range, the slope of the line for zone \( i \) \( (m_i) \) is calculated as portrayed in Figure 2.11.

\[
m_i = \frac{y_{\text{raw}}(7) - y_{\text{raw}}(4)}{u(7) - u(4)}
\]

![Applied voltage vs. raw sensor output](image)

Figure 2.11: Calculating the slope of the linear region of the raw sensor output.

After finding the slope value \( m_i \), the raw sensor output \( y_{\text{raw}}(t) \) is scaled by \( 1/m_i \). Next, the bias value that belongs to zone \( i \) is determined and summed up with the scaled output signal \( y_{\text{scaled}}(t) \) in order to match 4V - 7V input region with the 4V - 7V calibrated sensor output region. If \( b_i \) is defined to be the bias value for zone \( i \), then the calibrated sensor output \( y_{\text{cal}}(t) \) is calculated as

\[
y_{\text{cal}}(t) := \frac{y_{\text{raw}}(t)}{m_i} + b_i 
\]

(2.1)

where

\[
b_i := 4 - y_{\text{scaled}}(4)
\]

(2.2)
Figure 2.12: Input-output characteristics after sensor calibration.

Note that bias value can also be defined as

$$b_i := 7 - y_{scaled}(7)$$

(2.3)

After these algebraic operations, the parameters required for sensor calibration are acquired. The result of this calibration process is depicted in Figure 2.12 for a single zone. Note that this illustration shows the matching of the linear region of input-output data in time.

If all raw sensor readings given in Figure 2.10 are calibrated by using the set of parameters determined previously, the results given in Figure 2.13 are obtained. Eventually, when a voltage value in the linear region (4V-7V) is applied to any of the bulbs, now, the same light level will be read by all the light dependent resistors.
2.2.3 Testbed Dynamics

Before starting to design a lighting control for the testbed, we examine an important assumption that will be utilized in the algorithm development. As already shown in Figures 2.10 and 2.13, the relationship between the bulb voltage signals $u_i$ and the corresponding illuminations $y_i$ are assumed to be static for all $i \in \{1, 2, \ldots, 8\}$. To clarify how this assumption became possible, light voltage and raw sensor output vs. time is shown in Figure 2.14. The transient response is rapid enough to assume that the relationship between the input and the output is static. Intuitively, this makes sense: When a change occurs in the light in a room, the corresponding variation in the illumination is immediately sensed by the human eye.
Figure 2.14: System response to step inputs. Due to very quick transient response, the dynamics can be ignored and the relationship between input and output can be considered as static. This assumption is already utilized in sensor calibration. It also enables the development of the algorithms that are going to be described in Chapters 3 and 4.
The smart lighting problem is amenable to intuitive approaches to control due to the static mapping between the inputs and the outputs of the system. Unfortunately, this mapping varies according to the cardboard partition heights (the room geometry) and the intensity of the external light (variation in the daylight during the day). Nevertheless, we have acquired useful information (in voltage sweep experiments) that can be exploited in controller design: When one of the bulb voltage signals increases (decreases), the corresponding zone light level increases (decreases) as well in the linear region. A heuristic algorithm based on this fact will be developed in this chapter.

3.1 Single Room Case

3.1.1 Intuitive Design

A single room is enclosed by full height cardboard partitions and consists of one bulb and one photosensor. Due to isolation of the room from outside, there will be no cross-illumination nor external light effects; only the bulb affects the actual light level in the room. The bulb is initialized with an arbitrary voltage signal. Subsequently, the error signal which is the difference between the desired light level and actual
light level is computed. The sign of the error determines if the voltage on the bulb should be increased or decreased. If over-illumination occurs in the room, then the sign of the error will be negative meaning that the light should be dimmed. On the contrary, when the actual light level is less than the desired light level, the sign will be positive and the bulb voltage should be increased to reach the desired light level in the environment. The voltage value that should be applied to the bulb in order to obtain the desired light level will be found easily with this simple intuitive approach. The algorithm is expected to be successful even when there are external light disturbances that will be introduced to the testbed to test for daylighting performance.

3.1.2 Implementation of the Algorithm

Discrete time notation will be used here due to the digital implementation of the algorithm. The microcontroller works on sampled data, so the running system will be step based. The current voltage signal on the bulb should be generated by using the previous applied voltage and the error. The expression for the algorithm is given as

\[ u(kT) = u(kT - T) + \alpha e(kT - T) \]  

(3.1)

where \( T \) denotes the sampling period, \( u \) refers to voltage signal on the bulb, \( e \) is for the error signal, \( kT \) and \( kT - T \) denote the current and the previous steps, respectively for \( k = 1, 2, 3, \ldots \). The design parameter is \( \alpha \) and it determines the speed of convergence. Considering that the algorithm will be applied to zones with a decentralized approach (i.e., there will be eight control loops), the block diagram of the algorithm is illustrated as a subsystem of the \( i^{th} \) closed loop system in Figure 3.1.
In the figure, \( y_i(kT) \) represents the actual light level, and \( d(kT) \) denotes the desired light level for all the zones.

The algorithm converges when \( \alpha > 0 \). When \( \alpha = 0 \), the illumination stays constant since there are no updates on \( u(kT) \). If \( \alpha < 0 \), then the algorithm diverges. For positive values of \( \alpha \), convergence speed is illustrated in Figure 3.2. Note that when \( \alpha \) takes greater values, the convergence speed increases dramatically. However, after some point, it causes oscillations.

### 3.1.3 Analytical Form that Coincides with the Heuristic Design

Before applying the algorithm to the testbed, we look at the linear difference equation given in (3.1) from another point of view. The expression describes the algorithm in the discrete domain. It is trivial to go to \( z \)-domain by using the definition of the unilateral \( Z \)-transform given as

\[
U(z) = Z\{u(k)\} = \sum_{k=0}^{\infty} u(k)z^{-k} \quad \text{(3.2)}
\]
where \( z \) is a complex number. When the Z-transform is applied to both sides of (3.1), the equation becomes

\[
U(z) = z^{-1}U(z) + \alpha z^{-1}E(z)
\]

(3.3)

If the terms are grouped together

\[
(1 - z^{-1})U(z) = \alpha z^{-1}E(z)
\]

(3.4)

we obtain

\[
C(z) := \frac{U(z)}{E(z)} = \frac{\alpha}{z - 1}
\]

(3.5)

If the numerator and denominator are multiplied by the sampling period \( T \)

\[
C(z) = \frac{\alpha}{T} \frac{T}{z - 1} = \frac{\alpha}{T} F(z)
\]

(3.6)

where

\[
F(z) := \frac{T}{z - 1}
\]

(3.7)
$F(z)$ is the expression for the “forward Euler numerical integration method.” Hence, $C(z)$ can be considered as an integrator with a gain of $\alpha/T$. Consequently, the relationship between the integral controller in control theory and the intuitive design here is

$$K_i = \frac{\alpha}{T}$$

(3.8)

where $K_i$ denotes the gain of the integral controller. Thus, it is shown that the heuristic algorithm coincides with nothing but an integral controller. The design parameter $\alpha$ can be considered as the gain of the integral controller due to proportional relationship with $K_i$. In the following experiments, $\alpha$ is selected heuristically as 0.001 (i.e., sampling period $T$), and this case corresponds to an integral controller with $K_i = 1$.

### 3.2 Decentralized Integral Control Results: Full Height Partitions

The heuristic algorithm is implemented for each zone separately for all three cases of partition heights. This means a decentralized approach is used. In this decentralized approach, the actual light level in a zone is sensed by the corresponding LDR and this signal is used in determining the bulb voltage value applied to that particular zone. None of the light voltages are produced by considering the light levels of the other zones. A bulb voltage depends only on the light level right under it which means there is no communication between the lights.

Full height partitions case is actually trivial as the cardboard partitions isolate all eight zones completely from each other; it is expected that all the light levels converge to desired light levels similar to Figure 3.2. Still, experimental results are
shown to complete an overall picture of the testbed. The actual light levels and the bulb voltages can be seen in Figures 3.3 and 3.4, respectively ($\alpha = 0.001$). In all the zones, actual light levels converged to desired light level quickly. All control loops produced very similar voltage signals.

3.3 Integral Controller Results: Half Height Partitions

3.3.1 Uniform Lighting

In this case, due to the reduction in heights of the cardboard partitions, cross-illuminations affect all the photosensors (i.e., each light affects all the sensors). Still, each bulb voltage will be adjusted only with respect to the feedback from the photosensor right under it (i.e., corresponding light level). Note that half height partitions
case corresponds to a shared-space office in real life due to partial isolation created by the cardboard partitions. Results are shown in Figures 3.5 and 3.6 ($\alpha = 0.001$).

Similar to the full height partitions case, actual light levels quickly converged to desired light level in all the zones. The decentralized integral control became successful in reaching uniform illumination under restricted cross-illumination effects. Notice that there is a drop in bulb voltage signals that results in desired uniform illumination (i.e., solutions) when Figures 3.4 and 3.6 are compared. This reduction makes sense as now the illumination in a zone is a combination of all lights. It is not required to apply voltage signals equal to the previous case to acquire the same uniform light level.
Figure 3.5: Actual light levels (half height partitions case).

Figure 3.6: Voltage signals applied to bulbs (half height partitions case).
Figure 3.7: External light disturbance generated in order to test for daylighting. When the signal is $5V$, the external light turns on.

### 3.3.2 Daylighting

In this section, in addition to cross-illumination effects, an external light disturbance is introduced to the testbed. A bulb mounted on the left side of the testbed is used for this purpose (see Figure 2.1 (c)). Naturally, this light will affect the light levels of the zones located at the left side of the testbed more than the others. As a disturbance, pulse signals are generated in the microcontroller as shown in Figure 3.7. Via digital output channel 1, this signal is applied to a power transistor that provides sufficient current to the bulb. When the digital signal is $5V$, the external bulb is turned on due to structure of the transistor.

Desired light level is 6 for all the zones throughout the experiment. The results are given in Figures 3.8 and 3.9. The responses of zones 1 and 2 are much more obvious than the other zones. Other zones only reacted slightly. Whenever the external light is turned on, over-illuminations occurred for a while. The algorithm reacted to over-illumination by reducing the voltage signals on the bulbs, and hence the light level converged back to desired illumination level. Similarly, when the external
light is removed, suddenly the actual light level became less than the desired level (i.e., under-illumination), and bulb voltages are increased by the algorithm. Integral control became very successful in rejecting the light disturbances; artificial lights (i.e., internal bulbs) are adjusted very quickly according to presence of external light.

In Figure 3.10, total energy consumption (i.e., sum of squares of voltage signals on the bulbs) is shown. The energy usage is reduced when external light is present inside the testbed. In reality, more energy can be saved depending on the window size at the walls. In modern buildings, architects now take the daylight into account when designing the room structures. Utilizing natural light as much as possible in illuminating the environments will result in huge energy savings. Saving energy by taking advantage of daylight in buildings is called “daylight harvesting.”

Figure 3.8: Actual light levels (daylighting).
Figure 3.9: Voltage signals applied to bulbs (daylighting).

Figure 3.10: Energy consumption of the bulbs in daylighting test.
3.4 Integral Controller Results: No Partitions

When the partitions are switched from full height to half height, it is seen via the reduction of the bulb voltage values that cross illumination effects are observed by the photosensors. All eight control loops are affected from the light levels in the other zones. Due to these effects, a “struggle” occurred between control loops, but fortunately this rivalry did not end bad for any of the zones. The light contributions are restricted with half height partitions and all light levels converged to desired light levels successfully. Now, in the case studied here, half height cardboard partitions are removed; so there are no partitions hence the effects of cross-illuminations will be maximized. For this case, the performance of the decentralized algorithm cannot be predicted as the cross-illumination effects will be observed at the highest level possible for the testbed. However, it is anticipated that there will be drops in the bulb voltage values if the uniform illumination can be obtained. Results are shown in Figures 3.11 and 3.12 ($\alpha = 0.001$).

Very interesting responses occurred in this case with the decentralized approach. All zone light levels except zones 5 and 6 converged to desired light levels. Zone 5 (obviously) and zone 6 (slightly) are over-illuminated, despite the fact that respective bulb voltages dropped to zero. This unsuccessful performance proves how crucial the cross-illumination effects are. In order to analyze why over-illuminations occurred in zones 5 and 6, all sensor outputs are plotted together for the first five seconds of the experiment in Figure 3.13. It is observed that the sensed light level in zone 5 converged to the desired light level much quicker than the others. The corresponding control loop started to dim the light in zone 5 right after a little over-illumination occurred in there. However, dimming the light could not pull down actual light level
Figure 3.11: Actual light levels (no partitions case).

Figure 3.12: Voltage signals applied to bulbs (no partitions case).
Figure 3.13: All actual light levels together for the five seconds of the experiment (no partitions case).

do desired level due to excessive cross-illumination effects on sensor 5. At about $t = 3$, the light level in zone 6 reached the target illumination and a similar response occurred in zone 6 too. It took more time for bulb 6 to drop to zero as the light level in zone 6 always stayed very close to other light levels. However, the control loop of zone 6 could not prevent over-illumination as well. Bulbs are turned off after some time and actual light levels remained higher than the desired light level. Eventually, the cross-illumination effects caused over-illuminations in the no partitions case. Without considering light levels of other zones in generating voltage signals to be applied to bulbs, it becomes difficult to obtain uniform lighting in the testbed.
3.5 Conclusions

At the end of this section, all raw sensor outputs are illustrated for a voltage sweep in zone 1 in order to point out the importance of the cross-illumination effects in the no partition case. As can be seen in Figure 3.14, the sensor readings in the rest of the zones increase significantly when half height partitions are removed. Especially in the adjacent zones (i.e., zones 2 and 3), the sensor readings become very close to sensor 1. These increments caused over-illuminations in the no partition case. Unpredictable intensive interactions will always occur between the individual control loops with any decentralized approach that does not have communications between the lights. In order to overcome the negative effects of these interactions, using other zone light levels as well as the corresponding light level in adjusting a light voltage might be useful. It is desired to minimize the light level information used in separate control loops. Notice that if the local communications cannot overcome the cross-illumination effects, then a global communication between the lights (i.e., a centralized approach) may be required in tuning the light voltages in order to achieve uniform lighting.
Figure 3.14: Increment in the cross-illumination effects when half height partitions are removed (all raw sensor data shown here are captured in zone 1 voltage sweep).
In the previous chapter, the decentralized integral control failed in the no partitions case. The analysis of the light levels revealed that the cross-illumination effects became a major issue that has to be considered in algorithm design. This chapter introduces a new approach that takes these coupling effects into account by using light level information of the surrounding zones in tuning the bulb voltage signals. Local communications between the bulbs will be used to counteract the cross-illumination effects and hence to acquire uniform lighting across the testbed.

4.1 The Illumination Balancing Algorithm

The “illumination balancing algorithm” (IBA) is inspired by the “load balancing in processor networks” problem [15, 16]. In the load balancing problem, the system consists of multiple processors running in parallel. Each processor has its own buffer in which computational tasks are queued and the processors cooperate in the execution of the tasks. The aim is to avoid under-utilization of processors by passing load between the buffers. A processor network is depicted in Figure 4.1.

In Figure 4.1, an arrow starting from the $i^{th}$ processor, and terminating at the $j^{th}$ processor means that the $i^{th}$ processor can sense the load level of the $j^{th}$ processor, and
pass load to it if its neighbor is less heavily loaded. As there is always another arrow starting from the $j^{th}$ processor and terminating at the $i^{th}$ processor, both sides can pass load to each other when there is an imbalance between the load levels. Naturally, there will be no load pass when the neighbor processors are equally loaded. Notice that processors might be passing and receiving load at the same time since there can be multiple neighbors (e.g., processors 1,2,4,5 have two neighbors). The change in the load level of a processor is the sum of these transfers.

The design problem in the processor network is how much load should be transferred between the neighbors at each step. Since load levels of neighbors are compared at every step, it is possible to make the amount of load transfer between neighbors proportional to the difference between the individual load levels. In this way, the load transfer will be big when the difference between the load levels is big (in order to balance the load as fast as possible). Also, there will be small transfers when the load levels become close in size.
When the problem is switched to the smart lights problem, the first issue that should be considered is the choice of topology (i.e., how the lights should be interconnected). As can be seen in Figure 2.1, the zone layout is appropriate for a variety of neighborhood definitions in the testbed. However, actually, it is the cross-illumination effects (see Figure 3.14) that should be taken into account in determining the topology due to the fact that these coupling effects provide the essential neighborhood information. When this fact is considered, the network given in Figure 4.2 is used for the testbed. It is seen in this figure that the local communications are compatible with the physical neighborhoods.

![Figure 4.2: Topology used in the illumination balancing algorithm. Notice that half of the zones (i.e., zones 1,2,7,8) have two neighbors and the others have three.](image)

In the load balancing algorithm, the transferred load variable is also the affected variable. Explicitly, some amount of “tasks” are transferred between the processors, and it is the number of “tasks” that is desired to be balanced. On the other hand, in the smart lighting problem, there are two different variables; light voltage signals and the actual light levels. It is the light levels that we want to balance (uniform lighting), however there is no direct way of passing illumination from one zone to another. At this point, a fact is utilized in applying the idea of load balancing to
the smart-lights testbed: When the voltage signal on the $i^{th}$ bulb varies, the most affected sensor is the one directly under it (i.e., $i^{th}$ sensor) for all three cases in the testbed (i.e., full, half, and no partitions) where $i \in \{1, 2, \ldots, 8\}$. This information is acquired by voltage sweep experiments in the zones, and an example for this is the zone 1 voltage sweep given in Figure 3.14. Hence, it becomes reasonable to increase (decrease) the $i^{th}$ bulb voltage when $i^{th}$ zone is under-illuminated (over-illuminated). The light levels are compared, but the voltage signals on the bulbs are transferred between the zones. This is the prime distinction from the original problem; here the transferred variable (i.e., voltage signals on the bulbs) is not the affected variable (i.e., light levels). The IBA has one more difference from the load balancing algorithm: In the load balancing problem, the sum of load transfers, and the load level change in the $i^{th}$ processor are the same. On the other hand, in the smart lighting problem, the total change in the $i^{th}$ bulb voltage, and the corresponding light level variation due to this change is approximately equal in the full height partitions case while these two variations are definitely not equal to each other in the half height and no partitions cases.

4.2 The IBA: Stability Analysis

4.2.1 Model: Full Height Partitions

The zones, $Z = \{1, 2, \ldots, N\}$, are all connected to a network (see Figure 4.2) along which the bulbs in these zones can pass voltage to their neighbors. The network of zones is described by a directed graph, $(Z, A)$, where $A \subset Z \times Z$. For every $i \in Z$, there must exist $(i, j) \in A$ in order to assure that every zone is connected to the
network, and if \((i, j) \in A\) then \((j, i) \in A\). Bulb \(i\) can only pass a portion of its voltage to bulb \(j\) if \((i, j) \in A\). Finally, if \((i, j) \in A\), then \(i \neq j\).

We begin by specifying the discrete event system (DES) model. Let \(Y = \mathbb{R}^N\) be the set of states and \(y_k = [y_1, y_2, \ldots, y_N]^T\) and \(y_{k+1} = [y'_1, y'_2, \ldots, y'_N]^T\) denote the states at times \(k\) and \(k + 1\), respectively. Let \(y_i(k')\) denote the light level at zone \(i \in Z\) at time \(k'\). Let \(e^{i,p(i)}_\alpha\) represent that zone (i.e., bulb) \(i \in Z\) passes voltage to its neighbors \(m \in p(i)\), where \(p(i) = \{j : (i, j) \in Z\}\). Let the list \(\alpha(i) = (\alpha_j(i), \alpha_{j'}(i), \ldots, \alpha_{j''}(i))\) such that \(j < j' < \ldots < j''\) and \(j, j', \ldots, j'' \in p(i)\) and \(\alpha_j \geq 0\) for all \(j \in p(i)\); the size of the list \(\alpha(i)\) is \(|p(i)|\). For convenience, we will denote this list by \(\alpha(i) = (\alpha_j(i) : j \in p(i))\). The amount of voltage transferred from bulb \(i \in Z\) to \(m \in p(i)\) is denoted by \(\alpha_m(i)\). Let \(\{e^{i,p(i)}_\alpha\}\) denote the set of all possible such voltage transfers. Let the set of events be described by

\[
E = \mathcal{P}(\{e^{i,p(i)}_\alpha\}) - \{\emptyset\}
\]  

(\(\mathcal{P}(Q)\) denotes the power set of the set \(Q\)). Notice that each event \(e_k \in E\) is defined as a set, with each element of \(e_k\) representing the passing of voltage by some bulb \(i \in Z\) to its neighboring bulbs in the network. Let \(\gamma_{ij} \in (0, 1)\) for \((i, j) \in A\) represent the proportion of the light level imbalance that is sometimes guaranteed to be reduced when bulb \(i\) passes voltage to bulb \(j\).

Now we specify the enable function \(g\) and the state transition operator \(f_{e_k}\) for \(e_k \in g(y_k)\). For all \(e^{i,p(i)}_\alpha \in e_k\), where \(\alpha(i) = (\alpha_j(i) : j \in p(i))\) and for \(F_i = F_i(u_i) = y_i\) it is the case that:

(i) \(\alpha_j(i) = 0\) if \(y_i \leq y_j\), where \(j \in p(i)\),

(ii) \(F_i(u_i - \sum_{m \in p(i)} \alpha_m(i)) \geq F_{j**}(u_{j**} + \alpha_{j**}(i))\), where \(y_{j**} = \min_j(y_j)\) for all \(j \in p(i)\), and
(iii) \( \alpha_j(i) = \gamma_{ij}(y_i - y_j) \), where \( j \in p(i) \).

If all conditions above hold, then event \( e_k \in g(y_k) \). Condition (i) prevents voltage from being passed by bulb \( i \) to bulb \( j \) if zone \( i \) is less illuminated than zone \( j \). Condition (ii) implies that after voltage \( \alpha(i) \) has been passed, the new light level at zone \( i \) must be at least as large as \( F_{j**}(u_{j**} + \alpha_{j**}(i)) \) where \( j** \) is the least illuminated zone among the neighbors of zone \( i \). To see that this expression holds, we need to examine the amount of voltage that is passed from the \( i^{th} \) bulb to its neighbors (i.e., \( \alpha_j(i) \)). In the implementation of the IBA, the amount of voltage pass from bulb \( i \) to bulb \( j \) is \( \alpha_j(i) = \gamma_{ij}(y_i - y_j) \) as given in condition (iii). It is easy to see that \( \alpha_j(i) \leq \alpha_{j**}(i) \) as \( y_i - y_j \leq y_i - y_{j**} \) if the parameter \( \gamma_{ij} \) is chosen as the same for all \( j \in p(i) \) (i.e., \( \gamma_{ij} = \gamma \)). It is seen in Figures 3.3 and 3.4 that in the full height partitions case, the bulb voltage is approximately the same as the sensor output, so \( F_i(u_i) \approx u_i \). Thus, (ii) becomes

\[
\alpha_m(i) \geq u_{j**} + \alpha_{j**}(i)
\]  

(4.2)

We need to verify that this expression holds as it is going to be required in showing the selected Lyapunov function is a non-increasing function in the stability analysis of the system. Expand \( \sum_{m \in p(i)} \alpha_m(i) \) in order to analyze (4.2) explicitly. We have

\[
u_i - \alpha_j(i) - \alpha_j'(i) - \ldots - \alpha_{j''}(i) \geq u_{j**} + \alpha_{j**}(i)
\]  

(4.3)

Here, \( j, j', \ldots, j'' \in p(i) \). If the amount of voltage pass defined in condition (iii) is substituted into (4.3) and we use \( \gamma_{ij} = \gamma \) for all \( j \in p(i) \) and \( F_i(u_i) = y_i \approx u_i \), we get

\[
u_i - \gamma(u_i - u_j) - \gamma(u_i - u_{j'}) - \ldots - \gamma(u_i - u_{j''}) \geq u_{j**} + \gamma(u_i - u_{j**})
\]  

(4.4)

We see in (4.4) that parameter \( \gamma \) functions as a scaling factor. It affects all voltage passes from the \( i^{th} \) bulb to its neighbors; therefore, the choice of this parameter will
define if (4.2) will hold or not. To understand how to select the parameter $\gamma$, consider the extreme case where $y_j = y_j' = \ldots = y_j''$ (i.e., all neighbors of zone $i$ has the same light level). In this case, the inequality in (4.4) becomes

$$u_i - N_i \gamma d \geq u_j'' + \gamma d$$  \hspace{1cm} (4.5)$$

where $N_i = |p(i)|$ and $d = u_i - u_j$ for all $j \in p(i)$. With manipulation, it yields

$$d = u_i - u_j'' \geq (N_i + 1) \gamma d$$  \hspace{1cm} (4.6)$$

To satisfy this inequality, $\gamma$ should be selected as $\gamma \leq 1/(N_i + 1)$. In the testbed, considering that a zone connected to the network has at most 3 neighbors according to Figure 4.2, if $\gamma \leq 1/4$, then condition (ii) will hold for full height partitions case.

If event $e_k \in g(y_k)$ and $e^{i,p(i)}_{\alpha(i)} \in e_k$, then $f_{e_k}(y_k) = y_{k+1}$, where

$$F'_i = F_i(u_i - \sum_{\{j:j \in p(i)\}} \alpha_j(i) + \sum_{\{j:i \in p(j), e^{(j,p(j))}_{\alpha(j)} \in e_k\}} \alpha_i(j))$$  \hspace{1cm} (4.7)$$

It might be also useful to see this relationship from bulb voltages point of view.

$$u'_i = u_i - \sum_{\{j:j \in p(i)\}} \alpha_j(i) + \sum_{\{j:i \in p(j), e^{(j,p(j))}_{\alpha(j)} \in e_k\}} \alpha_i(j)$$  \hspace{1cm} (4.8)$$

The $i^{th}$ zone bulb voltage at time $k + 1$, $u'_i$, is the voltage at time $k$ minus the total voltage passed by bulb $i$ at time $k$ plus the total voltage received by bulb $i$ at time $k$.

Let $E_v = E$ be the set of valid event trajectories. We must further specify the sets of allowed event trajectories. Define a partial event of type $i$ to represent the passing of $\alpha(i)$ amount of voltage from $i \in Z$ to its neighbors $p(i)$. A partial event of type $i$ will be denoted by $e^{i,p(i)}$ and the occurrence of $e^{i,p(i)}$ indicates that $i \in Z$ attempts to further balance its light level with its neighbors. Event $e_k \in g(y_k)$ is composed of a
set of partial events. Next we define the allowed event trajectories \( E_a \). For \( E_i \subset E_v \), assume that each type of partial event occurs infinitely often on each \( E \in E_i \).

Clearly, \( Y_b = \{ y_k \in Y : y_i = y_j \} \), for all \((i, j) \in Z\) is an invariant set that represents perfectly balanced light levels across the testbed. Notice that the only \( e_k \in g(y_k) \), when \( y_k \in Y_b \), are ones such that all \( e_{\alpha(i)}^i \in e_k \) have \( \alpha(i) = (0, 0, \ldots, 0) \) (i.e., there is no more voltage transfer between the bulbs when the uniform lighting is acquired in the testbed).

### 4.2.2 Asymptotic Convergence to a Balanced State

To study the ability of the system to automatically redistribute the bulb voltages to achieve uniform lighting across the testbed, a Lyapunov stability theoretic approach will be used. Let \( S(Y_b; r) \) be an \( r\)-neighborhood of \( Y_b \) where \( r > 0 \). Let the value of the function \( Y(y_0, E_k, k) \) be the state reached at time \( k \) from \( y_0 \in Y \) by application of event sequence \( E_k \) such that \( E_k E \in E_v(y_0) \) where \( E_v(y_0) \) is the set of valid event trajectories when the initial state is \( y_0 \in Y \). Let \( \bar{y} = [\bar{y}_1, \bar{y}_2, \ldots, \bar{y}_N]^T \). Choose

\[
\rho(y_k, Y_b) = \inf \{ \max \{|y_1 - \bar{y}_1|, |y_2 - \bar{y}_2|, \ldots, |y_N - \bar{y}_N|\} : \bar{y} \in Y_b \} \quad (4.9)
\]

**Theorem 1.** For the network described above, the invariant set \( Y_b \) is asymptotically stable in the large with respect to \( E_i \).

**Proof** [16]: Choose a Lyapunov function

\[
V(y_k) = \max_i \left\{ \frac{1}{N} \sum_{j=1}^{N} y_j - y_i \right\} \quad (4.10)
\]

\( V(y_k) \) always takes positive values except in a uniform lighting situation where it becomes zero. Mathematically, \( V(y_k) \geq 0, \forall y_k \). Notice that

\[
\frac{1}{N} \sum_{i=1}^{N} y_i \geq \frac{1}{N} \left( \max_i \{y_i\} + (N-1) \min_i \{y_i\} \right) \quad (4.11)
\]
It is clear from Equations (4.9), (4.10) and (4.11) that the following relations are valid.

\[ \rho(y_k, Y_b) \geq \frac{1}{2} \left( \max_i y_i - \min_i y_i \right) \]  
\[ \rho(y_k, Y_b) \leq \max_i y_i - \min_i y_i \]  
\[ V(y_k) = \frac{1}{N} \sum_{i=1}^{N} y_i - \min_i y_i \leq \max_i y_i - \min_i y_i \]  
\[ V(y_k) \geq \frac{1}{N} \left( \max_i y_i + (N - 1) \min_i y_i \right) - \min_i y_i \]

Equations (4.12) and (4.14) yield 
\[ 2 \rho(y_k, Y_b) \geq \max_i y_i - \min_i y_i \geq V(y_k) \]  
Equation (4.15) can be manipulated to yield 
\[ V(y_k) \geq \frac{1}{N} \rho(y_k, Y_b) \]

Equations (4.13) and (4.16) directly imply that 
\[ V(y_k) \geq \frac{1}{N} \rho(y_k, Y_b) \]

We must also show that 
\[ V(Y(y_0, E_k, k)) \]  
is a non-increasing function for all \( k \in \mathbb{N} \), all \( y_0 \in S(Y_b; r) \) and all \( E_k \) such that \( E_k E \in E_i(y_0) \). To see that this is the case, notice that once \( y_0 \) is specified, \( V(y_k) \) varies only when \( \min_i y_i = y_j^{**} \) varies. This least illuminated zone in the network cannot possibly pass voltage, so \( y_j^{**} \geq y_j^{*} \). Assume an event \( e_k \in g(y_k) \) occurs. According to condition \( (ii) \) on \( e_k \in g(y_k) \), if \( e_{a(i)} \in e_k \) and \( j^{**} \in p(i) \), it is not possible that \( y_j' < y_j^{*} + a_j^{*}(i) \). Therefore, \( \min_i y_i \geq y_j^{**} \) and \( V(y_{k+1}) \leq V(y_k) \). Thus, \( Y_b \) is stable in the sense of Lyapunov with respect to \( E_i \).

In order to show that \( Y_b \) is asymptotically stable in the large with respect to \( E_i \), it must be shown that for all \( y_0 \notin Y_b \) and all \( E_k \) such that \( E_k E \in E_i(y_0) \), 
\[ V(Y(y_0, E_k, k)) \to 0 \text{ as } k \to \infty. \]  
If \( y_k \notin Y_b \), then there must be some least illuminated
zone \( j^{**} \) (there may be more than one) and some other zone \( i \) such that \((i, j^{**}) \in A\) and \(y_i > y_{j^{**}}\). Because of the restrictions imposed by \(E_i\), we know that all the partial events are guaranteed to occur infinitely often. According to condition \((iii)\) on \(e_k \in g(y_k)\), each time partial event \(e^{i,p(i)}\) occurs, \(y_{j^{**}}\) is guaranteed to increase by a fixed fraction \(\gamma_{ij^{**}} \in (0, 1)\) of \(y_i - y_{j^{**}}\) so that \(y_{j^{**}}' > y_{j^{**}}\). Thus, for every \(k \geq 0\), there exists \(k' > k\) such that \(V(y_{k'}) > V(y_{k'+1})\) as long as \(y_{k'} \notin \mathcal{Y}_b\) so that \(V(Y(y_0, E_k, k)) \rightarrow 0\) as \(k \rightarrow \infty\) and \(\mathcal{Y}_b\) is asymptotically stable in the large with respect to \(E_i\).

4.3 The IBA: Regulation Problem

In this section, there are several groups of experiments. In each group, the sum of the applied bulb voltages is kept constant, and the system is released from a different set of initial bulb voltages. A variety of initial conditions are set, and we determine if the IBA can acquire balanced illuminations every time or not. It is important to note here that it is not known what the balanced light level will be if it can be attained. The only anticipated behavior is that if the sum of applied bulb voltages is set to a greater (less) value, then the balanced light level would be higher (smaller). There is no desired light level in these “regulation problem” experiments; the only aim is to obtain uniform lighting across the testbed by passing voltages between the bulbs. We refer to this as a regulation problem although there is no reference light level here. Moreover, this reference signal should be zero for the system to be called as a regulation problem [17]. However, when the same total applied voltage is set for experiments with different initial conditions, we expect to see the balanced light level
value always the same. We think of it regulating to this final balanced light level. Hence the terminology “regulation problem” makes sense.

As informative examples among the experiments made for this section, two experiments with initial conditions of $u(0) = [3, 5, 3, 5, 6, 5, 7, 4]^T$ and $u(0) = [7, 7, 7, 5, 5, 0, 0]^T$ are selected. The first one has relatively distributed initial bulb voltages while the other one is obviously not distributed. However, both of the implementations satisfy $\sum_{i=1}^{8} u_i = 38$ throughout the experiments. The value of 38 Volts is selected as it results in balanced illuminations in the linear region for all three partition cases. For the first five seconds of all experiments, initial bulb voltages were held constant to show that the light levels of the zones are initially unbalanced. Then at $t = 5$ seconds, the IBA is turned on.

Manipulating the definition of the voltage to be passed between the bulbs given in condition (iii) (see Section 4.2) with the Equation (4.8) yields the following expression that describes the IBA for the regulation problem:

$$u_i' = u_i - \sum_{j \in P(i)} \gamma(y_i(kT) - y_j(kT))$$  \hspace{1cm} (4.18)

The control loop of zone 1 according to (4.18) is depicted in Figure 4.3.

4.3.1 Full Height Partitions Results

The system is asymptotically stable in the linear region of the full height partitions case as shown in Section 4.2.2, so we expect to see the algorithm achieve uniform lighting. However, some zone light levels start in the nonlinear region when the initial conditions are $u(0) = [7, 7, 7, 7, 5, 5, 0, 0]^T$. Therefore, asymptotic stability is not assured for this experiment. Figures 4.4 and 4.5, and Figures 4.6 and 4.7 show the experimental results where $\gamma = 0.02$. 

46
Figure 4.3: Block diagram of the zone 1 closed loop in the regulation problem. Notice that as \( p(1) = \{2, 3\} \) according to Figure 4.2, the light levels of these zones (i.e., \( y_2 \) and \( y_3 \)) are used as well as the zone 1 light level \( y_1 \) in generating the bulb 1 voltage signal \( u_1 \). The usage of the light levels besides \( y_i \) in the \( i^{th} \) control loop (for all \( i \in Z = \{1, 2, \ldots, 8\} \)) distinguishes the IBA strategy from the decentralized integral control in the sense of having “communication” between the lights.

Figure 4.4: Actual light levels (regulation problem, full height partitions, \( u(0) = [3, 5, 3, 5, 6, 5, 7, 4]^T, \gamma = 0.02 \)).
Figure 4.5: Voltage signals applied to bulbs (regulation problem, full height partitions, $u(0) = [3, 5, 3, 5, 6, 5, 7, 4]^T$, $\gamma = 0.02$).

Figure 4.6: Actual light levels (regulation problem, full height partitions, $u(0) = [7, 7, 7, 7, 5, 5, 0, 0]^T$, $\gamma = 0.02$).
The light levels are balanced in both of the experiments, and the uniform light level is $y_{\text{balanced}} \approx 4.75$. In the rest of the experiments that satisfy the $\sum_{i=1}^{8} u_i = 38$ condition (the results of these experiments are not shown due to lack of space), the IBA always acquired the same uniform illumination level as well. Remarkably, the solutions (i.e., applied bulb voltages that result in $y_{\text{balanced}} \approx 4.75$) are approximately the same for all the experiments.

### 4.3.2 Half Height Partitions Results

When we switch to half height partitions, cross-illumination effects can be seen. Section 3.3 shows that these effects are restricted and do not dominate the input-output relationship of the system. It is reasonable to expect an increment in the $y_{\text{balanced}}$ value due to contributions from other lights even though they are restricted.
Figure 4.8: Actual light levels (regulation problem, half height partitions, \( u(0) = [3, 5, 3, 5, 6, 5, 7, 4]^T, \gamma = 0.02 \)).

Note that the sum of applied voltages is preserved as 38 Volts again throughout the experiments. Figures 4.8 and 4.9, and Figures 4.10 and 4.11 show the experimental results where \( \gamma = 0.02 \).

In both of the experiments, the illuminations at the zones are balanced successfully, and \( y_{\text{balanced}} \approx 5.1 \) Volts. This value confirms the contributions from other lights as \( y_{\text{balanced}} \) was 4.75 in the full height partitions case. The bulb voltages converged to the same values despite a very different selection of initial conditions similar to the full height partitions case.
Figure 4.9: Voltage signals applied to bulbs (regulation problem, half height partitions, \( u(0) = [3, 5, 3, 5, 6, 5, 7, 4]^T, \gamma = 0.02 \)).

Figure 4.10: Actual light levels (regulation problem, half height partitions, \( u(0) = [7, 7, 7, 7, 5, 5, 0, 0]^T, \gamma = 0.02 \)).
4.3.3 No Partitions Results

The results that will be shown in this section are very important since this was the case where the decentralized integral control failed in Chapter 3. The cross-illumination effects proved how crucial they are in no partitions case in Figures 3.11 and 3.12. It becomes impossible to predict the system response when the cross-illumination effects are maximized. The results are given in Figures 4.12 and 4.13, and Figures 4.14 and, 4.15 respectively where $\gamma = 0.02$.

In Figures 4.12 and 4.14, the illuminations are balanced at about 6.35 consistently. The applied bulb voltages that result in uniform lighting are:

$$u^* \approx [4.25, \ 4.98, \ 6.42, \ 5.09, \ 3.27, \ 3.95, \ 5.05, \ 4.97]^T$$
Figure 4.12: Actual light levels (regulation problem, no partitions, \( u(0) = [3, 5, 3, 5, 6, 5, 7, 4]^T, \gamma = 0.02 \)).

Figure 4.13: Voltage signals applied to bulbs (regulation problem, no partitions, \( u(0) = [3, 5, 3, 5, 6, 5, 7, 4]^T, \gamma = 0.02 \)).
Figure 4.14: Actual light levels (regulation problem, no partitions, $u(0) = [7, 7, 7, 5, 5, 0, 0]^T, \gamma = 0.02$).

Figure 4.15: Voltage signals applied to bulbs (regulation problem, no partitions, $u(0) = [7, 7, 7, 5, 5, 0, 0]^T, \gamma = 0.02$).
in Figures 4.13 and 4.15. This is a remarkable result showing that whatever the initial conditions of the system are, the IBA always balances the illumination by converging to the same applied voltage values $u^*$. In the previous two partition cases, the solutions were consistent as well. However, the final applied bulb voltages are not close to each other in this case unlike the previous cases. Meanwhile, the increments from 4.75 to 5.1, and from 5.1 to 6.35 have confirmed the increment in the cross-illumination effects from another perspective as the cases are switched from full height to half height, and from half height to no partitions, respectively. Consequently, in spite of the domination of the cross-illumination effects on the system behavior, the IBA achieved uniform lighting across the testbed by converging to the same light voltages every time.

4.4 The IBA: Tracking Problem

In this section, the goal is not only balancing the light levels (i.e., regulation) but also tracking a desired light level. The IBA derived for the regulation problem (4.18) will remain running here. Furthermore, it should be improved in a way that it can decide to raise, reduce or preserve the overall applied voltage when required. The most convenient way to achieve this is to combine the heuristic algorithm developed in Chapter 3 with the IBA. Notice that it is sufficient to run the integral controller in a single zone as long as the speed of the IBA is higher than the speed of the integral controller. Otherwise some fluctuations might occur in bulb voltages and so the light levels. The IBA will run simultaneously with the integral controller in zone 1 which is selected arbitrarily. The expression of the algorithm for the zone 1 is given as:

$$u'_1 = u_1 + \alpha e_1 - \gamma(y_1(kT) - y_j(kT))$$  \hspace{1cm} (4.19)
Figure 4.16: Block diagram of the zone 1 closed loop control system in the tracking problem.

while (4.18) applies to the rest of the zones. Here, parameter $\alpha = K_i T$ as given in (3.8) and $e_1$ denotes the error signal for the zone 1. The control loop for the zone 1 is shown in Figure 4.16. Due to the integral controller, zone 1 functions as an external voltage transfer gate (i.e., if the testbed is under-illuminated, zone 1 increases bulb 1 voltage which is distributed to the rest of the zones via IBA. On the contrary, if the testbed is over-illuminated, the integral controller will dim the light 1, and the IBA will cancel this imbalance). In the following experiments, $\gamma$ will be set to 0.02 as this selection resulted in very quick convergence in the regulation problem. The value of $\alpha$ is tuned to 0.008. This choice makes sense when $\alpha = 0.001$ is recalled for the individual zones in Chapter 3. The initial bulb voltages are set to $u(0) = [3, 3, 3, 3, 3, 3, 3, 3]^T$. 
4.4.1 Full Height Partitions Results

As no contributions from neighboring lights are observed in the full height partitions case, a good performance is expected. Moreover, if the IBA can eliminate the effect of the external voltage transfers due to the integral controller, then the results will most likely be very similar to the Figures 3.3 and 3.4. The results are given in Figures 4.17 and 4.18.

As can be seen in Figure 4.18, the IBA overcame the imbalance effect created by the integral controller in a very quick way such that the bulb voltages varied similar to each other. As a result, the actual light levels tracked the desired light level signal without any fluctuations in Figure 4.17.

Figure 4.17: Actual light levels (tracking problem case, full height partitions, $\gamma = 0.02$, $\alpha = 0.008$).
Figure 4.18: Voltage signals applied to bulbs (tracking problem, full height partitions, $\gamma = 0.02$, $\alpha = 0.008$).

### 4.4.2 Half Height Partitions Results

The results of the previous section have proven that the combined strategy is working well. Also, the regulation case has already shown the IBA obtains uniform lighting in the half height and no partitions cases. Hence, good results are expected here. The results are given in Figures 4.19 and 4.20.

Uniform lighting is obtained as in the full height partitions case. The results are similar to Figures 3.5 and 3.6. Reductions in the final values of the bulb voltages indicate the cross-illumination effects.
Figure 4.19: Actual light levels (tracking problem, half height partitions, $\gamma = 0.02$, $\alpha = 0.008$).

Figure 4.20: Voltage signals applied to bulbs (tracking problem, half height partitions, $\gamma = 0.02$, $\alpha = 0.008$).
4.4.3 Half Height Partitions Results: Daylighting

In this section, the same square wave signal as in Figure 3.7 is applied to the external bulb that is placed at the left side of the testbed. Via this disturbance signal, the performance of the IBA will be monitored under sudden illumination imbalances. The results can be seen in Figures 4.21 and 4.22.

External light disturbance is rapidly rejected as shown in Figure 4.21 by modulating the lights (see Figure 4.22). Reactions of lights 1 and 2 are more than the other bulbs as expected. The strategy provided energy savings by taking advantage of the external light in order to use the least amount of energy necessary to uniformly illuminate the testbed.

Figure 4.21: Actual light levels (tracking problem, half height partitions, daylighting, $\gamma = 0.02$, $\alpha = 0.008$).
Figure 4.22: Voltage signals applied to bulbs (tracking problem, half height partitions, daylighting, $\gamma = 0.02$, $\alpha = 0.008$).

### 4.4.4 No Partitions Results

The results are given in Figures 4.23 and 4.24. As can be seen in Figure 4.23, the actual light levels have shown no overshoot, a little overshoot, and some undershoot while the steps in the desired light level signal occurred at $t = 0$, $t = 20$, and $t = 40$, respectively. Yet the light levels tracked the desired light level in all the zones. As a matter of fact, the IBA worked so fast that it canceled the imbalance that the integral control creates rapidly and hence all the light levels moved together. By comparing Figure 4.23 with Figure 4.19, we deduce that the small overshoot and the undershoot in Figure 4.23 indicate the effects of the maximized couplings. Similar to the solution $u^*$ in Section 4.3.3, the applied bulb voltages that yield the desired uniform lighting (i.e., solutions) are not close to each other in Figure 4.24.
Figure 4.23: Actual light levels (tracking problem, no partitions, $\gamma = 0.02$, $\alpha = 0.008$).

Figure 4.24: Voltage signals applied to bulbs (tracking problem, no partitions, $\gamma = 0.02$, $\alpha = 0.008$).
4.4.5 Conclusions

The combined algorithm (i.e., the IBA in all the zones and an integral control in an arbitrarily selected zone) has repeated the success of the decentralized integral control in full and half height partitions cases. Moreover, it achieved desired uniform lighting in the no partitions case. The IBA uses local communications between the lights and this helped the controller to achieve uniform lighting across the testbed in the no partitions case, something that was not possible using the decentralized integral control. It is interesting that the goal of uniform lighting across the entire testbed was achieved without a centralized controller that requires global communications.
Chapter 5

CONCLUSIONS AND FUTURE DIRECTIONS

In this thesis, we have presented experimental studies on a smart lighting testbed where the goal is to obtain uniform illumination despite variations in partition heights and the presence of an external light disturbance. As the motivation of the research is to acquire a desired uniform lighting across the floor with as little information as possible, initially, a decentralized integral control is implemented that does not have any communication between the lights. All goals including daylighting are reached in the testbed with this method except achieving uniform lighting in the case where the cross-illumination effects are maximized. In order to avoid negative effects of these high cross-couplings on separate control loops, local light level information is utilized by each individual controller in the illumination balancing algorithm. This method achieved all the goals in the testbed without requiring a global communication between the lights. As a consequence, energy consumption is reduced by taking advantage of all light contributions and external light while providing the same light level to each zone.

This work studied smart lighting controls that have the ability to tune the lights for uniform lighting. The experimental testbed is very low-cost but reliable to test the implemented algorithms. Still, a better selection of photosensors would be more
realistic considering that the successful methods could be implemented for real life buildings. Also, as most of the smart light control systems use occupancy sensing to save greater amounts of energy, an improved testbed can be designed in which tuning and on/off functionalities of the lights are applicable. In addition to these practical improvements, the stability analysis of the IBA for the half height and no partitions cases can be investigated in order to assure the convergence of the algorithm theoretically for the regulation problem.
Bibliography


