DISTRIBUTED CONTROL FOR SMART LIGHTING

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

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2010

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ABSTRACT

In this research, we investigate designing a smart lighting system. By extending and enhancing the centralized and distributed control algorithms we try to address the lighting control problem and design a robust smart lighting system. The purpose of implementing various control strategies is to come up with a strategy that optimizes the power consumed by the system and its robustness to the problems of cross-illumination, external light disturbances, delays in the communication network, and the network topologies used for communication. The functionalities we try to achieve are uniform lighting, user-defined preference based lighting, maximum lighting mode and energy savings lighting mode by utilizing daylight. We study the performance of each control strategy and present a comparative analysis between the best strategies.
This is dedicated to my parents, Shripad Phadke and Shilpa Phadke, who have always been a great source of inspiration, support, love and knowledge throughout my life.
ACKNOWLEDGMENTS

First, I would like to thank my parents, Shripad and Shilpa, for their constant support, guidance and love throughout my academics. I had to stay away from them for the past two years, which have been the most difficult times I have seen in my life so far, and I believe I was able to sustain and achieve any success only because of the great values and passion for excellence they have imparted me over the years. I am also thankful for my sister, Sayali, for her support and encouragement.

I am filled with gratitude towards my adviser, Professor Kevin M. Passino. He is certainly one of the best Professors I have worked with. Working with him has been a great learning and fun experience. I admire him for his depth of knowledge, and more importantly his attitude towards research, students, and life in general. He has not only strengthened my understanding of research but also taught me to communicate effectively. With his leadership qualities and constant urge to serve the community as an engineer, he has always, and will continue to inspire me and all of his students. Without his guidance, motivation and support this work wouldn’t have been possible at all.

Any understanding that I have of Control Systems is entirely due to Professor Vadim I. Utkin. I thank him for teaching me all the fundamental courses in the control system’s field and encouraging me to go on and do research work in control engineering. With his greatness and equally humble nature, he has always served as
a role-model for all young engineers like me. I feel honored to have him on my M.S. committee.

Also, I am thankful to the Electrical and Computer Engineering Department for supporting me as a Graduate Teaching Associate for the complete second year of my Masters studies. Not only have they helped me financially, but also given me an opportunity to develop myself as a teacher and share my knowledge with my wonderful students.

Ted Pavlic and Fukui Xu helped me construct the testbed. Ted deserves special thanks for all the help he has provided for this research and in teaching. I would also like to thank Roger Beulow, Laszlo Takacs, and Keith Kazenski of Energy Focus Inc. for their initiative and support for this research.
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CHAPTER 1

INTRODUCTION

Energy conservation has certainly become the most important issue to address amongst engineers and environmentalists with the rising consumption of resources and deterioration of the environment. Conserving energy would reduce the rise in energy costs, and can reduce the need for new power plants, and energy imports. The reduced energy demand can provide more flexibility in choosing cleaner and efficient methods of energy production. Reduction in the emissions would certainly lessen the hazards caused to the environment. Energy conservation is often the most economical solution to energy shortages, and is a more environmentally benign alternative to tackle the ever increasing demand for energy.

The U.S. DoE says that in 2007 energy consumption in the U.S. composed of transportation (29%), residential (21%), commercial (18%), and industrial (32%). Also, in 2007 the electricity flow in the U.S. was composed of (in quadrillion BTU) residential (4.75), commercial (4.58), and industrial (3.43). The percentages of electricity used solely for lighting are: residential (16.5%), commercial (31.6%), industrial (10.7%). Hence, there is certainly a need for effective and efficient lighting control strategies
that would not only reduce the energy consumption but also impart additional functionalities such as uniform lighting, user preference lighting, daylight harvesting and energy savings.

Now, there are some elementary lighting control systems implemented these days in residential, industrial, and commercial applications. However, they are mostly confined to binary operation (on-off control) or control by human interaction through either a switch on the wall or over the internet. Most of the lighting control research, as in [2], [3], [6], [4], [5], [7], and [9], focusses mainly on utilizing centralized control strategies. From the point of view of implementation, most of the systems rely on heavy investments in infrastructure. They are not scalable with the retrofits already present in the buildings. Though some of them have wireless sensor networks involved for communications, its potential has been underutilized due to the centralized control strategies used in them. Also, the flexibility and functionalities are certainly quite less than what would be achieved if distributed control would have been implemented. In this work, we investigate distributed control strategies. Next, we discuss the structure of this thesis.

In Chapter 2, we discuss the testbed used for carrying out all of our experiments. The hardware and the software required for constructing the testbed are described here in detail. Also, we provide short discussion on calibration of the sensors and the cross-illumination characteristics of the testbed that have an effect over the performance of any control algorithm.

In Chapter 3, we present experimental analysis of centralized control strategies. We design control algorithms to make the average value and the minimum value of all the sensors track user defined reference values. The study done here certainly reveals
the interesting dynamics of the testbed and various possibilities of failure. It lays the base for designing the distributed control strategies.

Finally, in Chapter 4, we present the experimental analysis of the distributed control strategies. Here, we try to extend and enhance the virtual load balancing algorithm, as discussed in [8] and [1], and the conventional PID control techniques and apply them to the lighting control problem. We carry out a set of experiments to test the performance of both the algorithms under different conditions and also present a comparative analysis towards the end of the chapter.
CHAPTER 2

SMART LIGHT TESTBED

The experimental testbed shown in Figure 2.1 has eight incandescent (flashlight) bulbs fitted on the inside of the lid of a box. Power transistors are used to power the lights. Eight light-dependent resistors are fitted on the bottom of the box and serve as illumination sensors. The eight sensors are placed directly below the eight lights. We think of the light-sensor pairs as defining lighting “zones” and have removable cardboard partitions that can partially isolate the zones from each other for some experiments. These partitions are meant to simulate the presence of cubicles in an office building.

The sensors are connected in series with an external resistor to form a circuit such that the voltage output is directly proportional to the intensity of light falling on the sensor. However, the sensors have different physical characteristics so the voltage output obtained for same light intensity is different for each of the sensors. Thus, calibrating the sensors is essential in order to achieve uniform light intensity across the zones. It was found that all of the sensors show approximately linear characteristics when the voltage applied to the corresponding lights is in the range of 4V - 7V. For calibration, we note the sensor readings when 4V and 7V are applied to the lights in their respective zones. Based on the readings at 4V and 7V, we determine the slope
of the sensor characteristics. Now, any reading obtained from a sensor is first divided by the slope corresponding to that sensor and added to an offset value to make the line pass through origin. Thus, we obtain uniformity in sensor readings across the zones.

The controller is designed using Matlab & Simulink and compiled onto the dSPACE DS1104 Controller Board which is interfaced with the sensors and the lights. The dSPACE Control Desk is used to monitor the system performance and record the results.

Next, we present the tables that show quantitative analysis of the cross-illumination effects prevailing in the testbed for no partition case and half-height partition case. We test the cross-illumination effects by applying 7V at one zone, and 0V at rest of the zones, and measuring the sensed voltages at all of the zones. This procedure is repeated for all the zones and for the two cases of partition heights.
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Table 2.1: Cross-illumination effects for half-height partition case. Row $i$ has applied voltage at 7V at zone $i$, column $j$ has the sensed voltage at zone $j$ for respective row $i$.

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Table 2.2: Cross-illumination effects for no partition case. Row $i$ has applied voltage at 7V at zone $i$, column $j$ has the sensed voltage at zone $j$ for respective row $i$.

See Tables 2.1 and 2.2. Notice that the cross-illumination effect is considerably smaller in the half-height partition case than in the no partition case. In the no partition case we can find neighboring zones having maximum sensed voltages up to 6.8V which is certainly quite high. This causes problems of saturation and thus resulting in instability in some of the control strategies. We will discuss this in detail in next chapters.
CHAPTER 3

CENTRALIZED CONTROL

3.1 Using the Average of the Sensed Voltages

In this experiment, we have a centralized control implemented on a single processor that controls all of the lights. We have no partitions between any of the zones (the strategy works similarly if partitions are present). Let \( y_i \) be the value of the voltage sensed at each of the sensors for all \( i = 1, 2, ..., N \) where \( N = 8 \). Let \( y = [y_1, y_2, ..., y_N]^T \). We compute the average value of these sensed voltages at all of the zones and make it track a desired lighting intensity profile using a Proportional-Integral (PI) controller. Let \( u_i \) denote the value of voltage applied to light \( i \) for all \( i = 1, 2, ..., N \) where \( N = 8 \). Let \( u = [u_1, u_2, ..., u_N]^T \). The output of the controller is applied at all of the zones so at each step all these \( u_i \) values are the same. Let that value be equal to \( v \). Let \( v(k) \) be the input applied at time \( k \) to all of the lights, and let \( d \) be the desired average value. Let \( K_p \) be the proportional gain, \( K_i \) be the integral gain, and \( T_s \) be the sampling time. Then, the control law is

\[
v(k) = K_p \left\{ d - \frac{1}{N} \sum_{i=1}^{N} y_i(k) \right\} + K_i T_s \sum_{j=0}^{k} \left\{ d - \frac{1}{N} \sum_{i=1}^{N} y_i(j) \right\}
\]

The results are summarized in Figures 3.1 and 3.2. While Figure 3.1 shows that the centralized PI control strategy succeeds in maintaining the average sensed voltage
value to the desired value, Figure 3.2 demonstrates that the light intensity is not uniform across the zones.

Next, using a table lamp, we introduce an external light disturbance from an opening close to zones 7 and 8. In particular, the light from the lamp is turned on at $t = 25\, \text{sec}$ and turned off at $t = 50\, \text{sec}$. Since there are no partitions, the disturbance enters all of the zones. The desired average value is kept at 5.5V throughout the experiment. Figures 3.3 and 3.4 show the results obtained. Figure 3.3 shows that the centralized PI controller succeeds in maintaining the average sensed voltage value to the desired level in spite of the disturbance. However, it should be noted that the light intensity is not uniform across the zones as shown in Figure 3.4.

![Figure 3.1: Average sensed voltage and the reference profile.](image)

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8
Figure 3.2: Sensed voltage $y_i$ for “average of the sensed value” technique.

Figure 3.3: Average sensed voltage.
3.2 Using the Minimum of the Sensed Voltages

In this experiment, we again have a centralized control implemented on a single processor that controls all of the lights. We have no partitions between any of the zones. We compute the minimum value of the sensed voltages at all of the zones and make it track a desired lighting intensity profile using a PI controller. The output of the controller is applied at all of the zones. Let that value be equal to \( v \). Let \( v(k) \) be the input applied at time \( k \), and let \( d \) be the desired average value. Let \( K_p \) be the proportional gain, \( K_i \) be the integral gain, and \( T_s \) be the sampling time. Then, the control law is

\[
v(k) = K_p \{d - \text{min}_i \{y_i(k)\}\} + K_i T_s \sum_{j=0}^{k} \{d - \text{min}_i \{y_i(j)\}\}
\]

Figure 3.4: Sensed voltage \( y_i \) for “average of the sensed value” technique.
The results obtained are summarized in Figures 3.5 and 3.6. Figure 3.5 shows that the centralized PI control strategy succeeds in maintaining the minimum sensed voltage value at the desired value. It should be noted, however, that as shown in Figure 3.6, the light intensity is not uniform across the zones. It is the case, however, that all of the zones have their sensed voltage values at least above the desired voltage level.

Next, using a table lamp, we introduce an external light disturbance from an opening close to zones 7 and 8. In particular, the light from the lamp is turned on at $t = 30$ sec and turned off at $t = 60$ sec. Since there are no partitions, the disturbance enters all of the zones. The desired minimum value is kept at 5.5V throughout the experiment. Figures 3.7 and 3.8 show the results obtained. It is observed from Figure 8 that the centralized PI controller succeeds in maintaining the minimum of the sensed voltage value at the desired level in spite of the disturbance. However, it can be seen from Figure 3.8 that the light intensity is still not uniform across the zones.

![Figure 3.5: Minimum sensed voltage and the reference profile.](image)
Figure 3.6: Sensed voltage $y_i$ for “minimum of the sensed value” technique.

Figure 3.7: Minimum sensed voltage.
3.3 Using An Optimization Technique: The Genetic Algorithm

In this experiment, we again have a centralized control implemented on a single processor that controls all of the lights. We have no partitions between any of the zones. We view the lighting control problem as an optimization problem. The cost function that we aim to optimize is the sum of the squares of the error between the desired light sensor value and actual value at each zone. We do not know the cost function and so we need to apply a non-derivative optimization technique. Hence the choice of GA. We consider the applied voltages at each zone as a chromosome. Thus, we start with an initial population of eight corresponding to the applied voltages at eight zones. We assume that zone 1 knows the reference voltage and tracks this reference voltage using a PI controller. This is equivalent to declaring the first zone as a elite member of the population. We set the crossover probabilities to be zero.

Figure 3.8: Sensed voltage $y_i$ for “minimum of the sensed value” technique.
Thus, the GA proceeds with each step and optimizes the cost function only due to mutation of the chromosomes at each step. The results obtained are summarized in Figures 3.9 and 3.10. Figure 3.9 shows that the genetic algorithm stabilizes very fast. It should be noted that the light intensity is uniform across all the zones. The algorithm stabilized irrespective of the partition height.

Next, using a table lamp, we introduce an external light disturbance from an opening close to zones 7 and 8. In particular, the light from the lamp is turned on at $t = 40\ sec$ and turned off at $t = 70\ sec$. Since there are no partitions, the disturbance enters all of the zones. The desired minimum value is kept at 6V throughout the experiment. Figures 3.11, 3.12, and 3.13 show the results obtained. It is observed that the genetic algorithm also succeeds in maintaining the minimum of the sensed voltage value at the desired level in spite of the disturbance.

However, the light intensity is not uniform across all the zones. The genetic algorithm tries to pull down the applied voltage from the zones affected by sunlight, but probably it gets locked in the local minimum when it tries to do so. Thus we can see a drop in the applied voltages at all of the zones in Figure 12 but still it does not achieve uniform lighting across all of the zones.

Figure 3.9: Sensed voltage $y_i$ for genetic algorithm optimization technique.
Figure 3.10: Applied voltage $u_i$ for genetic algorithm optimization technique.

Figure 3.11: Sensed voltage $y_i$ for genetic algorithm optimization technique.
Figure 3.12: Applied voltage $u_i$ for genetic algorithm optimization technique.

Figure 3.13: Total applied voltage for genetic algorithm optimization technique.
4.1 Distributed Control: PI Controller for Each Zone

The problem of non-uniform light intensities across the zones encountered with the centralized control approach is solved in this section by having a separate PI controller for each zone. There is no communication present between the controllers. We assume that we have a special dimmer control switch available to the user to set the desired light intensity for the room. This dimmer control switch sets the reference value that is broadcasted via its transmitter and received by the receivers present at each of the controllers. The PI controllers then try to achieve the desired light intensity for their respective zones. In order to simulate the real life implementation, we introduce different delays between the transmission of the signal from the dimmer switch and its reception at each zone.

It was observed that the coupling between the zones need not to be restricted in the case of PI controller at each of the zones, since the algorithm is quite robust and does not get driven to saturation due to the excessive interference from neighboring zones. However, to maintain consistency in the discussion and allow the operation at lower error values we insert cardboard partitions between all of the zones. The height
of the cardboard partitions is almost half of the height of the box. The control law is at zone $i = 1, 2, ..., N$ are

$$u_i(k) = K_p \{d - y_i(k)\} + K_i T_s \sum_{j=0}^{k} \{d - y_i(j)\}$$

### 4.1.1 Uniform Lighting: Profile Tracking

In this experiment, we show that we achieve uniform sensed voltages in all of the zones by allowing the controllers track a desired voltage profile. The profile is obtained by setting the desired voltage to $6V$ initially. Then at $t = 30 \text{ sec}$, the desired voltage is changed to $7V$ and at $t = 75 \text{ sec}$, the it is dropped down to $5.5V$. Figure 4.1 shows that the distributed PI controllers succeed in maintaining the sensed voltages at each of the zones and track the profile with small response times and zero steady state errors. Thus, uniform light intensity is maintained across all of the zones.

![Graph showing voltage sensed $y_i$ for uniform lighting.](image)

Figure 4.1: Voltage sensed $y_i$ for uniform lighting.
4.1.2 Effect of Light Disturbance

Next, we introduce an external light disturbance in the system. This is done by allowing the light from a lamp to enter through a opening close to zones 7 and 8. We keep the partitions between the zones, but since they are only half-height, the light disturbance affects all of the zones. The desired sensed voltage value is held constant at 6V for all of the zones.

Figures 4.2 and 4.3 show the sensed voltages and applied voltages at each of the zones respectively. Figure 4.4 shows the total sensed voltage in the system. The external light disturbance is applied at \( t = 25 \text{ sec} \) and removed at \( t = 65 \text{ sec} \). It can be seen from Figure 4.2 that the PI controller at each zone helps maintain the desired voltage level at the respective zone even after the external light disturbance is introduced. We can see from Figure 4.3 that the applied voltages in zones 5 and 6 fall down slightly and that in zones 7 and 8 they fall down considerably after application of the external light disturbance and this results in the reduction in the total applied voltage as observed in Figure 4.4. This reduction shows that our system can save energy when natural light enters a room.

4.2 Distributed Control: Voltage Balancing

In this case, the controller is implemented as if it is a distributed controller with a separate processor associated with each zone. It is for this reason that we will discuss the controller as if it were a set of processors, each with only local inputs and outputs.
Figure 4.2: Sensed voltage $y_i$ for effect of disturbance.

Figure 4.3: Applied voltage $u_i$ for effect of disturbance.
We want the smart light grid to be able to adjust the light intensity profile according to user preferences. Let $p_i > 0$ be inversely proportional to the light intensity preferred by the user for zone $i$, for all $i = 1, 2, \ldots, N$. We will refer to $p_i y_i(k)$ as the “preference weighted voltage” at zone $i$ at some time $k$. Our algorithms will seek to equalize the preference weighted voltages at all zones and thereby achieve a user-specified light intensity profile. For example, if we have 3 lights in our system and the user-preferred lighting intensities are in the proportion of 3:2:1, then $p_i$ takes values $\frac{1}{3}$, $\frac{1}{2}$, and 1 for $i = 1, 2, \text{ and } 3$ respectively. In this case, the user prefers to have zone 1 three times as bright as zone 3 and zone 2 two times as bright as zone 3. Thus, $\frac{1}{3} y_1 = y_3$ and $\frac{1}{2} y_2 = y_3$. To get uniform light intensity the user would pick $p_i = 1$ for all $i$.

Here, we will consider controllers that are composed of processors that are connected in different prototypical “topologies”. We create topologies in the following
way: First, we represent processors with nodes (circles). Second, we represent communications with bidirectional arrows. See Figure 4.5 for examples of the line, loop, and multi-neighbor topologies. For these, we let \( n_i \) denote the set of neighbors of processor \( i \) and \( N_i = |n_i| \) is the number of neighbors of processor \( i \). If there is a bidirectional arrow between \( i \) and \( j \in n_i \), this means that processor \( i \) can sense the voltage and it can pass voltage to, and receive voltage from, processor \( j \in n_i \).

\[
\alpha_{ij}(k) = \gamma (p_{iy_i}(k) - p_{y_j}(k))
\]

Figure 4.5: Line, loop, and multi-neighbor network topologies for communication between lights.

To define the distributed control algorithm we use the following basic rule at each processor \( i \): if the preference weighted voltage at zone \( i \) is greater than the preference weighted voltage at zone \( j \), for some \( j \in n_i \), we reduce the applied voltage at zone \( i \) by a fixed amount and add that same amount to the applied voltage at zone \( j \). To define this rule precisely, let \( \alpha_{ij}(k) \) denote the amount of voltage transferred from zone \( i \) to zone \( j \) at some time \( k \). Let \( \gamma \) be a tunable constant, such that \( 0 < \gamma \leq \frac{1}{N_i} \). Then, for some \( j \in n_i \) and for some time \( k \), if \( p_{iy_i}(k) \leq p_{y_j}(k) \), then \( \alpha_{ij}(k) = 0 \). If, however, \( p_{iy_i}(k) > p_{y_j}(k) \), then

\[
\alpha_{ij}(k) = \gamma (p_{iy_i}(k) - p_{y_j}(k))
\]
The constraint of $\gamma \leq \frac{1}{N_i}$ is needed so that if, for example $p_iy_i(k) > p_jy_j(k)$ for all $j \in n_i$, then a limited amount of voltage is transferred so that an imbalance in the opposite direction is not created. The application of this rule at every processor results in a redistribution of voltages across the light grid. In particular if $u_i(k)$ is the voltage applied to light $i$ at time instant $k$ and $u_i(k+1)$ is the voltage applied to light $i$ at time $k+1$, then, for $i = 2, \ldots, N$ and $j = 1, 2, \ldots, N$

$$u_i(k+1) = u_i(k) - \sum_{j \in n_i} \alpha_{ij}(k) + \sum_{i \in n_j} \alpha_{ji}(k)$$

Here, $\alpha_{ij}(k)$ is calculated by processor $i$ but $\alpha_{ji}(k)$ is calculated by processors $j \in n_i$ that are connected to processor $i$. The result is that the voltage applied to light $i$ at time $k+1$ is the voltage applied to light $i$ at time $k$, minus the net transfer of voltage from zone $i$ to its neighboring zones $j \in n_i$, plus the voltages transferred to $i$ from any zone $j$ that has $i$ as its neighbor, $i \in n_j$.

Next, we implement a PI controller at zone 1. Let $K_p$ be the proportional gain, $K_i$ be the integral gain, and $T_s$ be the sampling time. The role of this PI controller is to maintain the light intensity at zone 1 to a desired level, denoted by $d$. Thus, for $i = 1$ and $j$ such that $j \in n_1$, the dynamics are

$$u_1(k) = d + K_p \{d - p_1y_1(k)\} + K_i T_s \sum_{j=0}^{k} \{d - p_1y_1(j)\}$$

Thus, the PI controller works independently to keep the preference weighted sensed voltage at zone 1 to the desired value by getting rid of any noise and disturbances. The voltage balancing algorithm at zone 1 ensures that the preference weighted voltage of the neighboring zones remains balanced with the preference weighted voltage at zone 1. The net result obtained is that the desired light intensity $d$ is achieved across all of the zones. Thus, we can control the light intensity
level for the whole grid by just changing the desired value, \( d \), at zone 1. This strategy indirectly gives us the control on the total applied voltage in the system without having complete knowledge of applied voltages at all of the zones.

4.2.1 Experimental Conditions

Next, we perform a set of experiments to analyze the performance of the smart light system. First, we evaluate the controller’s ability to achieve uniform lighting irrespective of the network topology. Second, we show that user-defined preferences can be used to set a user-defined light intensity profile. Lastly, we show that the system is robust to external light disturbances.

As discussed earlier, the system has a linear range of operation from 4V to 7V. Therefore, we should apply voltages that lie within this range and also make sure that the system achieves an equilibrium within the same range. For all the experiments, we hold the system to its initial condition for first 5 seconds in order to get rid of the start-up transients. For all the experiments, there are delays introduced in the communication lines between the processors. Two types of delays are used. First, there are “sensing delays” for processor \( i \) to sense the voltage \( y_j, j \in n_i \). Second there are “transmission delays” in transferring voltages from processor \( i \) to processor \( j \in n_i \). Here random delays are used for sensing and transmission. In particular, delays of no more than 0.01 sec are used. After repeated trials, it was observed that the system gave the best results when the tunable constant \( \gamma \) was set to be equal to 0.02. If we increase this value we can generally reduce the amount of time it takes to achieve equilibrium. However, larger values of \( \gamma \) cause instability in the system due to rapid transfers of larger amounts of voltage between the zones. Thus, choosing the value
for $\gamma$ is a trade-off between the ripple content (stability) and the settling time. We may be able to afford to have some ripple to be present in the applied voltage at the lights without causing undesirable fluctuations in the light intensity noticeable to the human eye. However, we have tuned the value of $\gamma$ to get rid of all the ripples.

Now, for the PI controller at zone 1, it is required to tune the $P$ and $I$ gain values such that the speed of convergence of the PI controller is slower than the speed of convergence of the voltage balancing algorithm. This ensures stability for the system and also increases the speed of convergence of the combined control strategy.

### 4.2.2 Uniform Lighting: Effect of Processor Topology

We number the zones as shown in Figure 4.5. We consider the line topology and insert cardboard partitions between all of the zones. The height of the cardboard partitions is almost half of the height of the box. Thus, we allow for restricted coupling between light from all of the zones. This simulates the case of commercial buildings where there are multiple cubicles in rooms (the strategy works similarly if partitions are present). For this experiment, we have $\gamma = 0.02$, $p = [1, 1, 1, 1, 1, 1, 1]^T$ (uniform light intensity), $K_p = 2$, $K_i = 1$, and initial condition $u(0) = [6, 6, 6, 4, 6, 5, 7, 5]^T$. The system is made to track a desired voltage profile that is obtained by setting desired sensed voltage level initially to 6V and then changing it to 7V at $t = 30\ sec$ and then to 5V at $t = 60\ sec$. Figures 4.6, 4.7, and 4.8 show the plots for sensed voltage $y_i$ for each zone, for the line, loop, and multi-neighbor topologies respectively.
Figure 4.6: Sensed voltage $y_i$ for line topology.

Figure 4.7: Sensed voltage $y_i$ for loop topology.
It can be seen from Figures 4.6, 4.7, and 4.8 that the system tracks the desired voltage profile and maintains uniform illumination across all of the zones. In each case, the coupling between the zones does not affect the stability of the system. As a result of improved connectivity among the zones the speed of convergence for the voltage balancing algorithm increases as we switch from line to loop to multi-neighbor topology. The PI controller gains are kept the same for all the topologies. We observe significant changes in the response times from the plots. Generally, it may be preferrable to have slow and steady changes in the lighting intensities from the human acceptance point of view. We can adjust the rate of convergence to user desired value by changing the PI controller gain values.
4.2.3 User-Defined Light Intensity Preferences

In this experiment, we input via $p_i$ user-defined light intensity preferences. We keep the partitions in place as discussed in the previous experiment (but if the half-height partitions are removed instability results). Suppose that the user wants zones 1, 3, 5, and 7 to have 1.25 times the light intensities at the zones 2, 4, 6, and 8. This translates approximately to $p = [0.8, 1, 0.8, 1, 0.8, 1, 0.8, 1]^T$. Let $\gamma = 0.02$. The initial condition is $u(0) = [7, 4, 6, 4, 6, 5, 7, 5]^T$. We have used the line topology for this experiment. The system is made to track a desired voltage profile that is obtained by setting desired sensed voltage level initially to 6V and then changing it to 7V at $t = 50$ sec.

Figure 4.9 shows the sensed voltage $y_i$ at each of the zones. We can see that the PI controller in combination with the load balancing algorithm brings the sensed voltage at zone 1 to the desired value. The voltage sensed at zones 1, 3, 5, and 7 is approximately 6V and that in zones 2, 4, 6, and 8 is 4.8V. Thus, zones 1, 3, 5, and 7 achieve 1.25 times the light intensities at the zones 2, 4, 6, and 8. At time $t = 50$ sec, when we change the desired voltage value at zone 1 to 7V, the voltage sensed at zones 1, 3, 5, and 7 is approximately 7V and that in zones 2, 4, 6, and 8 is 5.6V. Thus, the desired light intensity profile is maintained across all of the zones. We have shown that the distribution of voltages across the zones need not be uniform. Thus, the user can demand any arbitrary light intensity profile for the grid, and it can be achieved by maintaining the desired voltage levels. Also, the response time of the system is small with zero steady state error.
4.2.4 Effect of Light Disturbance

Next, we introduce an external light disturbance in the system. This is done by allowing the light from a lamp to enter through a opening close to zones 7 and 8. We maintain the partitions between the zones as discussed in earlier experiment. Thus, the light disturbance affects all of the zones. We have used the line topology for this experiment. The parameters used for this experiment are: $\gamma = 0.02$, $p = [1, 1, 1, 1, 1, 1, 1]^{T}$, and initial conditions $u(0) = [7, 4, 6, 4, 6, 5, 7, 5]^{T}$.

This experiment is divided into two parts: First, we do not use the PI controller at zone 1. Second, we use the PI controller. For the first part, the disturbance was introduced at $t = 25\ sec$ and removed at $t = 65\ sec$. As can be seen from Figure 4.11, as soon as the disturbance is introduced, the applied voltage, $u_i$ to the zones 7 and 8 is reduced and this voltage is distributed on to other zones. Figure 4.10 shows that the sensed voltage, and thus the light intensity, in each of the zones is uniform inspite of the disturbance. Essentially, the system “harvests” the daylight and redistributes the
lighting benefit uniformly across all zones. It can be seen that when the disturbance is removed the system settles back to the values seen before applying the disturbance. Of course, this could be an undesirable feature if the user wants the light intensity in the room to remain at a fixed level.

To solve the above problem, we use the PI controller at zone 1 and set the desired sensed voltage level at 6V. The results can be seen in Figures 4.12, 4.13 and 4.14. In this case, the external light disturbance is applied at $t = 30 \text{ sec}$ and removed at $t = 60 \text{ sec}$. It can be seen from Figure 4.12 that the combined effect of the PI controller and the voltage balancing controller helps maintain the desired voltage level at all the zones even after the external light disturbance is introduced. We can see from Figure 4.13 that the applied voltages in zones 1, 2, 3, 4, 5 and 6 fall down slightly while that in zones 7 and 8 they fall down considerably after application of the external light disturbance and this results in the reduction in the total applied voltages, as observed in Figure 4.14.

![Figure 4.10: Voltage sensed $y_i$ for effect of disturbance.](image)

30
Figure 4.11: Applied voltage $u_i$ for effect of disturbance.

Figure 4.12: Sensed voltage $y_i$ for effect of disturbance.
Figure 4.13: Applied voltage $u_t$ for effect of disturbance.

Figure 4.14: Total Voltage for effect of disturbance.
This reduction shows that our system can save energy when natural light enters a room, just like in the distributed PI controller case. Note, however, that the communication and processing requirements to achieve this feature are different in the two cases. In the distributed PI controller case we needed unidirectional global (broadcast) communication from a special dimmer switch and \( N \) parallel PI controllers. In the voltage balancing approach we only need local communications, but they must be bidirectional, yet we also needed full connections with one light to implement the PI controller for it. Essentially, the voltage balancing approach replaces the cost of having broadcast communications and \( N - 1 \) PI controllers with one PI controller and local bidirectional communications. It seems that particular applications may demand the use of one or the other approach.

### 4.3 Effect of Partition Height

The effect of the height of the partitions is studied here by conducting multiple runs with full-height, half-height, and no partitions. The zones are made to track the same profile as discussed in the experiments on uniform lighting in Section 4.2. It was observed that the voltage balancing strategy saturates for no partition case. But, it stabilizes for the other two cases. On the other hand, the strategy of using the PI controller at each zone achieves uniform lighting across all zones in all three cases. Table 4.1 shows the mean squared errors for each case for the two strategies averaged over 10 experimental runs. Notice that when the voltage balancing scheme does not saturate, it outperforms the PI controller.

Next, we study the applied voltages at each zones for both the strategies with different partition heights. For studying this, the zones were made to track a fixed
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<tr>
<td>Voltage Balancing</td>
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<td>0.0151</td>
<td>325.09</td>
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Table 4.1: Mean of the mean squared errors.

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<tbody>
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<td>Mean of mean</td>
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<td>6.446V</td>
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<tr>
<td>Mean of variance</td>
<td>7.759e-4</td>
<td>9.236e-4</td>
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</table>

Table 4.2: Analysis of applied voltages for voltage balancing strategy.

Referene voltage of 7V and the experiment was run 10 times to collect the data for analysis. The analysis of the applied voltages for the voltage balancing strategy is shown in Table 4.2. The analysis for the strategy of using a PI controller at each zone is shown in Table 4.3. In both these tables, the values represent the mean of the applied voltages and the variance of the applied voltages averaged over 10 runs. Notice that the mean of the mean applied voltage across all the zones reduces with decrease in height of the partitions. However, the mean of the variance of the applied voltages increase as the height of partition decreases. This is essentially observed for both the strategies. Also, due to connectivity across all the zones the voltage balancing strategy has negligible mean of variance across the zones as compared to the other strategy.
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<td>0.0026</td>
<td>0.0342</td>
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Table 4.3: Analysis of applied voltages for PI controller at each zone.
A smart lighting system was designed using a cooperative control strategy based on distributed load balancing algorithm. The system was tested with a set of experiments and by conducting a number of runs to study its stability and robustness. The objectives achieved by the distributed control strategies are as follows:

1) Uniform lighting,
2) User-defined preference adaptive lighting,
3) Maximum lighting utilizing external light disturbance,
4) Energy saving operation utilizing the external light disturbance.

Importantly, both the strategies prove their robustness to transport and processing delays and operate equally well in a completely asynchronous mode. Also, the algorithm allows for preference lighting with just the introduction of new parameter $p_i$. Thus, preference lighting is achieved without needing any additional control. Though the strategy of PI controller at each zone stabilizes for even the no partition case, unlike the voltage balancing strategy, the voltage balancing strategy proves to be more efficient in all the other aspects. Thus, depending on the conditions and the extent of cross-illumination we can select one of the two strategies.
5.1 Contributions to Engineering

The lighting control techniques that have been used in the past rely on centralized control implementing simple reference tracking methods. However, this is the first time that a distributed control strategy has been implemented for lighting control. This imparts high flexibility and scalability to the lighting systems. Also, distributed control makes it possible to design lighting units that can be directly fixed into the retrofits and set up the smart lighting system without any additional cost for infrastructure and rewiring. This certainly can be the unique selling point for these systems. Its ability to cascade with higher levels allows us to design highly efficient smart lighting systems. Thus, distributed cooperative control strategy is an effective, efficient and robust lighting control technique for designing the smart lighting systems.

5.2 Future Work

It was observed that higher levels of cross-illumination caused instability in the voltage balancing strategy and caused the means and variances of the errors to rise in both the strategies. There is certainly room for improvement in this direction. Future studies could also be made in developing a model for the cross-illumination using a adaptive system identification techniques. There is also potential for viewing this problem as a distributed optimization problem and maybe a non-gradient optimization technique would also be a good possible solution to this problem.
BIBLIOGRAPHY


