Control System Development for Energy-efficient Lighting in Greenhouses

by

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M.Sc., Nanyang Technological University, 2013
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Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

in the
School of Mechatronic Systems Engineering
Faculty of Applied Sciences

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SIMON FRASER UNIVERSITY
Summer 2020

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Abstract

This thesis focuses on the development and implementation of feedback control with application to an energy-efficient lighting system for potential application in a greenhouse environment. The proposed control system was developed and implemented in four stages. First, the lighting model for the red and blue lights was identified separately to ensure uniform light distribution at plant canopies. Subsequently, a daylight environment was constructed using the MATLAB/Simulink environment. The performance of the system was evaluated on a proof of concept system through a series of simulations to verify the control performance.

In the second stage, the proposed concept was implemented to regulate the intensity of dimmable multi-spectrum LED fixtures for achieving desired spectral irradiance levels and color ratios while utilizing daylight harvesting to enhance energy-efficiency. To ensure the stability and performance, a Smith predictor was utilized to compensate for the delay introduced into the system by the communication hardware. Implementation of the proposed system with a smooth transient response ensured lower energy consumption for the LED panels.

In the third stage, a testbed with environment monitoring and intelligent LED lighting control system was implemented with potential utilization in an Internet of Things (IoT) smart greenhouse environment. The performance of the LED control system was verified through conducting plant experiments in the proposed testbed. It was shown that the proposed testbed is capable of achieving the desired light requirement for the tested plant while maintaining satisfactory plant growth results.

Finally, in the fourth stage, the proposed concept was extended to a small-scale plant growth and implemented on a Raspbian operating system with the IoT technology. The system was utilized to implement lighting control and environmental monitoring applications for greenhouses in remote areas. Results show potential for prominent energy savings when the proposed lighting system is utilized to grow kale microgreens, which further resulted in improved plant quality due to uniform lighting conditions achieved through feedback control.
Keywords: lighting control; daylight harvesting; LED lighting; mixing color; greenhouse; energy efficiency; plant growth
Dedication

“Your wisdom consists not of the knowledge you already have, but the continual search for knowledge, which is the highest form of wisdom.”

12 Rules for Life, Jordan B. Peterson
I would like to thank my senior supervisor Prof. Mehrdad Moallem for the inspiration and professional guidance of my research; as well as the financial, academic, and spiritual support he has given me throughout this endeavour. Prof. Mehrdad Moallem has not only been a mentor to me in regards to research but has also been a life mentor. His gentle heart, calm demeanour, patience, and generosity has helped shape my current conduct and values. I would also like to thank my other supervisors, Youbin Zheng and Jason Wang for providing constructive suggestions and critique to improve the quality of my work.

To the Pacific Institute of Climate Solution and NSERC, I would like to express my deepest gratitude for helping to fund this project and my doctoral studies for the past five years.

To all the members at the Motion and Power Electronics Control Lab at Simon Fraser University, thank you for creating a wonderful work environment and making the PhD study in the lab enjoyable. I want to express my thanks to Afagh Mohagheghi whom I had the pleasure of collaborating with on this project.

A special thank you to Seyed Hossein Kamali for providing technical support for my projects and always being there to give me professional advice; my best Canadian friends, Gian Rico, Miriam Sise-Odaa, Iiveoma Udevi-Aruevoru and Marcel Noel Etchu Njang, for providing me with academic writing advice and a strong and reliable support system. Amy Chen and Neo Cheng, my roommates, who have continuously provided a cozy home environment, and feedback during the final stages of my thesis writing and defence presentation. I would especially like to thank Shengyang Sha, who has been my best friend since primary school. Giving me confidence and support whenever I needed someone to be there, and helping me take care of my parents in my hometown during this despairing pandemic (Covid-19).

Last but not least, I would like to thank my family in China for their love, support and sacrifices. My mom, for showing admiration for the decisions that I have made in my life; adorning continual selfless love and support that drives my passion to pursue my goals. And my dad, who has taken care of the family while I was away. I am thankful to both of them for having worked arduously to give me the best education that they could offer.
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Chapter 1

Introduction

1.1 Motivation for the Research

Continual development of light-emitting diode (LED) lighting technology spanning the past few decades has reduced the manufacturing cost and increased energy efficiency and operational lifespan. In developing the LED lighting applications, new challenges come up which require new control strategies targeted for different environmental conditions.

In common lighting scenarios, LED fixtures are installed in several locations to distribute proper light intensity depending on the lighting object requirements. In an office and residential building environment, human eye comfort is considered along with the illuminator to regulate the illuminance such that it achieves optimal performance and energy efficiency. These systems mostly operate with consideration to occupancy of space and daylight as disturbances while also minimizing power consumption.

Another application scenario is the supplemental lighting system in a greenhouse environment, which provides supplemental light for plant growth and crop productivity. Through the use of a set of different lighting criteria, the supplemental growth light tailors to achieving a targeted amount of photosynthetic photon as the light requirement for plant growth. LED growth light, consisting of a mix of colour-based LED units and programmable dimming and spectral controls, can offer significant advantages in horticultural supplemental lighting such as mass production, plant quality, and energy efficiency.

Research and development of control strategies for LED lighting fixtures have been a topic for discussion over the years. While there are proposals for methods to achieve some of the desired control objectives, these proposals have been restricted to a residential and commercial building environment focusing on human-related factors. Whereas only a small number of proposed control methods apply to an indoor farming scenario, all of which do not consider energy saving. The latter aspect has motivated further studies in lighting control systems for plant growth in greenhouse environments, which is the subject of this thesis as discussed in the following chapters.
1.2 Background and Overview of the Present State of the Technology

1.2.1 Lighting System in Greenhouses

Building upon prior experience, the research work in this thesis is to develop a new intelligent supplemental lighting system for greenhouses. Specifically, photosynthetically active radiation (PAR) is a key process in plant growth and crop productivity. During the winter and fall seasons in BC and other northern regions, the daily PAR amount from sunlight, also called daily light integral (DLI), is far less than the minimum needed for plant growth. In greenhouse farming, LED grow-lights have been recognized as potential replacements for traditional supplemental lighting such as high-intensity discharge (HID) lighting system. LEDs have prominent features such as high energy to light conversion efficacy, flexibility in adjusting light intensity, spectral distribution, and long life spans. However, their utilization in greenhouse supplemental lighting is still at its infancy and further innovative products are required to take full advantage of their capabilities to make them economically viable.

By utilizing intelligent sensors that are physically scattered in an environment, the resulting distributed system would allow accurate real-time information about environmental variables at many points inside the greenhouse. This information is gathered and utilized by our proposed controller. The controller can perform the following functions that could otherwise not be possible using conventional greenhouse automation systems:

- Low-cost measurement of environmental climatic variables including photosynthetic light intensity, temperature, relative humidity, and carbon dioxide.
- Control of supplemental lighting (and shading) to achieve consistent daily light integral for maximizing photosynthesis activity with minimal energy consumption.
- Implementation of strategies based on off-peak electric rates, energy cost, and carbon footprint.
- Improving crop productivity by using the spectrum-selectivity capability of LED technology.
- Providing an environmental data monitoring system that can report the greenhouse health and status to the operators in real-time and alert them of possible malfunctions and hazards.

Further possible advantages of using spectrum- and intensity-selectable LED fixtures include the ability to increase crop’s monetary value by improving the quality such as flavour, colour, leaf shape, and the amount of daily light intake through intelligent sensing and controls.
Current conventional lighting control systems in the market do not have the functionality to improve energy-efficiency in greenhouse farming environments. However, in recent years there has been a push to develop LED lighting systems for the greenhouse industry as LED technology has become more affordable. The innovation involves feedback control strategies and sensing hardware aimed at optimizing the energy-efficiency and photosynthesis efficiency to achieve higher plant productivity.

1.2.2 Light Requirement for Plant Growth

Lumen, a unit of measurement based on the amount of perceivable light, is widely used as a reference input for lighting applications in residential and commercial buildings. Though this unit of measurement is useful in these environments, it is not useful in greenhouse environments as light sensitivity differs between humans and plants.

Photosynthetically active radiation (PAR) specifies the spectral range at which photosynthetic organisms undergo photosynthesis. This range is at 400 to 700 nanometers of solar radiation. During the photosynthesis process, different wavelengths of light show different utilization efficiency. Red light (600-700nm), as well as blue light (400-500nm), represents the main portions; whereas the green light is absorbed much less by plants reflecting in the green colour leaves that are commonly seen [1].

Photosynthetic Photon Flux (PPF) is a unit of measurement used to describe the total amount of PAR photons emitted by a lighting system. Considering that plant growth is dependent on photosynthesis activity, the amount of PPF that reaches the plant canopy surface, as well as the duration that it is available for, is an important measurement. We call this quantity Photosynthetic Photon Flux Density (PPFD), which is measured in micromoles per square meter per second, $\mu$mol $\cdot$ m$^{-2}$ $\cdot$ s$^{-1}$. Due to daylight changes, PPFD on the plant canopy level varies. To represent the overall influence of PPFD received within 24 hours, Daily Light Integral (DLI), can be used and expressed as $mol \cdot m^{-2} \cdot day^{-1}$.

Currently, the most common method used for plant growth in greenhouse environments requires the use of supplemental lighting that increases DLI through the extension of duration and strengthening of the PPFD during the winter and fall seasons. In large-scale indoor areas and greenhouses, high-intensity discharge (HID) lighting systems such as high-pressure sodium (HPS) and light and metal halide (HMI) are what is mainly used. One characteristic of HPS is that a high portion of light radiation emitted is on the far end of the light wavelength which produces high heat causing it to be an energy-inefficient system. In general, HID lighting systems generate high portions of waste heat and have a low electricity-to-light conversion rate. Moreover, due to the excess waste heat, fans are usually required to eliminate excess heat, increasing energy consumption. In some circumstances, however, the additional heat emission may be beneficial in warming up greenhouses during cold weather conditions. Consequently, the heating systems used in greenhouses to maintain optimal tem-
perature ranges operate with better energy efficiency. Thus, it is not necessary to use the excess heat emitted by lighting sources.

Comparatively, LEDs are more energy-efficient and have shown 30% of energy saving as compare to conventional lighting systems in greenhouses and indoor environment [2] [3] [4]. The waste heat emissions from the LEDs are relatively low and the need for additional cooling is reduced. As a result, concern over optimal temperature maintenance is lowered in greenhouse environments.

1.2.3 Effects of Lights with Mixing-color Control on the Plant Growth and Crop Productivity

The spectral light quality of the light source plays a crucial role in the photosynthesis process. According to the Plant Sensitivity Curve, also named as the McCree curve, the light spectrum on different wavelengths drives photosynthesis differently. On the red and blue spectrum, light is more easily absorbed during photosynthesis compared to those in green; influencing the development process of plant growth [5].

The red to far-red light is absorbed to convert phytochrome from one form to another directly stimulating processes such as flowering, stem elongation, leaf unrolling, and chlorophyll formation. Moreover, shade avoidance response, defined as the activation to the elongation of hypocotyl and attempt of the stem to out-compete surrounding plants, is triggered by the red and far-red photomorphogenic response [6].

Cryptochromes and phototropins, photoreceptor proteins that have an active influence on multiple aspects of plant growth, respond to blue light highly [6]. Generally, specific levels of blue light can restrain plant height, which can bring benefits to the plants in terms of fruit production. Similar to the use of red and far-red light, the combination of blue and near UV light plays a necessary role in the mechanism of crop production; specifically in the control of stem height and leaf area, as well as the flavour of fruits.

Though there are still unknowns in the influence mechanisms for plant growth; research on the effects of mixing colour ratios has been widely conducted. Results have demonstrated an important correlation between spectral distribution, light intensity, and other environmental conditions. The performance of the beneficial advantages brought from LED fixtures varies and depends on the specific species and requirements for plant growth.

A comparison between LED fixtures and conventional lighting fixtures, such as HPS and HM lighting fixtures, is evaluated based on different spectral ratios, commonly named *light recipes*. In a study on the effects of varying red and blue mixing colour ratios, LEDs have shown that a 7:3 (red: blue) ratio increases the water content and fresh weight of peppermint; while also shortening the flowering period for pot flowers. Comparatively, fewer improvements were observed in a white light environment [7]. Based on set target yield production and quality parameters, research on lettuce to compare different light colour ratios (9:1, 7:3, 5:5, LED red: blue, white LED, and HPS light, respectively) with identical
amounts of PPFD at 200 µmol·m⁻²·s⁻¹, and a photoperiod of 16 hours has been conducted [8]. Results indicated that lettuce harvested under the red: blue light treatment showed the highest dry mass and soluble sugar content comparatively. Moreover, the study notes that a red: blue ratio where the blue light is at 30% or higher, does not increase results. This indicates that correct ratios of red and blue light must be utilized to achieve an optimal enhancement in plant growth. It is also necessary to note that each plant species photosynthesize at different light saturation levels, and must be tailored to reach the highest efficiency. The light saturation level consists of specific ratios of different coloured lights for photosynthesis active radiation, as well as the specific amount of the cumulative PPFD to represent optimal light treatment. This is because, even with the same ratio of spectral distribution, light treatments perform differently under different PPFD outputs.

In an investigation on the effects of different PPFD outputs, pea plants were tested on and compared based on crop growth, yield production, and tastiness. All treatments used a fixed 4:1 (red: blue) ratio, and differed on the PPFD levels (0, 50, 80, 110 and 140 µmol·m⁻²·s⁻¹) [9]. Results indicate that treatment ranging from 110-140 µmol·m⁻²·s⁻¹ increases overall firmness and yields the most; however, it has the lowest level of succulence. Comparatively, treatment using natural daylight shows the lowest stem firmness and yield production but the highest succulence level. In practical settings, the desired target would be a light saturation level that balances taste and crop productivity to meet customer demands and be cost-effective.

### 1.2.4 Control Strategy and Application for Lighting Control

In the past few decades, energy efficiency and a combination of other considerations based on the use of lighting to achieve optimal functionality has been widely discussed in different lighting strategies. Of which, energy efficiency is the most important. Other factors mostly depend on the requirements for the specific objects and are mainly discussed in two environments: human comfort based environments such as offices and residential building, and plant growth based environments such as greenhouses and indoor farming.

In the following, control applications with a lighting system targeting several achievements are applied in an office environment, an indoor farming environment, and a greenhouse environment is introduced, respectively.

**Energy Saving Based Lighting Control System**

Fig. 1.1 depicts the control block diagram of a lighting control system with two control modes for energy-saving and colour-tuning based human comfort consideration [10]. In this study, a light transport map is built with the data collected from the light sensors and the system model is identified through the plant equations:
Figure 1.1: A lighting control system with two control modes for the consideration of energy saving and light color-tuning [10].

\[
\begin{align*}
\phi &= Pu + \psi \\
\psi^d &= C\phi + v \\
\end{align*}
\]  

(1.1)

where \( C \) represents the light transport map, \( v \) represents the noisy data acquired from the sensors, \( d \) represents the reading from the sensors, \( P \) represents the map of the system input \( u \), \( \psi \) refers the disturbance, and \( \phi \) refers to the generated light output.

To achieve energy savings, a gradient-based method is applied to the cost function and the models that were built with the light transport map introduced above. The optimization problem is expressed as

\[
\text{minimize } J(u) \\
\text{subject to } \phi^{\text{meas}} = Au + w
\]  

(1.2)

where

\[
J(u) = \alpha_L \left| L_{\phi}^{\text{des}} - L_{\phi}^{\text{meas}}(u) \right|_2^2 + \alpha_a \left| L_{\phi_a}^{\text{des}} - L_{\phi_a}^{\text{meas}}(u) \right|_2^2 + \alpha_b \left| L_{\phi_b}^{\text{des}} - L_{\phi_b}^{\text{meas}}(u) \right|_2^2 + \alpha_u \Gamma uu
\]  

(1.3)

In the Equation 1.11, the desired set point and the light measurement is denoted as \textit{des} and \textit{meas} and the weight for each term is denoted as \( \alpha \). Hence, the control law of the \( k-th \) time-step is expressed as
where the step size and gradient is represented by $\varepsilon$ and $\nabla_u(\cdot)$, respectively.

In this control, the colour quality from the light source is considered in addition to energy consumption. To achieve this, two optimizers are applied, to obtain an optimal point with the highest energy efficiency and input for the required LED dimming to fulfill the desired lighting condition. The optimization problem of the energy efficiency and the light quality is given by

$$
\begin{align*}
\text{minimize} & \quad \mu_E(u) \\
\text{subject to} & \quad (\phi_x^*, \phi_y^*, \phi_L^*) \in S, \\
& \quad \phi_L^* = \phi_{des}^L
\end{align*}
$$

(1.5)

$$
\begin{align*}
\text{minimize} & \quad \mu_Q(\phi_{des}, \phi_{meas}) \\
\text{subject to} & \quad \phi_{meas} = Au + w
\end{align*}
$$

(1.6)

where $\phi_{des}$ is denoted as the desired light condition of the projected vector $\phi_x, \phi_y, \phi_L$ on the XYZ colour space devised by the International Commission on Illumination (CIE). The results of this study have shown an energy-savings of up to 20%. However, the main drawback is that the enhancement of energy efficiency works best when no disturbance is applied, which is not realistic. Although this control is robust and light efficient, improvements on the challenges to maintaining light quality within a satisfactory range are still needed.

Occupancy detection is one of the most common lighting control methods that have been applied as an effective way to save on energy cost [11], [12], [13]. A study which formulates daylight harvesting and occupancy into an indoor lighting control has shown that 60% of energy saving has been achieved [14]. The concept of the control system is shown in Fig. 1.2. For every single luminaire, the illuminance on the workplace level, denoted as $E$, is expressed as followed

$$
E = \sum_{i=1}^{K} d_i \cdot l^i = \sum_{i=1}^{K} d_i \cdot \begin{bmatrix}
l_{11}^i & \cdots & l_{1n}^i \\
\vdots & \ddots & \vdots \\
l_{m1}^i & \cdots & l_{mn}^i
\end{bmatrix}
$$

(1.7)
where the $d_i$ represents the dimming level of $i^{th}$ luminaire, and the matrix $l^i$ represents the summation of the whole office space associated with $K$ luminaires.

Over frequent dimming with robustness can enhance energy-saving, but would also cause discomfort. Thus with consideration to an occupant’s tolerance and sensitivity, a certain tolerance index is applied as followed

$$\min \|d\|_1, \text{ subject to}$$

$$\begin{cases}
Ld \leq T_0 + \varepsilon_{tot}, \\
Ld \geq T_0 - \varepsilon_{tot}, \\
\dimLevel_{min} \leq d \leq \dimLevel_{max}
\end{cases}$$

where $T_0$ represents the desired illuminance value, $\varepsilon_{tot}$ represents the index range that the system tolerates, $\dimLevel$ and $\dimLevel_{max}$ restrain the dimming range of the physical light fixtures.

The advantage of this control when applied in an office workstation environment is that it offers the capability for users on each office table to set up their preferred light output. Energy efficiency performance, however, is determined by user configurations and occupancy conditions. For instance, this control would not show visible energy savings if all workstations are occupied during regular office hours, and the preferred light output on each table is set at full brightness. A study conducted in [15] uses similar control technology but added measurements for daylight illuminance value to enhance the performance on the balance between energy efficiency and user experience.

In addition to the stability of the illuminance output, the distribution uniformity of the illuminance is another key factor that directly affects human comfort. In commercial buildings and large office spaces, it is common for windows to be on one side of the room causing an unbalanced daylight distribution. The work in [13] demonstrates a localized
illumination rendering method to equalize the light distribution by taking advantage of daylight in the occupied zone. The uniformity is determined as

\[
\frac{|E(x, y, z; d) - L|}{L} \leq C_{th}
\]

(1.9)

where a uniformity contrast is defined as \(C_{th}\), for an illuminance level \(L\) in the illuminance pattern \(E\). The illuminance distribution is considered uniform if the illuminance value \(E\) is equal to or below the uniformity contrast value. In consideration of energy efficiency, occupancy detection is applied along with a uniformity distribution where two different rendering rules are applied to the occupied and unoccupied zones. Thus the constraint in an occupied zone is formulated as

\[
\frac{|E_T(x, y, z; d) - \bar{E}_{T,m}(d)|}{\bar{E}_{T,m}(d)} \leq C_{th}
\]

(1.10)

and the constraint in a unoccupied zone is formulated as

\[
E_T(x, y, z; d) \geq L_{min}
\]

(1.11)

where \(\bar{E}_{T,m}(d)\) represents the average illuminance level when the controlled dimming is \(d\), \(L_{min}\) represents the minimum illuminance value.

To consider both the uniformity of the rendered illuminance and the energy efficiency, and optimum dimming vector and the corresponding restraints are formulated as followed

\[
\min_{d} \sum_{m=1}^{M} (\alpha_m \eta P_{on} d_m + (1 - \alpha_m) U_m (\bar{E}_{T,m}(d), E_D, m))
\]

\[
\begin{align*}
\left\{ \frac{E_T(x, y, z; d) - \bar{E}_{T,m}(d)}{\bar{E}_{T,m}(d)} \right\} & \leq C_{th} \\
E_T(x, y, z; d) & \geq L_{min} \\
0 & \leq d_m \leq 1
\end{align*}
\]

(1.12)

where \(\alpha_m\) is denoted as the weighting value for the balance between energy efficiency and uniformity level, \(P_{on}\) is the energy consumption of LED, \(d_m\) is the dimming level of \(m\)th light unit.

The results of the uniformity under no daylight condition shows better performance than the results in a daylight condition. Deviations of the actual illuminance level from the desired illuminance set point are observed and are under the acceptable range [14].
The only drawback is that the proposed control method in this work is only tested in a simulation environment, not considering factors that affect the control performance caused by hardware implementation.

1.3 Summary of Contributions and Outline of the Dissertation

Regarding the supplemental lighting for plant growth in greenhouses, an energy-efficient, uniform light distribution that achieves light requirement for optimal conditions of crop productivity is to be desired. To this end, a novel lighting control system is proposed and its applications are studied. In this regard, the contributions of this thesis are summarized below.

1.3.1 Chapter 2: Development of Greenhouse LED System with Red: Blue Mixing Ratio and Daylight control

In this chapter, we present an energy-efficient control application that is capable of achieving optimal light conditions for plant growth in the greenhouse. By taking advantage of daylight harvesting, the system regulates the dimming level of LEDs based on the light irradiance data from red and blue channels of the light sensors located on the testbed. The state-space models for the red light and blue light are identified separately in the system to ensure uniform light distribution. A series of simulations and experiments are presented in this article to verify the control performance of the proposed system. Furthermore, the environment built for this application can be used to validate the performance of light control strategies in both office and greenhouse scenarios.

1.3.2 Chapter 3: Proof-of-Concept Control System for Supplemental LED Lighting with Application to Energy-efficient Greenhouses

The use of a multiple-input multiple-output (MIMO) control system integrated with daylight harvesting is presented for greenhouse lighting. The proposed controller is capable of regulating the intensity of a dimmable multi-spectrum LED light system for achieving desired light intensity at sensor locations. The control hardware consists of multiple light sensors, a micro-controller, and dimmable and spectrum selectable LED supplemental light fixtures. The proposed controller was tested in a grow tent environment which includes halogen light lamps acting as simulated daylight. Studies are conducted to evaluate the performance of the control system for supplemental lighting in the plant growth spectrum. The proposed control strategy can be used to achieve energy-efficient operation in a greenhouse environment. A Smith predictor is utilized to compensate for the delay introduced into the system dynamics by the hardware to ensure stability and performance. The Smith Predictor control and stability analysis was in collaboration with Ms Afagh Mohagheghi.
1.3.3 Chapter 4: Development of a Testbed with Intelligent LED Lighting Control System for IoT Smart Greenhouse

Our study aims to develop an intelligent control system for mixing colour ratios using LED lights in a greenhouse environment. Different components of an experimental testbed are presented for achieving the desired light requirements for plant growth in a greenhouse environment. The proposed testbed provides an easy-to-use plant growth system with IoT-enabled control and monitoring features. To testify the features mentioned above, a feedback lighting control method to achieve a desired photosynthetic photon flux density (PPFD) setpoint is implemented. A two-week experiment had been conducted on microgreen kale which was planted in the testbed and harvested at the end of the experiment. The experimental results showed that the tested microgreen kale grew in healthy conditions in the proposed testbed and lighting environment.

1.3.4 Chapter 5: An Intelligent IoT-enabled Lighting System for Energy-efficient Crop Production

Intelligent lighting control and management systems achieve high energy-efficiency in greenhouse environments using supplemental lighting based on the Internet of Things (IoT) technology. The system runs on a Raspbian operating system that interacts with wireless-enabled light-emitting diode (LED) fixtures for plant growth, an online data server, and different light sensors including RGB and quantum sensors. Communication is achieved through the use of RestFul API, UART, and I2C. This system is then utilized to implement a feedback controller that automatically adjusts the light dimming levels; particularly, the ratio of red and blue light required for optimal plant growth. In a series of experiments conducted involving plant growth, results indicated that the proposed system can achieve energy-savings up to 34% when compared to conventional time scheduling schemes. Additionally, the experiments demonstrated that the system achieves a highly uniform light distribution under unpredictable natural lighting conditions while saving energy due to supplemental lighting.

1.3.5 Chapter 6: Conclusions and Suggestions for Future Work

A review of the main contributions to this thesis on proposed lighting control systems will be discussed in this chapter using applicable theories, as well as simulations and experiments conducted for this thesis. Additionally, an outline of suggestions and ideas for further research is included.
Chapter 2

Development of Greenhouse LED System with Red:Blue Mixing Ratio and Daylight Control

2.1 Introduction

The light-emitting diode (LED), as an energy efficient light source, accounted for 35.2% of the overall light market in North America [16] [17]. Compared with conventional supplemental grow lights such as High Pressure Sodium (HPS) and Metal Halide (MD), LED achieves an increase in energy savings of up to 45% [3]. As a result, the lighting control system developed dramatically along with the growth of the LED light market and Internet of Things in smart applications [18], [19].

In recent years, there has been growing attention on taking advantage of daylight harvesting into lighting control system for cutting energy consumption. It has been proven as one of the useful solutions for energy saving by many studies. A control strategy with fuzzy logic programming applied at indoor lighting system was proposed to reduce the energy consumption [20]- [21]. Stefano et al. estimated the daylight illumination levels based on the sensor located at the ceiling to reduce under-illumination and energy consumption in the workplace environment [22]. An adaptive control method using the light sensor at the ceiling with prior calibrated information was presented in [23]. Also, neural network based lighting control, which did not need the model identification and disturbance information has been developed and discussed in [24]- [26]. Also, other factors such as the human comfort, uniform light distribution, system stability, operation feasibility were considered in a lighting system for different environments as well. All the strategies are aimed to achieve higher energy efficiency, more uniform light output, and better human experience at the office or residential environment.

On the other hand, LED has also shown lots of advantages in mass production, plant quality and energy efficiency in horticulture, based on the preliminary investigations led by NASA since the 1980s [27]. Experiments conducted in [28], [29] have shown that a
Figure 2.1: System set up diagram of the lighting system for plant growth.

A series of light treatments with specific mixing ratios of LED red and blue light significantly reduced harvesting time and increased yield performance. A series of comparative tests were conducted in [30] to determine some of the most suitable light recipes (specific mixing colour LED ratios) for efficiently improving nutritional quality of sweet basil and strawberry.

However, limited research on lighting control system with daylight harvesting applied in greenhouses has been discussed thus far. Akira and Kazuhiro applied PID control to their proposal lighting system for achieving a desired photon flux density (PFD) and mixing ratios of multiple wavelength-band LED lights. Since their system was designed for an indoor farming environment, daylight was not considered [31]. In [32], [33] the scheduling scheme for lighting and movable shades were combined to maintain the light intensity at a particular optimal range for achieving the growth condition. It was capable of achieving energy saving to a certain extent but did not consider the uniform light distribution.

Although most of the considerations were focused on energy savings and light uniformity, what differs in the lighting control between greenhouses and the ones in office and residential environments is the target. The latter scenario puts human comfort on the priority list. But since the objective is the plant in the former plot, the light system is required to provide a stable light irradiance output and a scheduled photoperiod to optimized the yield production. Meanwhile, under different growth stages of different plants, the colour ratio of light varies. In an office environment, researchers take advantages of occupation control to reduce energy consumption.

Daylight harvesting, which adjusts the dimming level of LED growth lights based on the daylight irradiance detected by the light sensor, is an efficient way to save on energy consumption. Daylight is also commonly considered a disturbance source for lighting control
systems as it tends to enter indoor environments from one window side. However, none of the related solutions applies to a greenhouse environment as this issue is less prevalent in greenhouse environments.

The second challenge is the cross-illumination effect. In the greenhouse space, there is no partition to isolate light sources. The irradiance outputs of different light sources cause a cross-illumination effect, affecting each other more severely than light sources in an office area with partial partition installed. Thus, the modelling and identification of lighting systems in greenhouses are more challenging. Light optimization for plant production and energy efficiency are two of the most significant challenges regarding the lighting system in greenhouses. Including daylight harvesting, it is hard to maintain a relatively uniform light output while optimizing energy consumption.

In this chapter, we first considered energy efficiency by taking advantage of daylight harvesting. Daylight also plays a role as a disturbance input in the feedback control algorithm. Secondly, achieving uniform light distribution is considered into the control system by putting multiple light sensor on the testbed. Thirdly, taking into account the red-blue mixing ratio light treatment for plant growth, the proposed system achieves a desire red-blue mixing ratio.

The organization of this chapter is as followed. In section 2.2, the development of the application was described. In section 2.3, the implementation and identification of the control part in the system were presented in detail. In section 2.4, the simulation and experimental
results were presented and discussed. The future improvements and summary were described in section 2.5.

2.2 System Development and Implementation

2.2.1 Background

In the preliminary stage, a testbed environment was built for the system set up in the experimental stage. As shown in the system diagram of Fig. 2.1, the grow tent (5’x5’x6’11” dimension, 7’11” height, from Gorilla Grow Tent Inc.) installed in the lab was used to isolate the distraction of light condition outside. Two units of 1 kW power rated halogen light were used in the system as the daylight emulator and hung on the middle top of the testbed. The illumination output of the halogen light was dimmed by a variac variable transformer.

Different types of light sensors have been considered. An ideal light sensor applied in the proposed system is expected to provide a series of light irradiance data in different wavelength ranges, such as red light (620-750 nm) and blue light (450-495 nm) for achieving...
mixing ratios. Illumination sensors are widely used in office lighting controls. They give \textit{lux} as a measurement unit for light intensity based on the perception by the human eye but not the plant objects. Whereas the quantum sensor was used for measuring the Photosynthetically Active Radiation (PAR, $\mu$mol m$^{-2}$ s$^{-1}$) in greenhouses. Since the quantum sensor is only able to give the overall photon value calibrated on specific light sources like sunlight and fluorescent lamps, it is still not possible to use it for measuring the photon levels at different colour wavelengths. Thus, we decided to use an RGB light sensor in the proposed system to measure the light irradiance on red and blue wavelengths.

LED units are the controlled target in the proposed system. The API was supposed to be designed for universal serial communication. For the experiments on the testbed, two units of programmable red and blue LED grow lights (Q400, QuanTech Inc.) were installed in the tent. A high power F28335 microcontroller (from Texas Instruments Inc.) was operated as the central controller for the proposed control system.

Listing 2.1: Part of the coding for system configuration.

```c
#define TCA_MUL 0x70
#define TCA_CHANNEL_0 0x01
#define TCA_CHANNEL_1 0x02
#define TCA_CHANNEL_2 0x04
#define TCA_CHANNEL_3 0x08
#define TCA_CHANNEL_4 0x10
#define TCA_CHANNEL_5 0x20
#define TCA_CHANNEL_6 0x40
#define TCA_CHANNEL_7 0x80

#define TCS_RGB_SLAVE 0x29
#define POINTER_CLR 0x94
#define POINTER_CONFIGURATION 0x80
#define POINTER_ENABLE 0x1B

int CLR1_temp;
int CLR2_temp;
int BLU1_temp;
int BLU2_temp;
int GRE1_temp;
int GRE2_temp;
int RED1_temp;
int RED2_temp;
```

2.2.2 Data Acquisition

In the proposed application, the light sensors (TCS3472, TAOS Inc.) were capable of capturing the light irradiance under three different colour channels (red, green, and blue) and
transmitted data through I2C communication. Since all the light sensors are identical, they have the same I2C address and not address changeable. We cannot directly connect multiple identical light sensors on the I2C bus line. To tackle this problem, a multiplexer (TCA9548A, Adafruit Inc.) was applied in the proposed system. As shown in Fig.2.2, all the RGB light sensors were connected to different channels of the multiplexer, and then triggered to send data in order. The switching delay was very short and had minimal effects on system performance.

Listing 2.2: Part of the coding for I2C communication with light sensors.

```c
void Read_I2C_Channel
(Uint16 Channel_Address, int *Pointer1,
 int *Pointer2, int *Pointer3,
 int *Pointer4)
{
    GpioDataRegs.GPBDAT.bit.GPIO34 = 0;
    for (b=1000;b>0;b--)
    {
    }
    GpioDataRegs.GPBDAT.bit.GPIO34 = 1;
    for (b=1000;b>0;b--)
    {
    }

    I2caRegs.I2CSAR = 0x70;
    for (b=10000;b>0;b--)
    {
    }

    I2caRegs.I2CCNT = 1;
    I2caRegs.I2CDXR = Channel_Address;
    I2caRegs.I2CMDR.all = 0x6E20;
    while(I2caRegs.I2CSTR.bit.XRDY == 0);
    while(I2caRegs.I2CSTR.bit.SCD == 0);
    I2caRegs.I2CSTR.bit.SCD = 1;
    for (b=10000;b>0;b--)
    {
    }

    I2caRegs.I2CSAR = 0x29;
    I2caRegs.I2CCNT = 2;
    I2caRegs.I2CDXR = POINTER_CONFIGURATION;
    I2caRegs.I2CMDR.all = 0x6E20;
    while(I2caRegs.I2CSTR.bit.XRDY == 0);
    I2caRegs.I2CDXR = POINTER_ENABLE;
```
while(I2caRegs.I2CSTR.bit.SCD == 0);
I2caRegs.I2CSTR.bit.SCD = 1;
    for (b=10000;b>0;b--)
    {
    }
I2caRegs.I2CSAR = 0x29;
I2caRegs.I2CCNT = 1;
I2caRegs.I2CDXR = POINTER_CLR;
I2caRegs.I2CMDR.all = 0x6620;
while(I2caRegs.I2CSTR.bit.XRDY == 0);
while(I2caRegs.I2CSTR.bit.ARDY == 0);
for (b=10000;b>0;b--)
    {
    }
I2caRegs.I2CCNT = 8;
I2caRegs.I2CMDR.all = 0x6C20;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
CLR1_temp = I2caRegs.I2CDRR;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
CLR2_temp = I2caRegs.I2CDRR;
*Pointer1 = CLR2_temp<<8|CLR1_temp;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
RED1_temp = I2caRegs.I2CDRR;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
RED2_temp = I2caRegs.I2CDRR;
*Pointer2 = RED2_temp<<8|RED1_temp;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
GRE1_temp = I2caRegs.I2CDRR;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
GRE2_temp = I2caRegs.I2CDRR;
*Pointer3 = GRE2_temp<<8|GRE1_temp;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
BLU1_temp = I2caRegs.I2CDRR;
while(I2caRegs.I2CSTR.bit.RRDY == 0);
BLU2_temp = I2caRegs.I2CDRR;
*Pointer4 = BLU2_temp<<8|BLU1_temp;
}

The system initialized the multiplexer to reset and power it on. Then the system initialized the I2C sensor on the first channel and started to send a reading command to read the data. Continuously, the sensors on the 2nd channel, 3rd channel, 4th channel until the 10th channel were waiting for readings respectively. For each channel, a series of light sensor data were sent during the trigger time, which included explicit light irradiance, red colour irradiance, green colour irradiance and blue colour irradiance. For the experiments on the testbed, two units of RGB sensors were located at the bottom of each LED panel. Moreover, only red and blue colour irradiance data were used as the input data for data capture.
Table 2.1: Configuration of the SCI communication with LED panels.

| SCI port 1 | LEDA  | Inclination | 35°   |
| SCI port 2 | LEDB  | Inclination | 145°  |
| Baud rate  | 115200| Height from | 1 meter|
| Data bits  | 8     | Dimming command range | 0 ~ 255 |
| Start/Stop bits | 1 | Dimming level range | 0% ~ 100% |
| Parity bits | None  | LED channel applied | Blue and Red |
| Flow control | None  | SCI API commands | API START; API ON; API SET |

2.2.3 Serial Communication with LED Panels

The dimming commands are sent from the microcontroller to LED panels via Serial Communication Interface (SCI). The configuration for the serial communication including baud rate, data bits is summarized in Table 2.1 for both LED panels. SCI port A and port B were connected with LED panel A and LED panel B, respectively. Both LED panels were identical with red LED units and blue LED units, which owned dimming levels ranging from 0 to 255.

As shown in the control flow diagram in Fig. 2.3, the SCI port communication was initialized with commands 'API ON' and 'API START'. 'API ON' was sent to trigger on the LED panel. 'API START' was sent to switch the LED from the local mode to 'remote control' and initialized all the units to the previous default state.

After the panel successfully initialized and powered on, an 'API SET' command is generated continuously to send the control outputs. As shown in the coding in listing 1, 'LED1b', 'LED2b', 'LED3b', 'LED4b', 'LED5b', 'LED6b' are defined as the variables of dimming command for red/blue channels on LED panel B. Specifically, 'LED2b' and 'LED3b' are for blue LED units while 'LED4b', 'LE5b' and 'LED6b' are for red LED units. The same definitions were applied to the LED panel A. For example, 'API SET 100,200,155,155,155,0,1' is defined to set blue LED at 200 out of 255 levels (78%) , and red LED at 155 out of 255 levels (61%).

Listing 2.3: Part of the coding for SCI communication with LED panels.

```c
void SCIA_init()
{
  SciaRegs.SCICCR.all =0x0007;
  SciaRegs.SCICTL1.all =0x0003;
```
```c
SciaRegs.SCIHBAUD = 40 >> 8;
SciaRegs.SCILBAUD = 40 & 0x00FF;
SciaRegs.SCICTL2.bit.TXINTENA = 1;
SciaRegs.SCICTL1.all = 0x0023;
```

```c
send control command to 2 LED panels
via SCIA and SCIB ports

snprintf(message2_a, 50, "API\_SET,\%u,\%u,\%u,\%u,\%u,\%u,0,1\n\r", LED1a, LED2a, LED3a, LED4a, LED5a, LED6a);
snprintf(message2_b, 50, "API\_SET,\%u,\%u,\%u,\%u,\%u,\%u,0,1\n\r", LED1b, LED2b, LED3b, LED4b, LED5b, LED6b);

message=&message2_a;
SciaRegs.SCITXBUF=message[index++];
for(b=10000;b>0;b--)
{
}
index =0;

message=&message2_b;
ScibRegs.SCITXBUF=message[index++];
for(b=10000;b>0;b--)
{
}
index =0;
```

### 2.3 Proposed Control Algorithm

Fig. 2.4 shows the block diagram of the proposed control algorithm. $Y_f$ is defined as the disturbance input, which refers to the emulated daylight. $Y_d$ represents the desire light irradiance, and $Y$ is defined as the output light levels, which relates to the data acquired by the light sensors located on the testbed. The whole system was assumed to be a multi-input and multi-output closed loop feedback system. The experiments conducted in [34], [35] had shown that the irradiance output is linearly related to the power input of the LED unit, and also the dimming command (0 ∼ 255 dimming levels, equivalent to 0% to 100% dimming percentage) was directly linear related to the LED power input.

By assuming the illuminance output $\varphi$ has linear relationship with the input power to the LED units [36] [37] [38], the relationship between light intensity detected at the sensor and the illuminance emitted from the light source is represented as followed
Table 2.2: System identification of red LED channel.

<table>
<thead>
<tr>
<th>0-255 dimming level</th>
<th>%dimming percentage</th>
<th>t11_sensor_red</th>
<th>t12_sensor_red</th>
<th>t21_sensor_red</th>
<th>t22_sensor_red</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0%</td>
<td>10</td>
<td>55</td>
<td>10</td>
<td>54</td>
</tr>
<tr>
<td>25.5</td>
<td>10%</td>
<td>523</td>
<td>248</td>
<td>170</td>
<td>807</td>
</tr>
<tr>
<td>51</td>
<td>20%</td>
<td>1080</td>
<td>463</td>
<td>343</td>
<td>1617</td>
</tr>
<tr>
<td>76.5</td>
<td>30%</td>
<td>1648</td>
<td>683</td>
<td>521</td>
<td>2446</td>
</tr>
<tr>
<td>102</td>
<td>40%</td>
<td>2184</td>
<td>894</td>
<td>692</td>
<td>3226</td>
</tr>
<tr>
<td>127.5</td>
<td>50%</td>
<td>2735</td>
<td>1114</td>
<td>868</td>
<td>4036</td>
</tr>
<tr>
<td>153</td>
<td>60%</td>
<td>3184</td>
<td>1354</td>
<td>1035</td>
<td>4786</td>
</tr>
<tr>
<td>178.5</td>
<td>70%</td>
<td>3698</td>
<td>1573</td>
<td>1207</td>
<td>5558</td>
</tr>
<tr>
<td>204</td>
<td>80%</td>
<td>4265</td>
<td>1781</td>
<td>1372</td>
<td>6285</td>
</tr>
<tr>
<td>229.5</td>
<td>90%</td>
<td>4664</td>
<td>1995</td>
<td>1541</td>
<td>7025</td>
</tr>
<tr>
<td>255</td>
<td>100%</td>
<td>5203</td>
<td>2233</td>
<td>1725</td>
<td>7942</td>
</tr>
</tbody>
</table>

\[ E_j = \frac{1}{4\pi} \sum_{i=1}^{n} \frac{\varphi_i}{d_{ij}^2} \]  

(2.1)

where \( E_j \) indicates the irradiance detected by the \( j \) light sensor, \( d_{ij} \) indicates the distance between \( i \) light source and \( j \) sensor, and \( \varphi_1, \varphi_2, ..., \varphi_n \) is defined as the illuminance output from the 1st, 2nd, 3rd, ..., nth light source.

We expand the formula for all \( n \) light units and \( m \) light sensors to get the expression as followed

\[
\begin{bmatrix}
E_1 \\
E_2 \\
. \\
. \\
E_m
\end{bmatrix}
= \frac{1}{4\pi}
\begin{bmatrix}
\frac{1}{d_{11}^2} & \cdots & \frac{1}{d_{1m}^2} \\
\vdots & \ddots & \vdots \\
\frac{1}{d_{m1}^2} & \cdots & \frac{1}{d_{mn}^2}
\end{bmatrix}
\begin{bmatrix}
\varphi_1 \\
\varphi_2 \\
. \\
. \\
\varphi_n
\end{bmatrix}
\]

(2.2)

\[
= T
\begin{bmatrix}
P_{d1} \\
P_{d2} \\
. \\
. \\
P_{dn}
\end{bmatrix}
\]

where \( P_{d1}, P_{d2}, ..., P_{dn} \) are defined as the input power of the 1st, 2nd, ..., n-th LED unit and \( E_1, E_2, ..., E_m \) are defined as the irradiance measured by the 1st, 2nd, ..., m-th light sensor, respectively. Thus, the plant is represented as linear model \( T \), a \( m \times n \) matrix.
Table 2.3: System identification of blue LED channel.

<table>
<thead>
<tr>
<th>0-255 dimming level</th>
<th>% dimming percentage</th>
<th>t11_sensor blue</th>
<th>t12_sensor blue</th>
<th>t21_sensor blue</th>
<th>t22_sensor blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0%</td>
<td>8</td>
<td>44</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>25.5</td>
<td>10%</td>
<td>941</td>
<td>314</td>
<td>343</td>
<td>919</td>
</tr>
<tr>
<td>51</td>
<td>20%</td>
<td>2070</td>
<td>640</td>
<td>746</td>
<td>1980</td>
</tr>
<tr>
<td>76.5</td>
<td>30%</td>
<td>3228</td>
<td>974</td>
<td>1166</td>
<td>3081</td>
</tr>
<tr>
<td>102</td>
<td>40%</td>
<td>4326</td>
<td>1290</td>
<td>1565</td>
<td>4137</td>
</tr>
<tr>
<td>127.5</td>
<td>50%</td>
<td>5442</td>
<td>1613</td>
<td>1976</td>
<td>5214</td>
</tr>
<tr>
<td>153</td>
<td>60%</td>
<td>6500</td>
<td>1918</td>
<td>2362</td>
<td>6225</td>
</tr>
<tr>
<td>178.5</td>
<td>70%</td>
<td>7564</td>
<td>2226</td>
<td>2759</td>
<td>7278</td>
</tr>
<tr>
<td>204</td>
<td>80%</td>
<td>8562</td>
<td>2516</td>
<td>3134</td>
<td>8264</td>
</tr>
<tr>
<td>229.5</td>
<td>90%</td>
<td>9595</td>
<td>2814</td>
<td>3514</td>
<td>9262</td>
</tr>
<tr>
<td>255</td>
<td>100%</td>
<td>10774</td>
<td>3155</td>
<td>3966</td>
<td>10449</td>
</tr>
</tbody>
</table>

As stated before, the proposed system was aimed to converge to the desire light irradiance defined by users and eliminate the cross-illumination effect to achieve light uniformity. Thus, model $T$ is identified before the gain matrix $K$ is conducted. Based on the set up of the testbed and testing environment, we considered $T$ as a $2 \times 2$ full rank matrix as follows:

$$T = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix}$$  \hspace{1cm} (2.3)

where $t_{ij}$ are unique coefficients representing the relationship between the $i$ – th luminaire and the $j$ – th light sensor.

The identification process is conducted to find the relationship between the input dimming percentage (0% to 100%) of the LED units (referred to as $LEDA$ and $LEDB$) and irradiance data acquired by the RGB light sensor. From the data shown in Table 2.2 and 2.3, the relationship between the dimming level and the irradiance data measured by the sensor is given as:

$$E_{1\text{red}} = 20.386x_{1r} + 6.724x_{2r}$$  \hspace{1cm} (2.4)

$$E_{2\text{red}} = 8.582x_{1r} + 30.695x_{2r}$$  \hspace{1cm} (2.5)

where $x_1$ and $x_2$ is defined as the dimming percentage of red channel on $LEDA$ and $LEDB$ and $E_1$ and $E_2$ is defined as irradiance data of red channel on the 1st and 2nd sensor, respectively.

Thus we combine (2.4) and (2.5) to get the model
Figure 2.5: Simulation results of scenario 1, when no daylight is applied and desired levels are at 500, 2000, 5000, 9000 in order from left to right.

\[
T_{\text{red}} = \begin{bmatrix} 20.386 & 6.724 \\ 8.582 & 30.695 \end{bmatrix}
\] (2.6)

By applying the same identification process for the results shown in Table III, we get

\[
T_{\text{blue}} = \begin{bmatrix} 42.342 & 15.551 \\ 12.234 & 40.902 \end{bmatrix}
\] (2.7)

where \(T_{\text{red}}\) and \(T_{\text{blue}}\) represent the system model in red light environment and blue light environment, respectively.

Based on the LQR theory, if we assumed the state-space format system matrices \(A = 0, B = -T\), the symmetric positive-definite weighting matrices \(Q = qI\) and \(R = rI\), the Algebraic Riccati Equation is expressed as following [37]

\[
qI - \frac{1}{r}P(-T)I(-TT^T)P = 0
\] (2.8)

Thus, \(P\) can be expressed as following

\[
P = \sqrt{rq}(TT^T)^{-1/2}
\] (2.9)

Therefore, the state feedback coefficient \(K\) is given by

\[
K = -R^{-1}B^T P = \sqrt{q/r}T^T (TT^T)^{-1/2}
\] (2.10)
Combined with the identification model $T$ from the results in the (6) and (7) into [39], we can get the state feedback gain

$$K_{\text{red}} = \begin{bmatrix} 0.9993 & 0.0363 \\ -0.0363 & 0.9993 \end{bmatrix}$$

(2.11)

and

$$K_{\text{blue}} = \begin{bmatrix} 0.9992 & -0.0398 \\ 0.0398 & 0.9992 \end{bmatrix}$$

(2.12)

where $K_{\text{red}}$ and $K_{\text{blue}}$ are the gains for red and blue channels, respectively.

2.4 Simulations and Experiments

2.4.1 Simulation Results

We set different scenarios for the simulations running on MATLAB/Simulink environment to verify the control performance. Primarily we focus on the following aspects:

1. Whether the system is capable of being stable at the desired light level that we set;
2. Whether the system is capable of overcoming the over-illumination effect so as to get a uniform light distribution;
3. When disturbance light applied, whether the actual light irradiance output measured by sensor is close to the desire light levels for each wavelength range (red and blue).

Scenario 1: No sunlight in greenhouse, refers to night time. This scenario applies to the night time where there is no sunlight but the plants still need supplemental lights for...
the optimal growth. Therefore, we set 4 different desired light levels 500, 2000, 5000, 9000 respectively, and disturbance light level as zero. As we expected, the simulation results shown in Fig. 2.5 indicated that the system was able to achieve the desired light levels uniformly with a slight overshoot.

Scenario 2: sunlight irradiated in greenhouse. All the settings are the same as in Scenario 1, except sunlight at 3000 levels is introduced to the system. The results in Fig.2.6 showed a significant impulse occurred then readjusted to a steady state quickly in all four cases. We noticed that both LED A and LED B were dimmed to zero after daylight interrupted the system in the 1st and 2nd images shown in Fig. 2.6. This indicated that the system only worked when the light requirement is higher or equal to daylight, so that it is capable of maintaining uniform light output. Otherwise, it has the same performance as a time scheduling control scheme that switches off supplemental lights.

Scenario 3: Different daylight levels, different time hours of the day. Based on the summary of the results in Scenario 2, we conducted four simulations to observe the performance under different daylight disturbance values for identical desired light settings. We assumed the optimal light level for a specific plant is at 8000 and set the daylight level at 500, 2000, 4000 and 6000 respectively, which simulates daylight during dawn, early morning, morning, late morning, and noon respectively. It can be seen from Fig. 2.7 that the impulse varied depends on the strength of the disturbance source. The system successfully utilized daylight harvesting while keeping the light output uniform by the dimming LED A and LED B accordingly.

Scenario 4: Daylight is simulated as following daytime change curve. The daylight change from 6 am to 7 pm during the daytime is simplified as a discrete half cycle sine wave. As
Figure 2.8: Simulation results of scenario 4, daylight varies based on daytime from 6 am to 7 pm.

shown in the first image of Fig. 2.8, the peak is at 8000 and sample time is one hour. Because the desire light level is set at 8000, both LED A and LED B are dimmed down gradually in the morning, and entirely off when the daylight is increased to its peak value around noon. Overshooting still occurs inevitably. The actual light levels on both locations of sensor 1 and sensor 2 are uniform and stable at 8000.

Scenario 5: Daylight was simulated at different locations and also following the change curve from 6 am to 7 pm during the daytime. As we noticed that the sensor on different locations would probably detect different daylight levels due to sunlight angle, shading, and other factors in real cases. Although the model that we identified in section 2.3 had corrected the over-illumination influence, a simulation including different daylight levels is still considered. Thus, the daylight detected by sensor 1 and sensor 2 is simulated as 4000 and 3000, respectively. The desired light levels are the same as in scenario 4. As the results shown in Fig. 2.9, the actual light levels on both sensor 1 and sensor 2 achieved a uniform target successfully. The LED units on panel A varied differently from LED B, which was caused by the unbalance of the daylight as we expected.

2.4.2 Experimental Results

A series of experiments are conducted in the testbed environment by following all the scenarios that we discussed in the previous section. For scenarios 1, 2 and 3, the experimental results shows the success of the control system working in the practical cases. Control response is similar to the results shown in the simulation results. We skipped the discussion on the experimental results for scenario 1, 2 and 3 instead of giving a detailed illustration.
A similar system set up was done in the testbed environment as the same as in scenario 5. The overview of the experimental results under scenario 5 are shown in Fig. 2.10. The daylight emulator was adjusted to be set for daylight radiance levels at 6 am, 10 am, 11 am, 1 pm, 3 pm and 7 pm, respectively; all responding to the same daylight changes as in Fig. 2.9. Meanwhile, the dimming levels of the controlled LED panels reduced down smoothly while the daylight was turned up from 6am to 11am; and increased up gradually again while the daylight was decreased from 1pm till sunset at 7pm. It should be noted that the dimming levels for both LED A and LED B are not the same; especially while occurring during the early afternoon and late mornings, verifying the simulation results we received from scenario 5.

2.4.3 Discussion of Future Improvements

The results from both the simulations show that the proposed control system tackled the cross-illumination problem and took advantage of the daylight harvesting for achieving energy saving. The system also is able to regulate mixing ratios of red and blue wavelength color lights. Thus, it is capable of being set at customized desired light levels to help farmers create a stable, uniform light treatment for plant growth.

2.5 Conclusion

In this work we developed a lighting control algorithm, based on state space control, which is aimed at achieving desired light levels combined with daylight harvesting. The control method showed the performance in terms of error and stability both in the simulations and
experiments. A low-cost lighting system was developed which emulates a real greenhouse lighting scenario to verify the performance of the proposed control algorithm. The experimental results show that the system can achieve uniform light distribution with mixing color ratios for red and blue lights. The results from simulations and experiments show that the proposed control system tackled the cross-illumination problem and took advantage of the daylight harvesting to minimize energy consumption. The system is also capable of regulating the mixed ratio of red and blue wavelengths. Thus it is capable of achieving desired light levels and create stable and uniform light treatments for plant growth. In future works, we will investigate a larger scale LED lighting system using a sensor/light network in an experimental greenhouse facility.
Chapter 3

Energy-Efficient Supplemental LED Lighting Control for a Proof-of-Concept Greenhouse System

3.1 Introduction

Greenhouse supplemental lighting has attracted a growing interest in energy-efficient agriculture [40]. Research results have shown that light-emitting diodes (LED) can offer advantages in terms of energy savings and spectral lighting treatment for plant growth when compared to conventional supplemental lighting such as Metal-halide (MH) or High Pressure Sodium (HPS) lamps [41]- [49]. Spectral tunable LED lighting is an attractive feature that has been commercialized and utilized in the field of greenhouse farming [50]- [53].

Control systems for lighting in indoor spaces were investigated in [54]- [57]. In particular, LED light units controlled by smart lighting systems using feedback control have been proven to achieve more energy savings [58]. Albright [33] developed a lighting control algorithm to achieve a consistent daily light integral without the requirement for availability of weather conditions. The control action was executed hourly and avoided the risk of mis-operation due to transient illumination changes. However, the control strategy was not capable of ensuring a stable and accurate lighting environment for the plants. Pinho [59] developed a dynamic lighting control (DLC) system for LED lighting in greenhouses. The system runs continuously based on the input value collected from a quantum sensor to achieve a constant Photosynthetic Photon Flux Density (PPFD). However, spectrum control and the relationship between energy-efficiency and plant photosynthesis conversion were not discussed. Gonzalez and Lumbreras [60] proposed a smart lighting control system for greenhouses in which the controller was designed to provide a high quantum efficiency in photosystem II instead of PPFD. Chang and Hong [61] developed a fuzzy control lighting
system for supplementary LED lighting. The proposed system was capable of adjusting the light spectrum and intensity to achieve energy savings and enhance the plant output.

The above works have either not considered daylight harvesting for energy savings or are based on single-input single-output controllers with a time scheduling strategy. All of which are not able to achieve a uniform irradiance for a targeted plant growing area. The aim of this study is to develop a lighting control system integrated with daylight harvesting for greenhouse supplemental lighting. To this end, the proposed lighting system is defined as a MIMO system in which control inputs are applied as dimming commands to the luminaries and system outputs are the light irradiance levels at sensor locations. The objective is to achieve the spectral irradiance equal to or above the desired levels and achieve a colour ratio of mixed LED lights while utilizing natural sunlight as much as possible. In addition, as this control scheme is to be implemented in real greenhouse applications, the unavoidable operating delay caused by factors pertaining to hardware elements is modeled, discussed, and then compensated by the design of an appropriate Smith predictor.

In summary, the contributions of this chapter are as follows: (i) Development of a lighting control system integrated with daylight harvesting consisting of a main controller, light sensors, and red-blue colour ratio adjustable supplemental LED panels; (ii) State-space modeling, identification, and MIMO feedback control for supplemental lighting; and (iii) Integrating a delay compensation technique to significantly improve stability and control performance and pave the way for using the controller in network controlled greenhouse systems in which network induced delay is a very important issue. Considering a growing amount of farmers utilize supplemental LED products for plant growth in greenhouses, the application developed in this chapter brings crucial significance in the field of colour ratio based LED lighting.

In section 3.2, modeling and control of a lighting system with energy harvesting based feedback control is presented. Section 3.3 will present the experimental system followed by the experimental results; proving the capability to achieve energy-savings when utilizing the proposed control system. Conclusions and future work are presented in Section 3.4.

### 3.2 System Modeling and Feedback Control

A block diagram of the proposed control system is depicted in Fig. 3.1 in which the plant is modeled by a matrix $T$; $E(t)$ is the error between desired and actual light levels; $Y_d$ and $Y$ are the desired and actual output light levels, respectively; $K$ is the controller gain; and $X(t), U(t)$, are the input and output of the controller, respectively. Note that in Fig. 3.1, daylight is modeled as a disturbance vector; the integrator term is used to achieve zero tracking error, and the elements of matrix $T$ represent the relationship between applied power to the luminaries and output luminous flux at desired points.
To find $T$, the system is modeled as a cascade connection of three subsystems: LED fixtures, LED power drivers, and the indoor environment with daylight. In the drivers’ subsystem, a linear relationship can be assumed between the inputs and outputs under normal operating conditions [62], [63]. An approximately linear relationship exists between input power $P$ and the output luminous flux vector $\phi$ of LED units for $P < P^*$, where $P^*$ is the point of maximum for $\phi$. Furthermore, the illuminance is linearly dependent on the luminous flux emitted by the light fixtures [38], [64]. As a result, the complete system can be represented by a linear, static, time-invariant MIMO system in the following form

$$Y(t) = T U(t) \quad (3.1)$$

where $Y(t) \in R^m$ and $U(t) \in R^n$ are the output and input vectors respectively and $T \in R^{m \times n}$ is the system model matrix.

### 3.2.1 Controller Design

Let us represent the plant model by a $n \times n$ full rank square matrix $T$. Considering the control system shown in Fig. 3.1, let us define

$$X(t) = \int_0^t E(\lambda)d\lambda \quad (3.2)$$

where $X(t) = [x_1(t), x_2(t), \ldots, x_n(t)]$ is the state vector, $E(t) = [e_1(t), e_2(t), \ldots, e_n(t)]$ represents the error vector between the desired and actual outputs, and $\lambda$ is a dummy
variable of the definite integral. Referring to Fig. 3.1, we have

\[ E = -TU(t) + Y_d - Y_l \] (3.3)

and

\[ \dot{X}(t) = -TU(t) + (Y_d - Y_l) \] (3.4)

Using the state feedback control law \( U(t) = KX(t) \), we have

\[ Y(t) = TKX(t) + Y_l \] (3.5)

which represents the relationship between state and output of the system.

The control objective is to achieve accurate light regulation at target points while minimizing energy usage by the supplemental LED fixtures. To this end, the theory of Linear Quadratic Regulation (LQR) (see e.g., [37]) can be used to minimize the following quadratic performance index

\[ J = \frac{1}{2} \int_0^\infty (E^T(t)QE(t) + V^T(t)RV(t))dt \] (3.6)
where \( E(t) \) represents the system error; \( Q \) and \( R \) are symmetric positive-definite weighting matrices; and \( V(t) \) is the time derivative of input vector \( U(t) \), i.e.,

\[
\dot{U}(t) = V(t)
\]  

(3.7)

By assuming a constant disturbance/reference (i.e., \( Y_d - Y_i = \text{const} \)), from (3.3) it follows that

\[
\dot{E}(t) = -TV(t)
\]  

(3.8)

Thus the feedback control law which minimizes the performance index (3.6) is given by [37]

\[
V(t) = -R^{-1}B^TPE(t)
\]  

(3.9)

where \( P \) is obtained by solving the Algebraic Riccati Equation, i.e.,

\[
PA + A^TP + Q - PRB^{-1}B^TP = 0
\]  

(3.10)

in which \( A, B \) are the state-space system matrices. Furthermore, the value of \( U(t) \) can be obtained as follows

\[
U(t) = \int_0^t V(\lambda)d\lambda = -R^{-1}B^TPX(t) = KX(t).
\]  

(3.11)

In a conventional LQR problem, \( U(t) \) is penalized, as a result of which it converges to zero to maintain a bounded cost function. By including the time derivative of \( U(t) \) in the performance index, \( U(t) \) does not need to converge to zero but instead converges to an appropriate constant value.

For the lighting control system we have \( A = 0, B = -T \). Taking \( Q = qI \) and \( R = rI \), (3.10) can be written as followed

\[
qI - \frac{1}{r}P(-T)I(-T^T)P = 0
\]  

(3.12)

from which \( P \) can be obtained,

\[
P = \sqrt{rq}(TT^T)^{-1/2}
\]  

(3.13)

Thereby, the state feedback gain \( K \) can be explicitly obtained as

\[
K = -R^{-1}B^TP = \sqrt{q/rT^T(FT^T)^{-1/2}}.
\]  

(3.14)
3.2.2 Delay Modeling and Compensation

In practice, a time delay is introduced into the lighting system caused by sensor and actuator hardware, and communication channels. Time delays result in high order non-minimum phase systems and if the apparent delay time exceeds the dominant system time-constant, the system could be unstable even in the presence of best controller tuning [65]. In that case, even if the controller stabilizes the system, it will result in an extremely slow response. To deal with the above issue, we utilize a Smith predictor to avoid lowering the control gain to maintain closed-loop stability. The proposed delayed system and controller are shown in Fig. 3.2, in which the Smith compensator predicts the delayed effect that the input will have on the output and produces a compensation term to obtain the desired output in its presence.

To this end, let us update (3.4) to incorporate the Smith predictor based on estimates \( \hat{T} \) and \( \hat{D} \) of the system model \( T \) and time delay \( D \), respectively. Thus, the new system dynamics is as followed

\[
\dot{X}(t) = Y_d - Y_l - \hat{T}KX(t) + \hat{T}KX(t - \hat{D}) - TKX(t - D)
\]  

(3.15)

where \( K \) is the state feedback gain designed in (3.14). In the following, it will be shown that this structure results in uniform ultimate boundedness of the state \( X(t) \). The ultimate bound can be made arbitrarily small by reducing the error in system model (\( \Delta T = T - \hat{T} \)) and measurement error of the delay (\( \Delta D = D - \hat{D} \)) along with tuning some other design parameters.

3.2.3 Stability Analysis

In this section, the designed controller with the added Smith compensator is analyzed and its convergence is proven. The system error is shown to be uniformly ultimately bounded to an arbitrarily small ultimate bound and a discussion is provided on the effect of the design parameters on its value.

Let us choose a continuously differentiable Lyapunov function candidate \( V_L : [0, \infty) \times D \to R \) such that \( \forall t \geq 0, \forall X \in D \)

\[
\alpha_1(\|X\|) \leq V_L = \frac{1}{2}(X(t)^TPX(t)) \leq \alpha_2(\|X\|)
\]  

(3.16)

where \( \alpha_1 \) and \( \alpha_2 \) are the following class \( K \) functions

\[
\alpha_1(\|X\|) = \frac{\lambda_{\min}(P)}{2}\|X\|^2, \quad \alpha_2(\|X\|) = \frac{\lambda_{\max}(P)}{2}\|X\|^2
\]  

(3.17)

\(^1\)Section 3.2.2 and 3.2.3 were in collaboration with Ms Afagh Mohagheghi.

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Taking the time derivative of $V_L$ along the closed loop trajectories of (3.15) results in

$$
\dot{V}_L = X(t)^T P \dot{X}(t) \\
= -q\|X(t)\|^2 + qX^T(t)\{X(t - \hat{D}) - x(t - D)\} \\
+ X^T(t) P\{(Y_d - Y_l) - \Delta TKX(t - D)\}
$$

(3.18)

Assuming $X(t)$ is uniformly continuous, it satisfies a Lipschitz condition of the following form

$$
\|X(t - \hat{D}) - X(t - D)\| \leq M\|D - \hat{D}\|, \quad M = \sup_t \|\dot{X}(t)\|
$$

(3.19)

Utilizing the Mean Value Theorem, there exists a $t - D < \zeta < t$ such that

$$
X(t - D) = X(t) - \dot{X}(\zeta)D \\
\implies \|X(t-D)\| < \|x(t)\| + \sup_t \|\dot{X}(t)\|D
$$

(3.20)

Incorporating (3.19) and (3.20) into (3.18) yields

$$
\dot{V}_L \leq -(1 - \theta)q_1\|X(t)\|^2 - \|X(t)\|\{\theta q_1\|X(t)\| - \\
\{qM\|\Delta D\| + \|P\|\|Y_d - Y_l\| + \|P\Delta TK\|MD}\}
$$

(3.21)

where $q_1 = q - \|P\Delta TK\|$, $q$ is chosen large enough to satisfy $q_1 > 0$ and $0 \leq \theta \leq 1$ is a positive design constant.

From (3.21) and under the stated conditions, it can be concluded that there exists a $\mu > 0$ such that for states staying outside of a ball with the radius $\mu$, the derivative of the
Lyapunov function is negative definite, i.e.,

$$\dot{V}_L \leq -(1-\theta)q_1\|X(t)\|_2^2 \quad \forall \|X\| \geq \mu$$ \hspace{1cm} (3.22)

and the radius $\mu$ can be found as follows

$$\mu = \frac{qM\|\Delta D\| + \|P\||Y_d - Y_l\| + \|P\Delta TK\|MD}{\theta q_1}$$ \hspace{1cm} (3.23)

Utilizing the ultimate boundedness analysis in [66], and taking $r > 0$ such that $B_r \subset D$ and $\mu \leq \sqrt{\frac{\lambda_{\min}(P)}{\lambda_{\max}(P)}} r$, there exists a class $k$ function $\beta$ for every initial state $\|X(t_0)\| \leq \sqrt{\frac{\lambda_{\min}(P)}{\lambda_{\max}(P)}} r$ and there exists a $T(X(t_0), \mu) \geq 0$ such that the solution of the system satisfies

$$\|X(t)\| \leq \begin{cases} \beta(\|X(t_0)\|, t - t_0), & \forall \ t_0 \leq t \leq t_0 + T \ \\
 b = \sqrt{\frac{\lambda_{\max}(P)}{\lambda_{\min}(P)}} \mu, & \forall \ t \geq t_0 + T \end{cases}$$ \hspace{1cm} (3.24)

where $b$ is the ultimate bound to which the state $X(t)$ converges in finite time $T$. Utilizing (3.23), (3.24) we have

$$b = \sqrt{\frac{\lambda_{\max}(P)}{\lambda_{\min}(P)}} \times \frac{qM\|\Delta D\| + \|P\||Y_d - Y_l\| + \|P\Delta TK\|MD}{\theta q_1}$$ \hspace{1cm} (3.25)

Examining (3.25), this ultimate bound is dependent on the the modeling error $\Delta T$, delay measurement error $\Delta D$, delay value $D$, and the Lipschitz coefficient $M$ from (3.19).

For an ideal system (i.e., $\Delta T = 0$, $\Delta D = 0$), the ultimate bound $b$ in (3.25) converges to

$$b = \sqrt{\frac{\lambda_{\max}((TTT)^{-\frac{1}{2}})}{\lambda_{\min}((TTT)^{-\frac{1}{2}})}} \sqrt{\frac{\tau}{q}} \frac{\|\Delta T\|MD}{\theta}$$ \hspace{1cm} (3.26)
In this case, the ultimate bound is determined by the disturbance value as well as the relative relationship of the optimization weights. As $\frac{q}{r}$ is increased, the ultimate bound of the error is reduced, which matches the original purpose of $q$ and $r$ as defined in the performance index in (3.6).

If $\hat{T}$ converges to $T$ but the delay measurement has some error (i.e., $\Delta T = 0, \Delta D \neq 0$), the ultimate bound is only affected by the delay measurement error value $\Delta D$. Finally, if both modeling and delay measurement errors are non-zero ($\Delta T \neq 0, \Delta D \neq 0$), in addition to these additive error terms, the actual delay value $D$ would affect the ultimate bound which is consistent with the fact that Smith predictors are working in a condition when the mismatch between the model and system is minimal.

### 3.3 System Implementation and Experimental Results

#### 3.3.1 Experimental Set-up

The system set up was housed in a 5′ × 5′ grow tent (from Gorilla Inc.) used as a mini greenhouse as shown in Fig 3.3. Two units of spectral adjustable LED light panels (from
QuanTech Inc.) hang on the top of the tent which acts as the supplemental grow lights consisting of programmable blue and red LED units which can provide up to Photosynthetic Photon Flux (PPF) \(960 \mu\text{mols/s}\) with dimming levels ranging from 0 to 100\% in 255 steps [67]. In addition, two units of 1kW halogen lamps hang over the centre of the tent roof to emulate daylight. Those units are dimmed by a 2 kVA variac to emulate variable sunlight. Two units of TCS34725 light sensors, from Adafruit Industries, are used for acquiring the light irradiance index at different colour wavelengths including red (615nm) and blue (465nm). The blue and red channels utilize high brightness InGaN and AlInGaP light-emitting diodes, respectively. The data is transmitted via an I2C communication protocol to the F28335 micro-controller board (from Texas Instruments, Inc.) as shown in Fig 3.4. The control command is calculated and transmitted via a serial communication SCI port to the panel to change ratio of the spectral distribution and light intensity of LED lights. The PC is interfaced with the micro-controller for data monitoring.

A series of experiments were conducted to study the light characteristics of halogen lamp and blue-red mixed colour LED. In the first step, the spectrum data from the halogen lamp and mixed-colour LED lights were collected by SS-110 Field spectroradiometer (from Apogee Instruments) as shown in Fig 3.5. The dimming levels of red and blue lights were adjusted to 100\%, 100\% respectively. Next, we obtained the relationship between light intensity and dimming levels of LED red and blue units. To this end, the dimming levels of blue and red LED light were increased from 0\% to 100\% in steps of 10\%. The red and blue units were tested separately. As seen in Fig 3.6, the light intensity of both red and blue light is linearly dependent on the dimming level.
3.3.2 Model Identification

Since two units of LED panels and two units of red, green, blue (RGB) light sensors were used in the experiment, two $2 \times 2$ matrix $T_{blue}$ and $T_{red}$ were considered

$$T_{red/blue} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix}$$ \hspace{1cm} (3.27)

where $t_{ij}$ are the coefficients representing the relationship between the $i$ – th luminaire and the $j$ – th light sensor, and therefore the system matrix is

$$T = \begin{bmatrix} T_{red} & 0_{2 \times 2} \\ 0_{2 \times 2} & T_{blue} \end{bmatrix}$$ \hspace{1cm} (3.28)

Four identification tests were conducted to obtain the relationship between sensors and the LED panels for blue light and red light, respectively. The sensors were denoted by $RGB1$ and $RGB2$, and the LED panels were denoted by $LED1$ and $LED2$. Since the blue and red channels on the LED panel were adjusted independently, the identification tests were conducted separately for each color channel. Hence, the blue channel and red channel on two units of the LED panel were defined as $LED1b$, $LED2b$, $LED1r$ and $LED2r$, respectively. The data collection channels for blue light and red light on two units of the RGB light sensor are defined as $RGB1b$, $RGB2b$, $RGB1r$, and $RGB2r$.

First, only the blue channel on panel $LED1$ was turned on and increased in 10% increments (i.e., 0%, 10%, 20%... 100%) and the data from channel $LED1b$ and $LED2b$ were recorded. The same procedure was followed for the red channel on panel $LED2$. The results of the identification tests are shown in Fig. 3.7. By utilizing the least square estimation [68] the best fits for obtained data sets of red channel are given by

$$y_{11r} = 18.997x_{1r} + 13.455$$
$$y_{12r} = 8.192x_{1r} - 136.682$$
$$y_{21r} = 7.831x_{2r} - 6.954$$
$$y_{22r} = 15.593x_{2r} + 15.364$$ \hspace{1cm} (3.29)

where $y_{ij}$ represents the effect of $i$ – th luminaire on the $j$ – th sensor, and $x_{i}$ is the dimming level of the $i$ – th luminaire. Also the data sets for blue light are represented by
Figure 3.7: System identification in response to red and blue LED channels.

\[ y_{11b} = 41.489x_{1b} - 48.001 \]
\[ y_{12b} = 18.143x_{1b} - 18.318 \]
\[ y_{21b} = 18.921x_{2b} - 44.955 \]
\[ y_{22b} = 38.695x_{2b} - 96.227 \]

(3.30)

The illuminance at any level is the summation of the light intensity from all the luminaries in the environment. Thus, we have

\[ y_1 = y_{11} + y_{21} \]
\[ y_2 = y_{12} + y_{22} \]

(3.31)

where \( y_i \) is the total illuminance level at \( i \) th sensor. Resulting in

\[ y_{1r} = 18.997x_{1r} + 7.8307x_{2r} + 6.5 \]
\[ y_{2r} = 8.1922x_{1r} + 15.593x_{2r} - 121.32 \]

(3.32)

and

\[ y_{1b} = 41.489x_{1b} + 18.921x_{2b} - 92.955 \]
\[ y_{2b} = 18.143x_{1b} + 38.695x_{2b} - 114.545 \]

(3.33)
Hence the matrix $T_{\text{red/blue}}$ is given by

$$T_{\text{red}} = \begin{bmatrix} 18.997 & 7.8307 \\ 8.1922 & 15.593 \end{bmatrix}$$

and

$$T_{\text{blue}} = \begin{bmatrix} 41.489 & 18.921 \\ 18.143 & 38.695 \end{bmatrix}$$

where $T_{\text{red}}$ and $T_{\text{blue}}$ represent the system model under red and blue lights environment, respectively.

Substituting $T_{\text{red}}$ and $T_{\text{blue}}$ into (3.14), and choosing $q = r = 0.5$ to give equal weights to minimizing the error and energy consumption, the state feedback gain is obtained as

$$K_{\text{red}} = \begin{bmatrix} 0.9999 & 0.0105 \\ -0.0105 & 0.9999 \end{bmatrix}$$

and

$$K_{\text{blue}} = \begin{bmatrix} 1 & -0.0097 \\ 0.0097 & 1 \end{bmatrix}$$

where $K_{\text{red}}$ and $K_{\text{blue}}$ are the gains for red and blue channels, respectively.

### 3.3.3 Modeling for the Solar Hourly PPFD

Daily light integral (DLI), which refers to the number of photosynthetically active photons accumulated in a square meter during a 24 hour period, has been widely used as the light measurement unit for plant growth [33], [71]. Peppers and tomatoes are the two most popu-
lar crops for greenhouse production, which account for 80% of the greenhouse growing area (see e.g., [74]). For optimal plant growth, different types of plants have different daily light integral (DLI) requirements. The recommended DLI index for various plants was summarized in a research paper by Faust [69] which indicates that both tomatoes and peppers need around 14-30 mol·m⁻²·d⁻¹ average DLI to achieve good quality production.

Korczynski [70] mapped the sunlight irradiation distribution across United States. Using this study, the DLI monthly index in Seattle and other northwestern regions of North America can be as low as 5-10 mol·m⁻²·d⁻¹ from Nov-Jan, 15-20 mol·m⁻²·d⁻¹ in Oct, and 20-25 mol·m⁻²·d⁻¹ in April, respectively. Since the weather in Vancouver, BC is very similar to Seattle, the sunlight DLI data in December in Vancouver was assumed to be 5-10 mol·m⁻²·d⁻¹.

To use the halogen light to emulate the solar light, the modeling of hourly solar PPFD is needed. The solar PPFD is modelled as a half sine curve, where the sunrise and sunset are located at the starting and ending point, respectively [33], [79], [80]. Let us assume the model for a day with clear sky conditions located in Vancouver, BC on December 14th, 2016. The time range of solar light is between 8:00 AM to 4:14 AM, with the solar noon (peak solar PPFD) at 12:08 PM (based on the data from National Research Council Canada [81]). The PPFD at solar noon is at its peak. Thus, we can get the hourly \( PPFD_t \)

\[
PPFD_t = PPFD_{max} \cdot \sin \left( \frac{t}{T} \cdot \pi \right)
\]

(3.38)

where \( T \) is the total hours of daylight duration in the whole day, \( t \) is the total hours of daylight since sun rises, and \( PPFD_{max} \) is the peak value of PPFD.

Table 3.1: hourly solar PPFD data on a winter day with clear sky condition.

<table>
<thead>
<tr>
<th>time</th>
<th>relative solar PPFD (%)</th>
<th>solar PPFD outdoor (mol·m⁻²·hr⁻¹)</th>
<th>solar PPFD in greenhouse (mol·m⁻²·hr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:00 AM</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>8:00 AM</td>
<td>0.31</td>
<td>0.49</td>
<td>0.34</td>
</tr>
<tr>
<td>9:00 AM</td>
<td>0.59</td>
<td>0.93</td>
<td>0.65</td>
</tr>
<tr>
<td>10:00 AM</td>
<td>0.81</td>
<td>1.28</td>
<td>0.90</td>
</tr>
<tr>
<td>11:00 AM</td>
<td>0.95</td>
<td>1.51</td>
<td>1.05</td>
</tr>
<tr>
<td>12:00 PM</td>
<td>1.00</td>
<td>1.5838</td>
<td>1.10866</td>
</tr>
<tr>
<td>1:00 PM</td>
<td>0.95</td>
<td>1.51</td>
<td>1.05</td>
</tr>
<tr>
<td>2:00 PM</td>
<td>0.81</td>
<td>1.28</td>
<td>0.90</td>
</tr>
<tr>
<td>3:00 PM</td>
<td>0.59</td>
<td>0.93</td>
<td>0.65</td>
</tr>
<tr>
<td>4:00 PM</td>
<td>0.31</td>
<td>0.49</td>
<td>0.34</td>
</tr>
<tr>
<td>5:00 PM</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>In total</td>
<td>6.313752</td>
<td>9.99972</td>
<td>6.999804</td>
</tr>
</tbody>
</table>
Figure 3.9: Dimming levels of red and blue channels on LED1 and LED2 by proposed control (black line) and conventional time-scheduling control (grey line) during daylight hourly change from 5AM to 8PM.

Due to the light reflection and absorption by the tent and greenhouse structure, a specific DLI loss ranging from 30% to 70% is expected [70], [71]. Thus, the solar PPFD getting into the greenhouse $DLI_s$ is given by

$$DLI_s = DLI_{max} \cdot (1 - L) \quad (3.39)$$

where $DLI_{max}$ is the DLI value in a clear sky condition, $L$ is the loss constant.

Combining (3.39) and (3.38), we obtain the relationship between hourly PPFD and DLI as follows

$$DLI_s = \sum_{i=1}^{n} PPFD_{max} \cdot sin(\frac{t}{T} \cdot \pi) \quad (3.40)$$

Assuming that $DLI_{max} = 10 m^2 \cdot m^{-2} \cdot d^{-1}$, $L = 0.3$, and $T = 10$, we combine (3.38)-(3.40) to get the hourly PPFD value in a day, as shown in Table 3.1. Based on the calculation, the model of hourly sunlight is shown in Fig. 3.8. It can be seen that the trendline of hourly sunlight approximates to the simplified solar sine curve, which verifies the feasibility of the proposed model.
3.3.4 Sensor Calibration and Data Conversion

Research has been conducted to verify the effects of LED light treatment on plant growth in terms of spectral manipulation. Specifically for the growth of tomatoes. It has been proven that a specific minimum amount of light irradiance by a mixed ratio of blue and red LEDs is capable of increasing the field output and stimulating other features such as accelerating the growth and expanding the leaf growth and stem length [75]- [78].

Thus, it is a crucial advantage that the proposed system can maintain a PFD equal to or above a minimum value on the red and blue spectrum zone, which we named $PFD_{r_{\text{min}}}$ and $PFD_{b_{\text{min}}}$ respectively. And the overall minimum PPFD $PPFD_{\text{min}}$ from the supplemental red and blue LEDs can be derived from

$$PPFD_{\text{min}} = PFD_{r_{\text{min}}} + PFD_{b_{\text{min}}}$$ (3.41)

Since the measurement unit of the RGB light sensor $\mu W \cdot cm^{-2}$ used in the system stands for the integrated total value of Energy Flux Density (referred as EFD below) on a specific range of wavelength, the PFD data measured by the calibrated spectroradiometer is used as a reference to convert it. A series of experiments are conducted to get the correlation of the EFD and PFD by comparing the data that we captured by the light sensor in the set up stage as shown in Fig.3.6. According to the experimental results, we get
Figure 3.11: Transient response of LEDs and sensory data for blue and red channels.

Figure 3.12: Dimming levels and sensory data for blue and red channels when the system is subjected to a disturbance (daylight).

\[ PFD_r = 0.0215 \times EFD_r + 1.3927 \quad (3.42) \]

\[ PFD_b = 0.0031 \times EFD_b + 0.0273 \quad (3.43) \]

where \( PFD_r \) and \( PFD_b \) are the PFD value at spectrum range of red and blue, respectively, and \( EFD_r \) and \( EFD_b \) are the data acquired from the red and blue channel of light sensors respectively.

In addition, a proportional error is observed from both the blue and red channel of the RGB sensor, which is affected mutually. They are given by

\[ e_r = 0.0259 \times EFD_b + 6.9388 \quad (3.44) \]
\[ e_b = 0.1447 \times EFD_r + 1.4712 \]  

(3.45)

where \( e_r \) and \( e_b \) refers to the error value on red and blue channel of RGB sensor, respectively.

By combining (38) - (41), the ideal PFD of both blue and red channel after subtracting the proportional error is given by

\[ PFD'_r = 0.0215 \times (EFD_r - e_r) + 1.3927 \]  

(3.46)

\[ PFD'_b = 0.0031 \times (EFD_b - e_b) + 0.0273 \]  

(3.47)

In the next section, we assume a targeted light environment for tomato growth is capable of achieving \( DLI \ 17 mol/m^2 \cdot d^{-1} \) and maintaining a constant ratio 3.5:1 (red:blue). The model that we built in section 3.3 shows the daylight \( DLI_s \) that reached into greenhouse is \( 6.999 mol/m^2 \cdot d^{-1} \), we can easily get \( DLI_{min} \ 10 mol/m^2 \cdot d^{-1} \). As we know that the relationship between DLI and PPFD is given by

\[ PPFD_{min} \times 60 \times 60 \times T_p \times 10^{-6} = DLI_{min} \]  

(3.48)

where \( T_p \) is the photoperiod. By assuming \( T_p \) is 24 hours and combining (38)-(45), we get the set point for achieving the desire light levels are as follows

\[ EFD_b \approx 8000 \mu W \cdot cm^{-2} \]  

(3.49)

\[ EFD_r \approx 4000 \mu W \cdot cm^{-2} \]  

(3.50)

where \( EFD_b \) and \( EFD_r \) refer to the energy flux density at blue and red channels, respectively.

### 3.3.5 Results and Discussion

The sunlight, referred to as the disturbance light in the control system, is not controllable and predictable due to weather changes. For instance, the light irradiance from sunlight is expected to be highest at noon on a sunny day; however, a sudden cloud shadow can decrease the expected light irradiation. The objective of the control system is to maintain an irradiance value close to a specified value in the greenhouse under different sunlight conditions.

The halogen light was dimmed according to Fig. 3.8 to emulate the disturbance daylight changes from 7AM to 5PM on a day with clear sky conditions in December located in Vancouver, Canada. Fig. 3.9 shows comparison of the performance of proposed control system and conventional time-scheduling for maintaining the light irradiance at 8,000 \( \mu W \) ·
Table 3.2: Results of MIMO lighting control performance under different Red:Blue mixing color ratios.

<table>
<thead>
<tr>
<th>Desired light $Y_d$ (blue/red, LEDA/LEDG)</th>
<th>sunlight $Y_i$ (%)</th>
<th>Light output $Y_i (uW/cm^2)$</th>
<th>Error rate (red/blue)</th>
<th>time to stable state (samples)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LED A</td>
<td>LED B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red/LEDA+B:3000</td>
<td>0%</td>
<td>2965</td>
<td>2987</td>
<td>0.82%</td>
</tr>
<tr>
<td>Red/LEDA A: 3000, Red/LEDA B:3500</td>
<td>75%</td>
<td>2996</td>
<td>3474</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>87.5%</td>
<td>3088</td>
<td>3505</td>
<td>1.52%</td>
</tr>
<tr>
<td>Blue/LEDA+B:4000, Red/LEDA+B:3000</td>
<td>100%</td>
<td>2989/3980</td>
<td>3002/4001</td>
<td>0.21%/0.26%</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>2963/4037</td>
<td>2989/3976</td>
<td>0.8%/1.02%</td>
</tr>
</tbody>
</table>

$cm^{-2}$ on blue channel and 4,000 $\mu W \cdot cm^{-2}$ on red channel as daylight changes. The method we used for comparison is one of the conventional time scheduling methods utilized widely in greenhouse farming. It is an open loop based on/off control to provide a number of hours of artificial lighting with fixed light intensity. As shown in Fig. 3.9-(a), Fig. 3.9-(b), Fig. 3.9-(c) and Fig. 3.9-(d), with our method, all the LEDs are dimmed down until fully off at noon due to daylight harvesting and increase of emulated sunlight. The saturation period on blue LEDs are shorter than that on red LEDs if compared (a) with (c), and (b) with (d). It is reasonable because the PFD amount on blue provided by sunlight is much less than the PFD amount on the red spectrum. Furthermore, the dimming level curve on LED1 and LED2 is slightly different (i.e., LED2 − red is dimmed more than LED1 − red) which is due to the light leaked into the tent from the outside. As for the conventional time-scheduling control method, both LED1 and LED2 keep a fixed dimming level from 5AM to 8PM, shown as grey line in Fig. 3.9. The outputs of the overall EFD sensed by red and blue channel light sensors are maintained relatively stable and fixed along with the targeted desired values, indicated as Sensor1 − blue, Sensor1 − red, Sensor2 − blue and Sensor2 − red in Fig. 3.10. The only exception occurs on the red channel around noon, which is due to the over saturation from the irradiance of red spectrum of daylight while the red LEDs are fully dimmed off to minimize the energy consumption.

Since the power input is linearly related to the total light output, the total energy consumption per day is given by

$$W = \sum_{i=1}^{N_p} \left( P_{red} \times \sum_{n=1}^{N_i} D_{rni} + P_{blue} \times \sum_{n=1}^{N_i} D_{bni} \right)$$  \hspace{1cm} (3.51)
where $W$ is defined as the total daily energy consumption of the lighting system; $D_{rni}$ and $D_{bni}$ are the dimming percentages (0% to 100%) of red and blue units of the $n_{th}$ LED at $i_{th}$ hour, respectively; $N_p$ is the total photo-period time; and $N_l$ is the number of LED units.

For a system with conventional time-scheduling based control, dimming levels are unchanged during the photoperiod from 1th hr (5AM) to 16th hr (8PM). To achieve the same desired light levels as the ones with proposed control system applied, combining (3.29), (3.30), and (3.51) we have: $D_{r11} = D_{r12} = \cdots = D_{r116} = 50.59\%,\ D_{r21} = D_{r22} = \cdots = D_{r216} = 69.8\%,\ D_{b11} = D_{b12} = \cdots = D_{b116} = 43.53\%,\ D_{b21} = D_{b22} = \cdots = D_{b216} = 56.08\%$.

We consider $N_l = 2,\ N_p = 16,\ P_{red} = 295.65,\ P_{blue} = 121.74$ in (3.51) to get the total energy consumption with conventional control as follows

$$W_n = 6.630\ kWh$$

(3.52)

By taking advantage of the daylight harvesting, the LEDs are automatically dimmed and the red-blue ratio is adjusted to save energy while meeting light demand of crop production. By utilizing the hourly dimming data of red and blue LEDs shown in Fig. 3.9 in (3.51), the estimated overall daily energy consumption is given by

$$W_c = 4.458\ kWh$$

(3.53)

Thus the estimated energy savings achieved is

$$\eta_s = 1 - \frac{W_c}{W_n} = 32.76\%$$

(3.54)

Fig. 3.10 demonstrates the capability of the proposed controller in set-point tracking while saving energy in our experimental setup. However, experiments show that the hardware introduces a time delay into the system that, despite not causing any problems when a small number of sensors and actuators are used ($D = 20\ ms$), would lead to performance depreciation and loss of relative stability as the system grows larger. To implement the Smith predictor, the system delay was manually increased to 150$\ ms$ and the experiments were repeated. The set-point tracking and disturbance rejection responses were deteriorated due to the long delay but improved by adding the Smith predictor.

Fig. 3.11 shows the controller performance in regulating light levels at points of interest when the system is not affected by any disturbances. Different set-points were chosen for the red and blue irradiances to demonstrate that they can be controlled independently. The top and bottom four graphs indicate the blue and red lights control performances, respectively. In each graph, the red line shows the transient response of the controller and the blue line displays the response when the Smith predictor is utilized. The figure indicates that the increased delay of 150$\ ms$ leads to oscillations, reduced relative stability, a rather
large overshoot, and a considerably slower settling time. The Smith predictor successfully dampens the oscillations, reduces the settling time and increases relative stability of the system. The Smith predictor also improved the control input since reduced oscillations in these signals would mean reduction or removal of flickers for the LEDs.

Fig. 3.12 illustrates the disturbance rejection performance of the controller. A pulse emulating daylight disturbance with a magnitude of $2500 \mu W \cdot cm^{-2}$ and 60s duration is applied to the system. The increased delay causes depreciated transient performance as the controller tries to reject the disturbances and re-regulate the EFD levels to the desired values as the red lines in each graph show. Similar to the the previous case, addition of the Smith predictor provides a faster, smoother, and more stable disturbance rejection response while conserving energy and reducing equipment fatigue and maintenance costs.

### 3.4 Conclusions

A proof-of-concept lighting control system was developed for regulating LED lights that can be used for supplemental lighting regulation in greenhouses. The proposed multi-input multi-output (MIMO) control system receives feedback from multiple light sensors and controls the LED supplemental light to achieve customized light intensity. The experimental results indicate that the proposed system was capable of achieving desired daily light integral (DLI) for specific crops and maintain desired red and blue ratios. A Smith predictor was added to the designed controller to compensate for the unwanted effects of delay in the system in larger scales. The results indicate a more stable system with smooth transient response ensuring lower energy consumption for the LED panels. Future work will include validating the system in a real greenhouse environment consisting of a larger number of sensors and LED fixtures and developing a networked control system.
Chapter 4

Development of a Testbed with Intelligent LED Lighting Control System for IoT Smart Greenhouse

4.1 Introduction

In recent years, the research on LED lighting control has reached significantly a peak demand due to the continuous cost reduction and large scale manufacturing of LED fixture and [82]-[85]. Control technologies that consider the optimal combination of energy saving and other factors are comprehensively discussed, such as human eye comfort, colour temperature, daylight harvesting and special user scenario and requirements [86], [87].

However, discussions on lighting control strategies have been mostly limited in the residential and commercial office areas [88], [89], [90]. Meanwhile, the use of LED applications in horticulture has been increasingly spreading because of the advantages in the energy saving, controllability, and support for Internet of Things (IoT) technology based smart horticulture [91], [92], [93]. The combination of reaching a targeted photosynthetic photon flux density (PPFD) and mixing color ratio between blue, red, or UV light, which mostly named light recipe, has been widely investigated in the horticulture field. The research achievements have shown that light recipe plays a key role on improving the plant growth and increasing the crop productivity [94] - [97].

Being different from the LED fixtures for an environment suited for human activity, the supplemental LED grow light consists of mixing colour based LED units and tailoring to achieve a targeted amount of photosynthetic photon as the light requirement for plant growth. The past research for the control on the LED grow lights in horticulture have focused on mixing colour ratio controls and achieving the required PPFD or daily light integral (DLI) for plant growth [31], [98]. In the aspect of energy efficiency performance, researchers have proposed several methods from the view of the whole greenhouse system and electricity market [99], [100], [104]. In contrast to that, research on achieving optimal light performance for plant growth while improving the energy efficiency of mixing colour LED in greenhouses
has not been widely discussed. As the concept of precision agriculture and unattended operation technology is continuously developing at a fast pace, greenhouse farmers continue to elevate the levels of requirements for LED control systems in terms of light output quality and energy efficiency. Therefore, in this chapter we propose a testbed system, which built a plant grow system and a supplemental LED lighting control system, with it’s intended target users being both horticulture researchers and lighting control related researchers. The proposed environment aimed to provide a easy-to-use lighting system with adjustable PPFD output and mixing color ratio for creating customized light recipe. Also we have integrated the IoT technology with the testbed that offers the user remote monitoring and control via mobile network.

The rest of the chapter is organized as follows: in section 4.2, a demand analysis is introduced and the development process is illustrated including the work in the early stage and the proof of concept related work; in section 4.3, the features of the proposed system are specified and the implementation details are introduced; experimental results and the discussion are shown in section 4.4 and 4.5.

4.2 Testbed Design and Development Process

The testbed infrastructure we need to develop and design includes a compact plant ecosystem, a low cost embedded control system with affordable and easy-to-use hardware set up, a easy maintained wireless network that supports for remote access and a plug-and-play programmable LED lighting system that supports for mixing color and dimming control. Overall, it has the capability to conduct testing for a wide range of research activities. The topics covers LED lighting control system, IoT monitoring and management, investigation on the affect of mixing color ratio and light intensity on the plant growth and crop production, other potential sensor data in the smart greenhouse field that contribute to the development of plant health tracking.

4.2.1 Requirements

Essentially the testbed solution plays a key role in giving the capability of controlling the dimming and color ratio for LED lights, at the meantime it has the ability to control a wide range of environmental parameters for the study of different variety of affects on the plant growth. A series of requirements and expectations that we consider for the choice of hardware and the design of the testbed infrastructure are listed below.

**Scalability.** Ideally, the testbed should support for expanding the sensors and control nodes to a larger scale in the future work, without changing much of the existing system structure. This is a quite realistic requirement, as we aimed to develop it into a prototype application for the use of horticulture researchers in a large scale greenhouse environment.
Low maintainability. From engineering background based lab environment to horticulture background based greenhouse scenario, the horticulture experts and onsite researchers not only expect this LED lighting control testbed provide all the necessary configuration and measurement to fulfil the light environment, but also require a easy maintainable application that they can easy to use with a stable light output.

High flexibility. As experiments involving various research topics conduct on this testbed in a compact size, it should be designed to support a high flexibility for experiments and evaluation in a wide range of research topics, which covers from the light effect on the plant growth to provide system support for running control actions on light fixtures and other control appliances applied in the greenhouse.

Automation and remote control To vividly evaluate the performance of a tested lighting control method and the effect of a assigned lighting recipe on plant production, it requires the data logging running for a long time period from a few days to a couple of weeks. It is not possible that the staff supervises the testbed environment on-site all the time and run the system manually. This brings up the requirement that the testbed should run in full or half automated mode. Considering that the greenhouses are usually located in the rural areas, the remote control and monitoring feature through cellular network is necessary as well.

Low cost. With all the requirements listed above, we aim to control the cost of the solution at a minimized value that make it feasible on a large scale. To achieve this, calibration process for low cost sensors with professional light measurement equipments are conducted. This is part of the implementation that highly support for finding the alternative solution of the replacement of expensive components.

4.2.2 Development Process

The development and implementation of a testbed for intelligent LED lighting systems take multiple stages to incubate from lab environment to real greenhouse. Not only the technical challenges such as control strategies for LEDs, system reliability and stability performance, energy efficiency improvements, uniformity of light distribution, but also the functionality that we considered to bring to the end user in the agriculture field, such as customization of light recipes on different plants, measurement and data logging of color mixing control on crop quality and production, benefit of the integration of plant health data with the LED lighting in the precision agriculture. In this section, two stages of the development process is introduced as follows:

Stage 1: Design of daylight harvesting based lighting control strategy on simulation environment In the very beginning stage, a daylight harvesting based lighting control system was studied. The results published in [56] has shown that the energy saving is possibly achieved through daylight harvesting while keeping the illuminance level in
the office room environment at a acceptable level. The control algorithm was running on a simulated office environment with a clear sky daylight model. According that, the author in this paper has designed a multi-input-multi-output (MIMO) feedback control system for a group of red and blue mixed colored LED light fixtures in order to investigate the control and stability performance [101]. A series of different light conditions, which stand for indoor farm environment, constant peak sunlight exposure environment, ideal daylight environment from sunrise to sunset, respectively has been modelled in the MATLAB/Simulink environment. The control performance running in the MATLAB/Simulink simulation have shown that the proposed feedback MIMO lighting control is able to achieve the desired set points on both red and blue channel with daylight harvesting.

**Stage 2: Implementation of embedded lighting control system for energy efficiency and daily light integral (DLI) target** As the simulation results have shown the feasibility of the proposed control algorithm on mixed color LEDs, a embedded lighting control system which consists a microcontroller, a group of RGB light sensors and dimmable LED fixtures with red and blue channels was implemented and run in a emulated daylight environment by the author in this paper and the related work was published in [102]. Two 1kW halogen lamps installed in a 5’x5’ grow tent emulated the daylight change, according to a sunlight modelling that was built based on the hourly solar PPFD data collected locally. Additionally, a time delay, which was caused by the reading process from the sensors and control signal delivery to the actuator, was found during the hardware implementation at this stage. In the practical use, a Smith predictor is introduced along with the proposed control function and coded into the controller to maintain the close loop stability. The results in the energy saving performance has proven the concept while the system runs in a smooth and stable response.

### 4.3 Design Implementation of the Testbed System

Based on the solid foundation that the author built in stage one and stage two, the proposed testbed system is designed as shown in Fig. 4.1. We proposed the testbed system as a key milestone towards to the part of IoT smart greenhouse, by integrating the lighting control system that we have developed with other control factors such as environmental data, plant health and growth status, requirement information from end users and capability of remote access and monitor. Specifically, the features of the proposed testbed system are including as follows:

**A IoT based controller platform for running different LED lighting control strategies.** The proposed MIMO feedback lighting control method is optimized and re-modelling for the real daylight environment, although it has been studied and tested in simulation and
emulated sunlight environment during stage one and stage two, respectively. Additionally, we consider the testbed as an evaluation platform that can contribute to the studies of different lighting control algorithms in the future use, for instance neural network control, machine learning prediction. To support that, sensor groups that covers a wide range of factors to the plant growth is considered into the design of the testbed as system input, such as soil moisture, height between LED fixture and plant canopy.

**Environmental monitoring and control.** In addition to the mixing ratio of different color lights and light intensity, there are some other environmental factors that trigger the optimal performance of plant growth, such as temperature, humidity, CO2. In the proposed testbed, a humidity sensor with temperature output, a UV light sensor, and soil moisture sensor are installed and the collected data is transmitted via I2C and external ADC to the main controller.

**Small scale hydroponics system for leafy green plants and microgreens.** Running with time scheduling and ON/OFF control, a small scale hydroponics system is set up as part of the testbed to provide plant grow environment. We consider leafy greens and microgreens as the primary plant subject to evaluate the performance of proposed control methods for two reasons. Firstly, microgreens show a relatively high sensitivity to the different mixing red/blue ratio for the growth and a vivid fresh mass yield output to the different light PPFD within a relatively short growth cycle [8] [9] [98]. Secondly, leafy greens have shown that the leaf size and leaf color are both affected vividly by the supplemental grow lights with specific spectral and intensity control [103].
Customized *light recipe* for the research of light affect on plant growth and crop productivity. In addition to conducting experiments and development of lighting control and IoT applications, the proposed testbed is designed for building as a mini garden environment for plant growth. The plant ecosystem is designed in the system that provide the opportunities for the interdisciplinary related research. There is a great need in the study of light recipe applied on the plant growth and crop productivity. In this stage the correlations between the measurements of light RGB sensors with the readings from quantum meter is investigated to build a mapping for the reference use of *light recipe*. The proposed feedback control with a new identified model is processed to offer lighting control actions while energy saving is achieved. Instead of using the F28335 MCU (Texas Instruments Inc.) as the controller in stage two, Raspberry Pi is applied for the development of the IoT system and lighting control application in the proposed testbed to support the wireless network communication and IoT technology.

**Internet of Things (IoT) based remote monitoring platform.** As the key component that provide support for the unattended operation and remote control and monitoring, the main control system embedded in the proposed testbed enabled the IoT technology to allow the users acquire the real time plant growth status and take manual settings for the control applications via 4G LTE mobile network. This feature offers the convenience to the
Figure 4.3: Overview of the implementation of the proposed testbed with (a) controller and sensor board, (b) testbed set up, (c) LED fixture, (d) greenhouse set up.

practical scenario that the data analysis and research staff works in the school while the greenhouse maybe located in the rural area with limited access. Fig. 4.2 shows the overview of the proposed testbed system in a greenhouse environment which is equipped with the proposed intelligent lighting control system, plant grow system, local controller, remote data serve and end side user with access through cellular network.

Fig. 4.3 (a) shows the assembled main controller with sensor board and Photosynthetically Active Radiation (PAR) meter. The PAR meter is installed to conduct the calibration process for the correlations between readings from RGB sensors and PPFD from the quantum sensor. Additionally, it is open for use as part of the PAR control in the future work.

The testbed is implemented placed at the corner of a school building where have fully sunlight exposure. As shown in Fig. 4.3 (b), the plant grow environment in the proposed testbed system is built on a 2’x4’ flood tray with a 40 gallon capacity based hydroponic system assembled for the irrigation. Two LED units are fixed by adjustable steel wire ropes and hang on top of the flood tray. The direction and height of the LED fixture are controlled by DC motors and the control actions are generated by the main controller. Temperature and humidity sensor are installed at the corner of the testbed and the RGB light sensors are installed at each corner of the plant canopy area. A additional RGB light sensor and UV
sensor are installed on top of the LED panel. All of them are wired to the a I2C multiplexer board for the data transmission to the main controller via I2C protocol.

The raspberry Pi controller is installed with a 4G LTE cellular mobile router together as the control and network center. As a low cost, IoT friendly microcomputer, it brings more convenience and provide affordable solution for supporting a variety of features added in this stage, such as the wireless communication with WiFi enable control nodes, integration of different types of GPIO sensors, remote access and local data sever etc. To ease the limitation of wired communication, a RESTful communication based wireless network is built for the LED light units, as a upgrade of the UART communication in the second stage. It offers the system with plug-and-play feature and increase the number of control nodes. The installed LED fixtures and the color ratio is customized by the main controller, as shown in Fig. 4.3 (c). A communication module is programmed in Python3 to support for control of the detectable LEDs in the WiFi network via RESTful API communication. The overview of the proposed testbed structure and related set up in greenhouse scenario is designed and targeted for the use in a greenhouse environment located at Langley, BC, Canada, as shown in Fig. 4.3 (d).

4.4 Testbed Evaluation and Experimental Results

A sunny day in December with clear sky condition is selected to conduct the experiment for testing the lighting system performance in the proposed testbed system. Fig. 4.4 shows results of the total Photosynthetic Photon Flux Density (PPFD) on the plant canopy level in 24hours, based on the testbed system with the proposed built in feedback lighting control system and daylight harvesting feature. The overall PPFD in the performance results have shown the system is capable of keep the PPFD stably at $250 \, \text{µmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Occasionally the PPFD was below the targeted value a bit, as we can see that at time 9AM and 12PM.
Figure 4.5: Light control performance on the proposed testbed from dawn to solar noon.

We believe this is because of the lack of sampling rate from the PAR meter logger and the sunlight blocking by the dark clouds.

Fig. 4.5 shows a overview of the LED dimming output change from dawn to solar noon. It shows that the plant tray area in the proposed testbed have received high supplemental light outputs from the LED fixtures in dawn, when the time that the sunlight was weak or not available. By taking advantage of the daylight harvesting, after the sun rose up, the dimming level gradually went down and reached to fully dim off at the time of solar noon. Combined with the PPFD output result shown in Fig. 4.5, we conclude that the lighting system is capable of achieving the targeted light requirement and as well as reducing energy consumption by dimming the LEDs.

In addition, microgreen kale is selected as the plant object to testify the growth performance. Three identical plant trays with identical amount of microgreen kale seeds are placed in three different different light scenarios: solo sunlight environment, mixing color control of LEDs in a grow tent with emulated daylight environment as developed in stage two, mixing color control of LEDs with calibrated PPFD desired point setting in a real sunlight environment as the proposed testbed in this chapter, respectively. All of the three sets are started and ended simultaneously with lasting for a two-week grow cycle. The growth status in the harvest day for each plant tray is shown in Fig. 4.6. As we can see that the microgreen kale grow in good conditions under all of the three environments, especially it shows a higher plant productivity and a more uniform distribution in the proposed testbed.

4.5 Conclusion

The study in this chapter addresses the applicability of a testbed with a intelligent LED lighting control system. The design concept has been depicted and different stages of the forming process has been illustrated. With the implementation of the testbed, an intelligent
LED control strategy has been tested using the growth of real plants in a real daylight environment. Microgreen kale were selected as the test object and the performance have shown that the proposed testbed was capable of achieving desirable light requirement for the tested plant and maintaining the plant at a better growth performance compared to the reference set.
Chapter 5

An Intelligent IoT-enabled Lighting System for Energy-efficient Crop Production

5.1 Introduction

LED supplemental lighting has attracted growing interest in the agriculture sector because of offering a relatively high energy-efficiency and the capability for automated dimming [104] – [106]. The flexibility to control light at a specific spectrum such as red, blue, and UV can have a positive influence on plant growth [107]– [110]. With rapid technology advancements in the field of the Internet of Things (IoT) and wireless communication, smart LED supplemental lighting systems can play a significant role in improving the performance of future intelligent greenhouses [111], [112], [113].

In a conventional greenhouse management system [114], the central control unit runs a combination of time scheduling and threshold-based control schemes to maintain a good growing environment for different plants. In particular, environmental factors such as $CO_2$, soil moisture, humidity, temperature, and light intensity have to be maintained at desired levels depending on the specific requirements of the plants [115], [116]. By setting a specific time schedule and a threshold range, the sensor and control equipment are triggered at appropriate times.

While there has been a lot of work on smart lighting in residential and office buildings [117], [118], smart LED control has been less discussed in greenhouse farming [119]. Research on optimization and improvement of greenhouse systems for supplemental lighting has attracted attention in recent years [120], [121]. Compared to indoor farming, in which LEDs are sole sources of light, greenhouse farming takes sunlight and supplemental light (e.g., from LED fixtures) as a combination of light sources to deliver uniform light for plant growth. In [9], the authors demonstrated that a specific ratio of red and blue, achieved through LED supplemental light, can increase the dry weight of pea shoots by increasing photosynthetic photon flux density (PPFD) in the winter dark months. In [122] a single-
input single-output control method was proposed that used a Photosynthetically Active Radiation (PAR) meter to monitor the PPFD from sunlight to adjust the dimming level of LED. Considering a high cost of PAR meter, it would be relatively expensive to incorporate them into a large-scale greenhouse. Also the uniform distribution of light would be an issue. An open-loop control ON-OFF strategy for lighting and shading was discussed using high pressure sodium lights (HPS) in [33], [123] to achieve constant daily light integrals (DLI). In [124], an ON-OFF lighting control scheme was presented for high-pressure sodium (HPS) lights based on weather forecast info and electricity price. However, an ON-OFF scheme is disadvantageous when it comes to maintaining lighting uniformity. Furthermore, the HPS light source has lower energy efficiency than LEDs [125], [126], and HPS is not good for frequent on and off.

In this chapter, an IoT based lighting system is proposed and tested on a prototype platform as an extension of the system described in [101] using feedback control of lighting. By taking advantage of feedback control and the dimmable feature of LED fixtures, our proposed system can maintain the PPFD at plant canopy at desired levels to meet the DLI requirement while minimizing energy consumption. The system proposed in this chapter uses WiFi communication with RESTful API for the dimming control of the LEDs and can achieve energy savings by utilizing dimming control and sensor data for the daylight harvesting.

The organization of this chapter is as follows. The IoT-based automation platform is introduced in section 5.2. In section 5.3, the model identification and its control system are introduced. Experimental results are presented in section 5.4 for lighting control which demonstrate the capability of the proposed control system to achieve energy-savings. Conclusions and future work are presented in section 5.5.
5.2 IoT System Architecture and Prototype Implementation

A small-scale indoor plant growth system was set up using supplemental lighting and other sensor modules. The system includes a garden system equipped with different sensors such as RGB sensors, UV index sensor, PAR quantum sensor, temperature and humidity sensor, soil moisture sensor, distance sensor, camera, a control unit, LED supplemental light fixtures, communication hardware, and a cloud data server. Specific details about this system are presented in the following.

5.2.1 Small-scale Indoor Garden System Set-up

As shown in Fig. 5.1, the system was built on a 2’ × 4’ flood table, assembled with an active aqua tray stand and a 50 gallon capacity reservoir. A Ebb and Flow hydroponic system was built for the irrigation and fertilization, which was equipped with a standard water pump, air pump, and timer. The plant growth system was placed in an indoor space facing the south-west direction alongside a transparent french window in order to achieve maximum sunlight exposure (geo-location: 49°11’14.4"N 122°50’59.4"W).

5.2.2 Environment Monitoring System

The proposed IoT-based measurement and control system is shown in Fig. 5.2 which consists of the following components:
Daylight Monitoring and Data Acquisition System

As a key part of the proposed management system, the light data were measured from the combined daylight and supplemental light fixtures. A group of RGB light sensors (TCS34725 from TAOS, Inc.), quantum sensor (MQ-501, from Apogee Instruments, Inc.), a UV light sensor (SI1145, from Silicon Laboratories) were used for real-time light sensor data and calibration processes.

Fig. 5.4 shows the overall set up of the sensors and the main controller prototype board. Four units of RGB light sensors were installed on each side of the flood tray to collect the combined light intensity coming from the sunlight and LED light units. This sensor set was used to provide real time lighting intensity system identification and control processes. A TCA9548A $I^2C$ multiplexer is used to allow identical $I^2C$ devices to be addressed and run on the same port. This is due to having a limited number of $I^2C$ ports on the raspberry Pi board and the identical $I^2C$ address issue. A quantum PAR meter (MQ-501 from Apogee Instruments, Inc.) was mounted on top of the LED fixture to evaluate the control performance by measuring PPFD as a reference. Through the serial communications interface (SCI) protocol, the main raspberry Pi acts as a main controller that requests the average value of PPFD data every 30 minutes from the quantum sensor. All the data were saved in a CSV file in the local drive and transmitted to the cloud server and end users.
Table 5.1: Mapping of the correlations between the height of LED fixture and the light distribution on red and blue channel.

<table>
<thead>
<tr>
<th>LED setting</th>
<th>red/blue= 1:1</th>
<th>red</th>
<th>100% blue</th>
<th>100% blue</th>
<th>RGB CLR_1</th>
<th>depth/cm (distance between led panel and rgb sensor)</th>
<th>LED setting</th>
<th>RGB BLU_1</th>
<th>depth/cm (distance between led panel and rgb sensor)</th>
<th>LED setting</th>
<th>RGB BLU_1</th>
<th>depth/cm (distance between led panel and rgb sensor)</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>1981</td>
<td>650</td>
<td>1190</td>
<td>73</td>
<td>16871</td>
<td>5225</td>
<td>10885</td>
<td>92.2</td>
<td>2094</td>
<td>673</td>
<td>1270</td>
<td>77</td>
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<td>84.8</td>
<td>1987</td>
<td>628</td>
<td>1212</td>
<td>87</td>
<td>19583</td>
<td>5986</td>
<td>12440</td>
<td>79.6</td>
<td>2158</td>
<td>679</td>
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<td>704</td>
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<td>106</td>
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<td>1401</td>
<td>119</td>
<td>28801</td>
<td>7203</td>
<td>19361</td>
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<td>683</td>
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<tr>
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<td>1179</td>
<td>2964</td>
<td>54</td>
<td>31180</td>
<td>4690</td>
<td>23062</td>
<td>9.6</td>
<td>3045</td>
<td>790</td>
<td>1974</td>
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<tr>
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<td>391</td>
<td>933</td>
<td>79</td>
<td>19180</td>
<td>4805</td>
<td>12891</td>
<td>17.1</td>
<td>1845</td>
<td>461</td>
<td>1214</td>
<td>71</td>
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<td>3288</td>
<td>1156</td>
<td>2264</td>
<td>74</td>
<td>35246</td>
<td>5113</td>
<td>14664</td>
<td>23.9</td>
<td>7092</td>
<td>228</td>
<td>685</td>
<td>52</td>
</tr>
</tbody>
</table>

**Legend:**
- RGB CLR_1: Red:Blue = 1:1
- RGB BLU_1: Red 100% Blue 100%
- RGB CLR_2: Red 80% Blue 80%
- RGB RED_1: Red 60% Blue 60%
- RGB BLU_2: Red 40% Blue 40%
- RGB RED_2: Red 20% Blue 20%
- RGB RED_2: Red 100% Blue 100%
- RGB BLU_2: Red 100% Blue 100%
- RGB RED_2: Red 80% Blue 80%
- RGB BLU_2: Red 60% Blue 60%
- RGB RED_2: Red 40% Blue 40%
- RGB BLU_2: Red 20% Blue 20%
Temperature & humidity and Soil Irrigation Monitoring System

To maintain the temperature and humidity within desired ranges required for plant growth, temperature and humidity sensors HTU210D, from Texas Instruments Inc.) were installed in the system along with a fan and humidifier. A capacitive soil moisture sensor from Grove was utilized to obtain real time soil moisture status. Since there was no analog port on the Raspberry Pi, a base hat with a built-in MCU equipped with a 12-bit 8 channel ADC was integrated with the prototype board to convert the analog signal into digital.

Since the sunlight intensity varies from one day to another, the water loss from soil would be different on a daily basis. A time-scheduling scheme for the irrigation water pump would not achieve an optimal soil moisture for the plant. To ensure that the soil humidity remains at the optimal level, a relay switch was used for controlling the power of the irrigation pump.

Plant Growth Monitor and Motion Detection System

A web-based camera was installed as a part of the management system for motion detection and on-site tracking of the plant growth progress. This subsystem was also set up for potential use of image recognition with OpenCV as part of future development of this prototype. A Pi Camera Module v2 was attached to the CSI port on the Pi microcontroller and placed on the side batten. The web-based camera monitor and motion detection CCTV system was programmed on Python which automatically captures the time lapse images every one second to share with the end users remotely through TCP/IP protocol and save in the local drive.
End User Remote Access and Data Storage

A standalone computer running as a data server was set up and connected to the same local network as the main controller. This workstation was used for storing the data collected by the controller, keep log files, display the GUI, and provide remote access. Furthermore, the computer was connected to the Internet for uploading data to a cloud data storage service, for example, by using the Google Drive API and support for remote access via the Virtual Network Computing (VNC) platform.

5.2.3 Integration of Wireless Supplemental LEDs

Two units of wireless controlled LEDs (Q400 from QuantoTech Solutions Ltd.) were used which allow implementation of features such as tunable red/blue ratios and programmable dimming levels. Both of the LED units were designed for a maximum Photosynthetic Active Radiation (PAR) output of 480 $\mu$mol/s.

Wireless Communication via RESTFul API for Spectral and Dimming Control

The wireless-enabled LED fixtures in the proposed system were controlled by a Raspberry Pi module through a local WiFi network on the platform using a RESTful API architecture. The WiFi module on each light fixture joins the local network with a self-defined IP address assigned automatically. The Pi controller, connected to the same network, calls for connection with requests library on Python3 platform. Since both light intensity on blue and red channels were dimmable from 0 to 100%, the output of the proposed control system would range from 0 to 1 for blue and red channels, respectively.

PWM DC Motor for Auto Height Adjustment and Anti-shading Control

To maximize the sunlight exposure on the plants and avoid the shading effect caused by the LED panels, two DC motors were installed on top of a wood frame to lift up and rotate the angles of LEDs to vertical orientation. This anti-shading feature was applied through the PWM signal output and controlled by the anti-shading control function integrated in the main controller. This feature would run at the time when the PPFD from the sunlight source meets or exceeds the light requirements, in which case it was necessary to power off the LEDs.

Since the plant height increases along with the growth, the height of the LEDs should be adjusted to keep them at a certain distance from the plant. Therefore, to determine the optimal distance, a set of experiments were conducted to get the relationship between the height of the LEDs and the effect of the light shading on the plant canopy surface. The height of the LEDs was adjusted from zero, as close to the plant as possible, to 100 centimeters from the plant canopy surface. The PAR sensor and RGB light sensors were both put near the plants’ canopy surface to record the light data. The step above were
repeated and the dimming levels of the LEDs were adjusted at 20%, 40%, 60%, 80% and 100%, respectively. As shown in Fig. 5.3, the results indicate that the optimal height is around 17 centimeters to 22 centimeters for achieving the maximum light exposure from the combination of both LEDs and sunlight.

5.3 Supplemental Lighting Control

The proposed feedback lighting controller is defined as a linear, static, time-invariant multi-input multi-output (MIMO) system. As per recent research on photometric, electrical, and thermal properties of LED in [127] [128], the power consumption presents a linear correlation to the dimming level applied on the LED drivers in a certain normal working conditions. The performance of the designated controller have been demonstrated in an indoor grow tent with emulated sunlight environment included in the previous research [101], [102]. In this chapter, we extend the above work to a real indoor garden exposed to sunlight. In particular, the sky conditions and shade from nearby fixtures can result in asymmetric light exposure on the testbed. For instance, in early mornings and late afternoons, the light distributed in the corner of the greenhouse would result in more shading than the plants located in the center or middle areas.

To tackle the issues mentioned above, certain parameter settings and automation schemes have to be configured. First, a state space matrix model was obtained using system identification for the real daylight environment. Secondly, a automated scheme for light model identification process was programmed in the controller to update the state space model on a daily basis. Third, the set point value for both red and blue supplemental light was adjusted along with the plant grow cycle. This is due to the fact that the required value and ratio of the red and blue light can vary during different stages of the plant growth.

5.3.1 Control Method

In the proposed system, daylight is harvested such that minimum supplemental lighting is required from the LED panels. To this end, the total light intensity, which is a combination of supplemental light generated by the LED fixtures and natural light, is measured by light sensors. The system model is given by [102]

\[ y(t) = Tu(t) + y_t \]

(5.1)

where \( y(t) \) is the total light intensity at sensor points; \( y_t \) represents the contribution due to daylight; \( u(t) \) is the LED lights dimming input command vector; and \( T \) is an \( m \times n \) full row rank transfer matrix, where \( m \) is the number of outputs and \( n \) is the number of inputs. The feedback control scheme is based on a state-space linear-quadratic regulation (LQR)
method given by (see e.g., [102])

\[ u(t) = K \int e(t) dt \]  \hspace{1cm} (5.2)

where \( e(t) = y_d - y(t) \) is the \( m \times 1 \) error vector, with \( y_d \) being the vector of desired light intensity; and \( K \) is the state feedback gain matrix.

### 5.3.2 Model Identification for the Supplemental Lighting Control

As shown in Fig. 5.4, the LED unit closer to the window is denoted by \( LED1 \) and the one farther from window is denoted by \( LED2 \). Therefore \( LED1\_R, LED2\_R, LED1\_B; \) and \( LED2\_B \) are defined as the output variables for the red and blue channels on \( LED1 \) and \( LED2 \), respectively. Linearization of the lighting model was discussed in [101]. Specifically, the identification process runs after the initialization process on a daily basis. The identification process is illustrated in Fig. 5.5. At the time when the disturbance light is at its minimum value, which is usually during midnight hours, the system is initialized by starting to re-build the identification model. It reduces the daily system accumulated errors so as to increase the control performance and avoid disturbance caused by human factors such as a change in the locations of sensors. Following a reset of LEDs, RGB sensors \( S1, S2, S3, \ldots, S_n \) record the data when the dimming levels of \( LED_{i\text{th}} \) are increased from 0\% to 100\% by steps of 10\%, as 10\%, 20\%, 30\%, 40\%...100\%. Therefore, the identification process takes the following stages
Figure 5.6: Process diagram of the proposed IoT management and lighting control system.

\[
T_{\text{red}} = \begin{bmatrix}
32.603 & 1.5009 \\
1.8709 & 32.928
\end{bmatrix}
\] (5.3)

and

\[
T_{\text{blue}} = \begin{bmatrix}
31.5100 & 2.8864 \\
4.1018 & 34.0210
\end{bmatrix}
\] (5.4)

where \(T_{\text{red}}\) and \(T_{\text{blue}}\) represent the \(2 \times 2\) matrix of the light model (see (5.1)) in red and blue channels, respectively.
Furthermore, we choose control gains $K_{red}$ and $K_{blue}$ for the red and blue channels as follows

$$K_{red} = \begin{bmatrix} 1 & 0.0056 \\ -0.0056 & 1 \end{bmatrix}$$ (5.5)

and

$$K_{blue} = \begin{bmatrix} 0.9998 & 0.0185 \\ -0.0185 & 0.9998 \end{bmatrix}.$$ (5.6)

### 5.3.3 Automation Scheme of the Lighting Control

The automation process of the proposed IoT plant management system include three main steps: IoT monitoring system (Fig. 5.2), automated scheme for lighting model identification (Fig. 5.5), and daylight harvesting lighting control (Fig. 5.6). For each daily system reset, the updated lighting model and control gains were generated and identified as $T'$ and $K'$. The value of the desired set-point on red and blue channels were configured and represented as $Desire_{red}'$ and $Desire_{blue}'$. The system initialization, including the identification and
Figure 5.8: Sunny day scenario: Dimming level variations in 24hrs for the red and blue channels of LED1 (left) and LED2 (right).

set point selection only runs once a day. Once the system initialization process was finished, the proposed algorithm acquires sensor data. The data from the red and blue channels of the $i$-th RGB light sensor are defined as $\text{Red}_1$, $\text{Blue}_1$, $\text{Red}_2$, $\text{Blue}_2$, $\cdots$, $\text{Red}_n$, $\text{Blue}_n$. The dimming command for the red and blue channels of $i$-th LED are defined as $\text{LED}_1\_\text{red}$, $\text{LED}_1\_\text{blue}$, $\text{LED}_2\_\text{red}$, $\text{LED}_2\_\text{blue}$, $\cdots$, $\text{LED}_n\_\text{red}$, $\text{LED}_n\_\text{blue}$. The execution cycle runs following the loop procedure as indicated above until the end of the photo-period which is determined by the timer in the main controller. Finally, the system enters sleep mode and turns off the LEDs until next daytime cycle.

5.4 Experimental Results and Performance Analysis

A series of experiments were conducted from August to November, which cover a broad range of the DLI index from the source of sunlight. To further discuss the system performance, two typical scenarios, including sunny and cloudy days were studied separately. The value of the photoperiod was set as 24 hours in order to evaluate the maximum energy savings and lighting system performance. According to photometric characteristics of the TCS24725 RGB sensor, reading on both red and blue channels are relative irradiance counts. In order to determine the set point value for the system output, calibration has been conducted through mapping the counts from the RGB sensor with the data measured from PAR quantum sensor. The desired PPFD that the system designed to achieve was $250 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.
Corresponding to the PPFD requirement and the calibration mapping results, the desired points of the RGB sensor output for the red and blue channels were determined as 3000, 3000, and 3000, 1000 counts, for sunny and cloudy days, respectively. The objective was to evaluate performance of the daylight harvesting scheme under different red/blue ratios.

As shown in Fig. 5.7, in sunny days, the plants were exposed to relatively high PPFD from the sunlight, specially during noon and early afternoon. As expected, the data on both blue and red channels of sensor S1, located on the edge of the plant tray close to the window side showed that the total light received on the plant surface is over saturated, which the peak point reaching over 10,000 counts. Note that the above numbers are sensor data representing relative irradiance counts and do not have any units. A calibration process is conducted and the corresponding values in PPFD units are presented later in this section.

The data shown for blue and red channels of sensor S4, located on the edge of the plant tray close to the inside of the room, show that a relatively smaller amount when saturation occurs, because of the fact that there was less sunlight exposed onto the area further from the window than the area closer to the window.
Fig. 5.8 shows the dimming output of the LED1 and LED2 on both red and blue channels in a sunny day. Clearly, LED2 (located further from the window) was dimmed with less fluctuation than the LED1 which was located closer to the window. Specifically, the range of blue and red channels was dimmed between 0.65 to 0.30 and 0.90 to 0.3, respectively, on LED2. The corresponding dimming ranges for LED2 for blue and red were between 0.8 to 0 and 0.9 to 0, respectively. The data measured by $S_1$ and $S_4$ in Fig. 5.7 indicate that the combined blue and red light outputs reflected on the plant area were maintained at stable levels, with both achieving the desired set points. Over saturation occurs on both red and blue channels of $S_1$ and $S_4$ during the time from noon peak to early afternoon.

Similarly, the system maintains good stability for cloudy day conditions. A typical cloudy day comes with a relatively low PPFD from the sunlight, while occasionally having randomly strong sunlight exposure during the day. As shown in Fig. 5.9, the data captured by the PAR sensor and the sensor $S_5$, located on the top of the LED panel to measure the sunlight only, indicate two big disturbances. Specifically, a sudden sunlight drop occurs at 4PM and a sudden sunlight exposure occurs at 5:30PM. Compared with the dimming levels of both LEDs in the sunny day scenario, the LEDs provide more compensation on both red and blue channels, due to less sunlight harvesting in a cloudy day. On the other hand, the total light data recorded on both sensors indicate a smoother curve, specially on the red channel of both $S_1$ and $S_4$. As shown in Fig. 5.10, both the blue and red channels on LED1 and LED2 act to compensate the light shortage meanwhile and maintain uniform distribution.
when a sudden shortage of daylight occurs and at 4PM. Also the light is dimmed down when a large sunlight exposure occurs at 5:30PM. Overall, the total light exposure at the red and blue channels on both sensors reached the desired set points at 3000 and 1000 counts, respectively.

A key benefit of real time feedback control with daylight harvesting is to achieve energy savings as discussed in the following. The energy cost in this chapter is compared to a conventional time-scheduling method applied to the same LED fixture where both the blue and red channels of all LEDs are fully turned ON, represented as \( LED_i_{\text{red}} \) and \( LED_i_{\text{red}} \), during the whole photo-period, and fully turned OFF during the sleep period. The dimming level of the \( i \)-th LED on red and blue channels, defined as \( LED_i \), changes from \( t_s \) to \( t_e \), which represents the start and end time of the photo-period, respectively. Thus the energy savings, on the red and blue channels of each LED unit, are given by

\[
E_i_{\text{red}} = 1 - \frac{\int_{t_s}^{t_e} LED_i_{\text{red}} \cdot dt}{LED_i_{\text{red}} \times T_p}
\]

and

\[
E_i_{\text{blue}} = 1 - \frac{\int_{t_s}^{t_e} LED_i_{\text{blue}} \cdot dt}{LED_i_{\text{blue}} \times T_p}
\]

and the overall energy saving \( E \) is obtained as

\[
E = 1 - \frac{\sum_{i=1}^{D_n} E_i_{\text{red}} + \sum_{i=1}^{D_n} E_i_{\text{blue}}}{2D_n}
\]

where \( d_s \) and \( d_e \) represent the start and end times of the total plant growth cycle, \( D_n \) represents the total number of days for the plant growth cycle, \( LED_n \) represents the \( n \)-th LED units, and \( n \) represents the total number of LEDs in the system.

After applying (5.7) and (5.8) to the data captured in the sunny day scenario, the energy savings on both red and blue channels are calculated as follows

\[
E1_{\text{red}} = 30.40 \\
E1_{\text{blue}} = 46.13 \\
E2_{\text{red}} = 16.35 \\
E2_{\text{blue}} = 42.73
\]

where \( T_p \) is 24 hours, and \( t_s \) and \( t_e \) are 0:00AM and 11:59PM, respectively, and \( LED_i_{\text{red}} \) is 1.0.

\[
E \approx 34
\]

where \( D_n = 1, n = 2, d_s = 1 \) and \( d_e = 1 \).
Applying equations (5.7)-(5.9) to the data in the cloudy day scenario, we obtain the energy savings for each channel for each LED as follows

\[ E'_{1\_red} = \%13.52 \]
\[ E'_{1\_blue} = \%33.80 \]
\[ E'_{2\_red} = \%5.77 \]
\[ E'_{2\_blue} = \%29.88 \]  \hspace{1cm} (5.12)

and

\[ E' \approx \%21 \]  \hspace{1cm} (5.13)

where \( E' \) represents the energy saving in the cloudy day scenario.

To investigate the energy saving for the whole grow cycle and verify the feasibility of the proposed system, a comparison experiments with applying onto live plants were conducted.
A conventional on-off time scheduling scheme lighting system was built at the same location as a comparison object. Both of the LED systems run for 16 hour photoperiod (5am-9pm daily) in a 2 week grow cycle. During the photoperiod, the conventional time scheduling lighting system ran the LED red and blue units at a consistent dimming level 100% and 20%, respectively. Except for the lighting scheme, all the other settings maintained as identical as in the proposed set up, such as the germination process, irrigation routine, humidity and temperature control. A summary of the parameter setting for the experiment is shown in Table 5.2. The photoperiod was set as 16 hours for both groups, which power on the system from 5am to 9pm daily. To determine the desired set point for the LEDs in the proposed system, calibration was conducted prior to the plant experiments in order to get the relationship between the DLI and the readings from the light sensor. For this experiment, the set point for the red and blue channel of LEDs were 3000 and 1000 counts, respectively, according to the calibration results. The desired DLI was expected to reach around 13 to 16 $\text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ with the proposed lighting system applied. Also the quantum PAR meter located near the surface of the tray shows the PPFD which, from the combination of the sunlight and the supplemental light, was maintained at 250 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ during the
Table 5.2: Parameters of the Comparison Experiment for Lighting Control System Performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>On and OFF Time Scheduling</th>
<th>Proposed Feedback MIMO Lighting Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting time</td>
<td>5AM</td>
<td>5AM</td>
</tr>
<tr>
<td>Ending time</td>
<td>9PM</td>
<td>9PM</td>
</tr>
<tr>
<td>Photoperiod</td>
<td>16hours</td>
<td>16hours</td>
</tr>
<tr>
<td>Number of days for supplemental</td>
<td>7 days</td>
<td>7 days</td>
</tr>
<tr>
<td>light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grow cycle</td>
<td>2 weeks</td>
<td>2 weeks</td>
</tr>
<tr>
<td>Red: blue ratio</td>
<td>0.83:0.17</td>
<td>n.a</td>
</tr>
<tr>
<td>Dimming level setting</td>
<td>Red: 100%</td>
<td>n.a</td>
</tr>
<tr>
<td></td>
<td>Blue: 20%</td>
<td></td>
</tr>
<tr>
<td>Set point for red/blue</td>
<td>NO</td>
<td>Red: 3000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blue: 1000</td>
</tr>
<tr>
<td>Dimming function</td>
<td>NO</td>
<td>Real time dimming</td>
</tr>
<tr>
<td>Number of LEDs</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Daylight harvesting</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Quantum sensor calibration</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

photoperiod. Thus, we could get the DLI maintained at 14.4 mol·m⁻²·d⁻¹, which fully met the expected target DLI requirement.

Microgreen kale was selected as the test object and 2 week grow cycle was applied. In the first week, the plants went from seeding to germination. The plant tray was covered fully by a cardboard to block the light. The cardboard was removed on the 1st day of the 2nd week and the plant tray was exposed to sunlight and supplemental LED light for one week before harvesting. Fig. 5.11 shows the different stages of planting of the microgreen kale vividly. Two plant trays were placed under each LED unit. Therefore, in total four plant trays were used for each set up. As shown in Fig. 5.12, the microgreen kale under the proposed lighting control system grew as perfectly as the ones under time scheduling system. A slightly more even height and uniform density distribution was observed from the tray under proposed lighting system than the ones under time scheduling system. The fresh weight of microgreen
Table 5.3: Comparison of the Effect on Plant Growth Performance.

<table>
<thead>
<tr>
<th>Control method</th>
<th>Plant Tray#</th>
<th>Fresh Mass* (gram)</th>
<th>Percent Deviation^ ( %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed Feedback Control</td>
<td>Tray #1</td>
<td>218</td>
<td>7.0%</td>
</tr>
<tr>
<td></td>
<td>Tray #2</td>
<td>204</td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td>Tray #3</td>
<td>201</td>
<td>-1.3%</td>
</tr>
<tr>
<td></td>
<td>Tray #4</td>
<td>192</td>
<td>-5.8%</td>
</tr>
<tr>
<td>ON and OFF Time Scheduling</td>
<td>Tray #5</td>
<td>158</td>
<td>6.2%</td>
</tr>
<tr>
<td></td>
<td>Tray #6</td>
<td>137</td>
<td>-7.9%</td>
</tr>
<tr>
<td></td>
<td>Tray #7</td>
<td>108</td>
<td>-27.4%</td>
</tr>
<tr>
<td></td>
<td>Tray #8</td>
<td>192</td>
<td>29.1%</td>
</tr>
</tbody>
</table>

# Each grow system is placed 4 units of plant trays as 2 rows in parallel.

* Harvest from microgreen kale at the end of 2 week growth cycle.

^ Percent deviation = \(\frac{\text{Fresh Mass of Tray#} - \text{Average Fresh Mass}}{\text{Average Fresh Mass}}\) \times 100%

Kale from all of the trays harvested at the end of the 2nd week is summarized in Table 5.3. The percent deviation shows the extent to which uniform light distribution can affect the growth. The fresh mass from trays under ON-OFF time scheduling method (Tray #5, #6, #7, #8) has higher percent deviation than the trays under the proposed lighting control (Tray #1, #2, #3, #4). Particularly, Tray #7 and #8 shows a relatively high deviations, i.e. -27.4% and 29.1%, respectively. It is concluded that the weight distribution of all the four trays under proposed lighting system had a more even fresh mass, compared to the fresh mass results from the time scheduling lighting based group. This proves the advantage of the proposed lighting system in providing a uniform light distribution on the plant surface during the daytime that sunlight varies from sunrise to sunset.

Under the proposed lighting control, red and blue channels on LEDs are dimmed to harvest the daylight. The dimming command is sent by the controller, according to the light data collected from the sensors located on the plant plane. The energy saving of the LED units were recorded during the whole 2nd week as shown in Fig. 5.13 and summarized in Table 5.4. For the specific light recipe given to the microgreen kale, we achieved an average 18.16% energy savings using the supplemental lighting during the grow cycle, while maintaining the plant productivity as regular as the conventional time scheduling lighting system produced.
5.5 Conclusions

A IoT-enabled monitoring and control system with a built-in daylight harvesting control algorithm was presented in this chapter. The experimental results and the system performance under two different sunlight conditions show that the system were analyzed. The compensation from the supplemental LEDs, specifically on red and blue channels, varied because of the daylight variations. The controller collected sensor data as the feedback signal provided and adjusts the dimming levels of LEDs to utilize in the daylight harvesting algorithm. Since over saturation occured, the system would have expected that the LEDs were fully dimmed off to save the energy cost while the light requirement were still being achieved. The proposed work has shown that a 34% and 21% energy savings were achieved in sunny and cloudy days, respectively, by applying the proposed lighting system, when compared to a conventional ON-OFF supplemental light control scheme. Also, the system achieved uniform lighting distribution and stable light output. Additionally, the live plant experiments conducted in this study had shown that the tested microgreen grew with even height and uniform density, while the system was able to achieve the targeted DLI requirement.
Figure 5.13: Overview of the energy saving on red and blue channels of LEDs with running the proposed lighting system over one week.
Chapter 6

Summary, Conclusion, and Suggestions for Future Work

6.1 Summary and Conclusions

In this thesis, an energy-efficient lighting control system in greenhouse environments is proposed; and its performance in energy efficiency, uniformity of light distribution, and crop productivity was studied in several control applications. The proposed lighting control system can increase savings on energy compared to conventional time-scheduling based lighting controls while achieving light requirements for plant growth in greenhouses.

1. The concept of the proposed lighting system was introduced and the system architecture was designed. Hardware implementation, including data acquisition from sensors and serial communication with programmable LED fixtures, were then studied and experimentally validated. Initially, the lighting model was identified in the proposed workplace and simulated in the MATLAB/Simulink environment with different daylight conditions. It showed that using the proposed lighting control method can achieve desired light set points on both the red and blue channels.

2. The proof-of-concept supplemental lighting system, equipped with programmable red/blue/UV LED fixtures, RGB light sensors, and controller board, was set up in a grow tent with emulated daylight to mimic a greenhouse environment. The proposed lighting control system was program tested on a C2000 real-time controller. The emulated daylight source, controlled by a voltage transformer with various illuminance levels, mimicked daylight from sunrise to sunrise. The mapping for one-day solar hourly PPFD on a Winter day with clear sky conditions in Vancouver, BC was built; and the control performance for a 24 hour daylight period was investigated. A Smith predictor, used as the delay compensation, was applied to the proposed system for improvements to the response robustness and system stability.
3. Integration of the proposed lighting system and Internet of Things (IoT) technology was presented for a new plant growth system. The design of the daylight harvesting based lighting control strategy was verified by the results of the plant growth experiment conducted on microgreen kale. The experimental results showed that the proposed lighting control method achieves the light conditions for plant growth, and the total Photosynthetic Photon Flux Density (PPFD) in 24 hours is maintained at the desired set point range.

4. An intelligent IoT-enable control application with wireless LED lightings for energy-efficient crop production is presented. The proposed system was programmed on a Raspberry Pi computer board. The control scheme was tested in the predesigned plant growth platform. The designed architecture integrates the lighting control with environmental monitoring as a ready-to-use autonomous smart farm solution for greenhouses in remote areas. During the full growth cycle of microgreen kale, investigations showed a 34% and 21% energy savings were achieved in sunny and cloudy days, respectively.

6.2 Future Work

Based on the results obtained and the knowledge learned from this research, the following step would be an application at a commercial greenhouse with larger-scale LED fixtures and test areas. Further exploration of the energy efficiency of LED lighting and the targeted requirements for plant growth should be done.

Starting from a pilot project, the research work in this thesis focused on the feasibility research of the proof-of-concept control scheme and verification on the performance of dimming command as the feedback signal for the LED fixtures. Based on the real-time light data collected from a series of light sensors located on the rooftop and the plant canopy level. One of the drawbacks in this system is the possibility of data overflow due to a high sunlight exposure or shading effect on the testbed from the light fixtures. Therefore, the investigation of a proposed control strategy with machine learning or image processing from a rooftop camera system may avoid tackle issues that mentioned above.

Another direction for research is the correlation between light reflection and direct light output. The development of a calibration model for the light sensor installed on the rooftop should be further improved. Ideally, light sensors attached to the LED panel has more flexibility and higher integration capability with LED panels than the sensors installed on the testbed surface, or the plant canopy. This study should aim to apply rooftop light sensors in the light system for higher light data measurement accuracy to support the intelligent supplemental light system.

The third idea is to integrate image processing technology with the proposed control system as one of the sensing parts to add the feature of the plant growth track. Monitoring
the growth status of a specific target such as the leaf, fruit, or flowering. Essential data for generating the optimal ‘light recipe’ to provide optimal light requirements.
Bibliography


[37] Albertos, Pedro and Antonio, Sala, Multivariable control systems, 2006


