LIGHTING CONTROL SYSTEMS:
AN ENERGY SAVINGS AND VISUAL COMFORT COMPARISON

By

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ABSTRACT

Energy consumption and visual comfort are areas of interest for new building owners, employers, and building occupants. Current lighting control systems can be costly and do not effectively alter the lighting system based on the human occupancy and comfort level. Most lighting control systems simply use a time clock system or occupancy sensor to turn the lights on or off. In addition, some lighting control systems may be difficult to use for the operator which leads to neglect and then the control system will not be used at all. Since the amount of lighting and the quality of light perceived by humans can have a direct impact on their health and productivity, this project is aiming to create a lighting control system that has the ability to reduce the energy consumption while considering the comfort of the occupants within the space. By combining machine learning and artificial intelligence, a lighting control system algorithm can be created to effectively change the light levels within a space without needing the occupant to control them manually. A system with these capabilities will effectively lower the overall energy consumption by reducing the light output when it is not needed by the occupant.

Due to the global shift after the pandemic, many individuals have shifted to a residential work environment as they are performing more remote work. While more people are working from home, this is making it even more important to have sufficient lighting within your space or the location that you have turned into your home office. Many people have shifted their spare bedroom within their home into a home office and a simple table lamp will no longer provide the light levels that are necessary to feel comfortable and complete work efficiently. It has become more relevant to bring the lighting systems and lighting controls that are present in commercial office spaces into residential homes at a scale and cost that can be accepted by most homeowners. As the energy consumption is constantly increasing for the residential sector, it is becoming more important for homeowners to actively control their energy use while keeping it a simple system.

To determine the effectiveness of the proposed system with the IR array sensor, data will be collected within a residential space using existing lighting control systems and this data will be compared to the proposed system. This data will be collected on various days when cloudy conditions are available outside. Cloudy weather conditions are used for this data collection process because this is considering worst case scenario and Michigan experiences mostly cloudy days throughout the year. Throughout this data collection process, the energy savings from each lighting control system will be documented and studied. In addition to the energy that is saved

from each system, the amount of times that the visual comfort is compromised will be documented. These factors will allow for an accurate comparison between the existing and proposed lighting control systems. Although energy consumption and visual comfort are the major components that will be considered for this project, cost savings will also be studied and discussed.

According to the analyzed results, the proposed system with the IR array sensor was successful at reducing the energy consumption and limiting the amount of times that the visual comfort was compromised. The proposed system with the IR array also had the largest amount of cost savings per month. Although there are not large cost savings, the proposed lighting control system does perform well enough to reduce the number of times that the visual comfort is compromised while reducing the overall energy consumption. The installation of the proposed lighting control system utilizing the IR array sensor would be more beneficial to homeowners that are looking to make their home spaces more customizable and comfortable. While analyzing the results obtained for the various trials of data collection throughout the duration of this project, there are also some considerations that can be made by the homeowner to determine which system is the most beneficial for them. For example, there is a cost and installation required for all of these systems, so the selected system may be dependent on the experience of the homeowner and how well they can be educated on the system.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Introduction

Energy consumption is becoming an important aspect within the design of new development residential and commercial buildings. Many customers and homeowners are looking for new ways to control their energy consumption and lower their electricity costs. The energy consumption percentage for lighting systems in the building sector ranges from about 20% to 45% of the overall building energy consumption which has increased by 20% since 2000 despite a slowdown during the period of the economic crisis (Doulos, 2019). Updating existing light fixtures to LED lamps can improve the overall energy consumption; however, various lighting control systems will be analyzed to determine the effectiveness of reducing energy consumption. Visual comfort will be an import factoring while analyzing the energy savings.

In addition to growing concerns with energy consumption, commercial building occupancy has been a major setback after the COVID-19 pandemic. Many commercial buildings, especially office buildings, have seen a decrease in occupancy following the large number of companies moving to remote work. “Depending on where you’re standing and what day of the week it is, daily occupancy in the world’s office buildings ranges from about 20% to 70%. That’s low when you stack it against pre-pandemic averages, which were consistently closer to 80%. In the U.S., daily occupancy is still low. Big cities range from 30-40% in New York and Chicago to 50% in Boston. There is general consensus that the U.S. is leading the charge in creativity and quality of office amenities, which is particularly important as owners and investors strive to bring a hospitality-focused environment to the office experience” (Zettl, 2022). Even with increasing office experiences, there has still not been a push for many companies to bring their employees back into the office. While this is a concern for commercial building owners, it is also a concern for architectural engineering. Many buildings now have to be designed differently in order to accommodate for the adjustments required to make people feel comfortable in commercial spaces after the COVID-19 pandemic. “It has become clear that viruses and diseases can live and thrive on many surfaces throughout an indoor environment after contact. As many businesses are implementing temporary “contact-less” features throughout their offices and services, it is reasonable to expect that many of these features may become standard. Ventilation systems that remove potentially contaminated air, automatic doors, smart phone linked elevator buttons, voice activated lights, and a plethora of other contact-less features may become the standard within indoor spaces nationwide. The pandemic appears to be reshaping the modern world in significant and unexpected ways, those who are resistant to change and view these new trends as temporary may be left behind, as those who understand these changes and their impact on society push architecture forward" (VIP Architectural Associates, 2022).

1.2 Background

Lighting within a space is very important and is known to directly relate to the mood and productivity of people working within space. "The lighting environment at indoor workplaces is important not only to provide vision and visual comfort, but also for light's direct influence on human physiology, cognitive performance and mood" (Benedetti, 2019). It is becoming more relevant to study the impact of a dynamic lighting control system that combines daylight and artificial lighting on occupants' visual comfort as well as cognitive performance.

Healthy lighting and visual comfort are the conditions of sufficient light quantity and quality that supports the clear vision of the space around you without straining your eyes while completing a certain activity (Seftyarizki, 2021). Good lighting is perceived by the human eye as a light source that is evenly distributed across the surface of interest while limiting the contrast between the light and dark areas. Lighting that meets the needs of the occupants within the space is believed to improve work productivity and alter the work rate of employees within a workplace environment. "Apart from its physical effects on workers, there are also psychological effects that can affect the productivity of a worker" (Robertson, 2018). As stated before, lighting that limits the amount of contrast between light and dark spaces will relieve the effect of the brightness of a computer screen, for example. The area around the computer screen should be just as bright as the computer screen itself to limit the amount of strain experienced by the user. According to a study by the American Society of Interior Design, approximately 68% of employees complain about the lighting in their office. This presents a relevant problem for many employers because they want their employees to have a comfortable place to work. Healthy lighting can vary for each person, which makes it difficult to provide quantitative evidence on how visual comfort effects occupants within a space.

There have been many changes within the lighting industry over the past years due to the global pandemic that changed the lives of many. The biggest change on the lighting industry is that many individuals began working from home and changed their spare bedrooms into a home office. “The pandemic brought about an acceleration of remote work. To appreciate how suddenly this arrived, consider that two years ago less than 25% of the U.S. workforce participated in some sort of remote work at home, and it was typically less than half their work hours. During the height of the pandemic, however, approximately 40% of the U.S. labor force participated in remote work, and it was full time at home” (Greenstein, 2021). With the large increase of individuals working from home, many people began looking for ways to make their at-home spaces feel more comfortable. Although switching a spare bedroom into a home office may not seem like a huge concern, this leads to homeowners changing an area of their home into a space that should be comfortable enough for them to work in for many hours during the day. The typical table lamp will no longer meet the lighting needs required for completing many typical office tasks. While keeping this information in mind, it is important for designers and engineers to ensure that individuals have sufficient light levels that will allow them to feel comfortable and productive within their space.

1.3 Current Lighting Control Systems

Many existing and current lighting control systems use a time clock schedule to turn the lights on or off depending on the occupancy of the space. Once the occupancy of the space became an important factor, lighting control systems began using an occupancy sensor in coordination with a time clock schedule. This would allow the lighting system to turn off if it detected that the space was unoccupied for a certain amount of time. Systems with occupancy detection were incorporated within building systems in order to reduce the amount of energy wasted from lighting systems. When the lighting systems are left on for long periods of time without occupants in the room, energy is being wasted and this will also reduce the lifetime of the light bulbs and/or lighting system. The lighting industry is currently overlooking lighting optimization and how a lighting control system can be used to effectively illuminate a space while maintaining visual comfort for the occupants.

The negligence of leaving the lights turned on when the space isn’t being used has led to the incorporation of occupancy detection sensors within most spaces. The most commonly used occupancy detection devices are the passive infrared (PIR), ultrasonic (US), and dual-technology (DT) sensors. These sensors provide results that control the lighting systems by turning the system on or off. Visual comfort for the occupants is very rarely considered and is something that should be studied to determine how these occupancy detection devices can be used to ensure that occupants are comfortable within their spaces. “Most of the present buildings still adopt a legacy light control policy. For example, an administrator usually binds a group of lights with a control switch or motion (occupancy) sensor for each space in a building. It can be efficient for a closed area like rest room or meeting room. Similarly, in an open-plan office, lights are usually selected in a straight line and mapped with a wall switch to be controlled by users. However, in this case, such control is not efficient as multiple users work and move individually” (Lee, 2018). With that being said, many individuals are completing different types of work at the same time. This may mean that one person is writing a paper on their desk while their co-worker next to them is only focused on their computer screen. Both of these employees require different levels of light to feel comfortable and it does not make sense to have the light fixture above their desk to be controlled with the same switch. This leads to the idea of having individualized lighting controls where each person can feel comfortable depending on the task that they are completing. For residential applications, it is important for the room occupant to feel comfortable no matter what task they are working on.

1.4 Proposed Lighting Control System

Artificial light is the main factor in energy consumption for most commercial buildings and residential homes so it is becoming more relevant to develop a system that can effectively reduce the energy consumption while maintaining visual comfort. Current studies have investigated the idea of using artificial intelligence algorithms and thermal cameras that can accurately detect human occupancy. For the purpose of this project, current lighting control systems will be studied and compared to the proposed lighting control system to determine the effectiveness at saving energy while maintaining visual comfort for occupants.

Returning to the thought of comfortable and effective light levels being more relevant for residential spaces as homeowners are working from home more often, the proposed lighting control system will allow homeowners to effectively control their lighting autonomously. The proposed lighting system will use an infrared array camera to detect occupancy and a light level sensor to detect the available illuminance within the space. If motion is detected and the light levels from natural daylight are too low, the system will automatically turn on the lights for the space. If the individual leaves the spaces, the system will turn off the light fixture automatically to save energy. In addition, if there is motion detected but the light levels from natural daylight are sufficient for completing a task on the work surface, the system will turn off the lights. This algorithm is expected to save more energy compared to current lighting control systems by combining human occupancy detection and light level sensors. A diagram of how this system will work and how the algorithm process is designed is illustrated below.

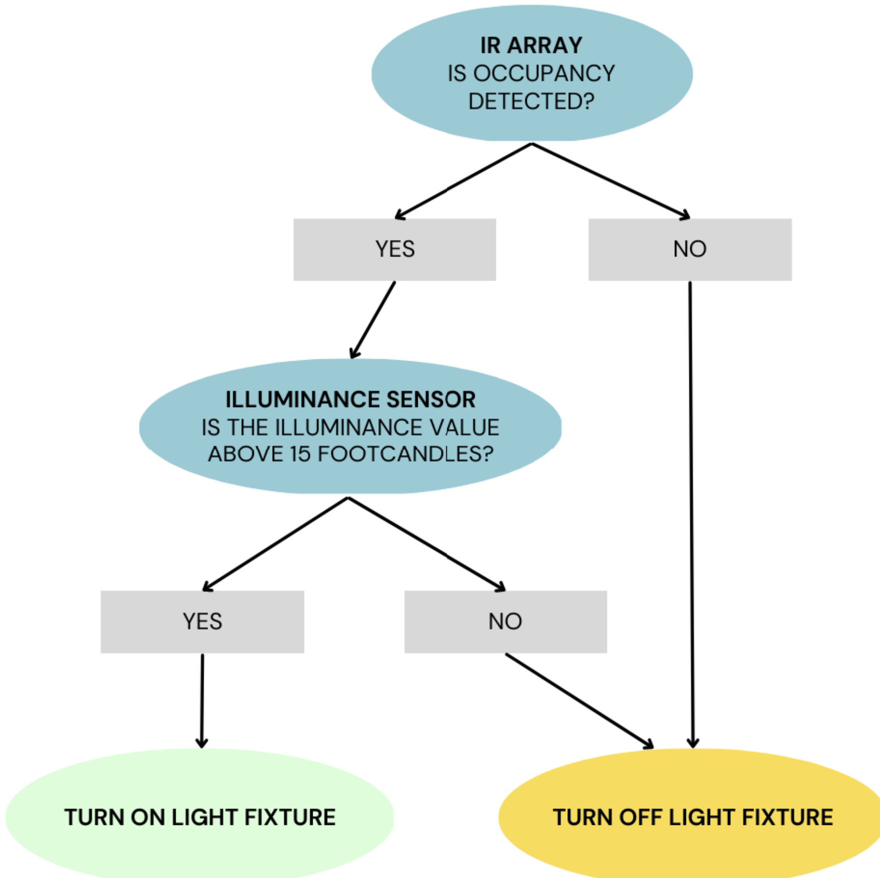


Figure 1.4-1: IR Array Occupancy Detection Flowchart

1.5 Lighting Control System Optimization

It is important to optimize visual comfort and energy consumption within a building because this will allow for increased performance as well as energy savings. Not only does optimization of the lighting control system include artificial light, but it also includes natural daylight. It is important to consider passive systems that can be used to alter the natural daylight when it is considered to be too intense for the occupants. Passive systems can increase the visual comfort of the occupants while also increasing the energy savings by reducing heating and/or cooling costs.

In addition to optimizing visual comfort and energy savings, lighting control systems can be used to optimize many other building systems. For example, occupancy detection with the proposed lighting control system could be used to coordinate with heating, ventilating, and air conditioning systems. “By allowing devices to reside on a networked control system, devices have the ability to communicate with each other, allowing many other possibilities. For example: the implementation of geofencing technology. Geofencing is the use of GPS or radio frequency identification (RFID) technology to create a virtual geographic boundary, enabling software to trigger a response when a mobile device enters or leaves a particular area. This is already readily available in the residential marketplace. A user can setup the system so when they leave the house with their mobile phone, the system will sense that they are outside the fence and complete automations, such as initiate the security system, turn down the heat, and make sure the lights are off. There are other, lesser-known purposes for this type of technology. A surgeon could enter an operating room and the temperature and lighting levels could automatically adjust to his/her liking. When entering a hotel, the RFID tag in room keys could sense an occupant in the building and heading toward a room. The networked control system could turn on lights and adjust the temperature before an occupant even enters” (Kondrat, 2021). This technology has already been implemented and studying using geofencing technology which means that there is the possibility and potential to incorporate this technology with IR array cameras and occupancy detection.

CHAPTER 2: LITERATURE REVIEW

Lighting control systems have greatly advanced over time. Many spaces are now required to include lighting control systems that will reduce the energy costs within the building automatically. The most commonly used lighting control system is a toggle switch that is located close to the door when entering a space. This toggle switch simply turns the system on or off when someone enters or leaves the space. Although this is effective when being used is various spaces, it is known that many people will forget to turn the lights off when they leave or leave the lights on when they leave the room for a period of time. The negligence of leaving the lights turned on when the space isn’t being used has led to the incorporation of occupancy detection sensors within most spaces. The most commonly used occupancy detection devices are the passive infrared (PIR), ultrasonic (US), and dual-technology (DT) sensors. The advantages and disadvantages of these sensors will be discussed throughout the remainder of this section.

2.1 ASHRAE 90.1 Recommended Controls

Most commercial buildings provide lighting controls for each space based on the requirements of ASHRAE 90.1 (2013). This technique requires using the space-by-space method to determine the requirements for each building area type. Most spaces need to have a local control and many spaces are recommended to have a daylight or occupancy control system. A local control requirement indicates that there must be at least one manual lighting control that controls all of the lighting within that space. When the local control is switched to the off position, it will turn off all of the lights in that space until the local control is switched backed to the on position. This control must be placed in a readily accessible location so that occupants can see the controlled lighting when using the control device. A daylight sensor will turn off the lighting within the space if the sensor determines that the light levels being provided by the exterior windows is adequate. A commercial space typically has a daylight zone around the perimeter of the space that is controlled independently. An occupancy control system is used to turn off the lights when there is no occupancy detected within the space. Once the sensor detects occupancy in the space, it will automatically turn the lights back on. Although following ASHRAE 90.1 will provide a control system that meets the requirements, it very rarely considers the visual comfort of the occupants. Shown in the table below is an example of the minimum lighting control requirements based on various building spaces.

Table 2.1-1: ASHRAE Minimum Control Requirements (ASHRAE, 2013)

			The control functions below shall be implemented in accordance with the descriptions found in the referenced paragraphs within Section 9.4.1.1. For each space type: (1) All REQs shall be implemented. (2) At least one ADD1 (when present) shall be implemented. (3) At least one ADD2 (when present) shall be implemented.								
			Local Control (See Section 9.4.1.1[a])	Restricted to Manual ON (See Section 9.4.1.1[b])	Restricted to Partial Automatic ON (See Section 9.4.1.1[c])	Bilevel Lighting Control (See Section 9.4.1.1[d])	Automatic Daylight Responsive Controls for Sidelighting (See Section 9.4.1.1[e][6])	Automatic Daylight Responsive Controls for Toplighting (See Section 9.4.1.1[f][6])	Automatic Partial OFF (See Section 9.4.1.1[g] [Full Off complies])	Automatic Full OFF (See Section 9.4.1.1[h])	Scheduled Shutoff (See Section 9.4.1.1[i])
Common Space Types[1]	LPD, W/ft^2	RCR Threshold	a	b	c	d	e	f	g	h	i
Atrium											
... that is <20 ft in height	0.03/ft total height	NA	REQ	ADD1	ADD1	—	REQ	REQ	—	ADD2	ADD2
... that is ≥20 ft and ≤40 ft in height	0.03/ft total height	NA	REQ	ADD1	ADD1	REQ	REQ	REQ	—	ADD2	ADD2
... that is >40 ft in height	0.40 + 0.02/ft total height	NA	REQ	ADD1	ADD1	REQ	REQ	REQ	—	ADD2	ADD2
Audience Seating Area											
... in an auditorium	0.63	6	REQ	ADD1	ADD1	REQ	REQ	REQ	—	ADD2	ADD2
... in a convention center	0.82	4	REQ	ADD1	ADD1	REQ	REQ	REQ	—	ADD2	ADD2
... in a gymnasium	0.65	6	REQ	ADD1	ADD1	REQ	REQ	REQ	—	ADD2	ADD2
... in a motion picture theater	1.14	4	REQ	ADD1	ADD1	REQ	REQ	REQ	—	ADD2	ADD2
... in a penitentiary	0.28	4	REQ	ADD1	ADD1	—	REQ	REQ	—	ADD2	ADD2

2.2 IES Recommended Illuminance Values

According to the U.S. Bureau of Labor Statistics, 77 million persons use a computer at work. These workers accounted for 55.5 percent of total employment. About 2 of every 5 employed individuals connected to the Internet or used e-mail while on the job. This data was collected in the year 2003 so it is assumed that these values have increased significantly since technology has progressed over time. “A total of 5.16 billion people around the world use the internet at the start of 2023, which is equivalent to 64.4 percent of the world’s total population” (DataReportal, 2023). Refer to the figure below for the percentage of people that use a laptop and/or desktop while completing their remote work.

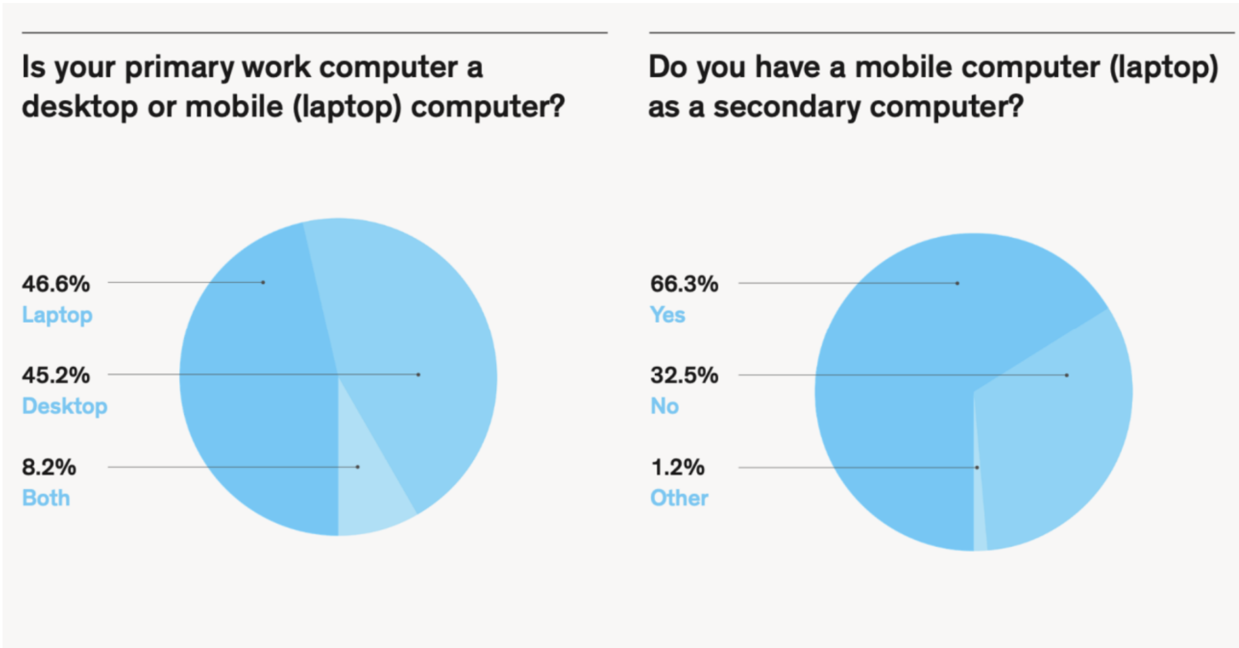


Figure 2.2-1: Technology Usage Data (Keskeys, 2021)

With this information, it can be considered that a majority of people that are working from home will be working on their computers. In order to determine accurate light levels needed for an individual performing work on their computer, recommended light levels are obtained from the Illuminating Engineering Society. For the purpose of this project, a baseline will be set at fifteen footcandles for all data collection assuming that this is a residential area and reading/writing will be completed on a computer or laptop keyboard. See the figure below for the recommended illuminance values provided by the Illuminating Engineering Society.

Table 2.2-1: IES Recommended Illuminance Values (IES, 2023)

Application Task/Area	Task or Area	Veil. Risk: High Med Low	E_h CAT	E_h (Horiz.) Fc@Ft	E_h Max Avg Min	E_h Unif.	E_h Unif. Ratio Basis	E_v CAT	E_v (Vert.) Fc@Ft	E_v Max Avg Min	E_v Unif.	E_v Unif. Ratio Basis
RESIDENTIAL, INTERIOR												
Reading and writing[1] | Refer to ANSI/IES RP-28-20: Table A-1 for older adults and visually impared people												
Office[12, 13, 14] | ANSI/IES RP-11-20 | Table A-1 — Room/Area: Room/Area												
Reading, Writing | ANSI/IES RP-10-20 | Table A-1 — Room/Area: Room/Area												
Computer, Tablets												
Computer or laptop keyboard	T		N	15@TS	Avg	2:1	Max:Avg					

Based on the recommended illuminance values from the IES, fifteen footcandles can be assumed an acceptable baseline for the consideration of this project. It is also important to consider that this illuminance value should be present at the task surface, which is typically considered to be three feet above the floor. Uniformity is also another important factor for visual comfort but this will not be considered for this project.

2.3 Passive Lighting Control Systems

Many individuals feel more comfortable within their space and will naturally feel more productive when natural daylight is present. When selecting a location for your office within your home, it is important to select a space that has an adequate amount of natural daylight. “47% of people admit they feel tired or very tired from the absence of natural light or a window at their office, and 43% report feeling gloomy because of the lack of light” (Meister, 2018). Although it is very important to have natural daylight within your space, it is also important to have a way to control the natural daylight in order to reduce the brightness or control the glare. If the sunlight is shining directly through your window onto your desk, you may feel discomfort from the intense brightness and it is possible to be distracted by the glare. “Nevertheless, large fenestration areas often result in excessive solar gains and highly varying heating and cooling loads. In addition, intense daylight leads to glare problems, especially for south-facing facades” (Tzempelikos, 2007). In order to limit these scenarios, passive lighting control systems can be implemented in the space to make the occupant feel more comfortable. Passive lighting control systems can be implemented within a residential space in the form of window blinds. Blinds allow for the control of the amount of light that can pass into the space and will allow for the occupant to feel more comfortable. “Advanced glazing and innovative daylighting/shading systems are being studied in order to control solar gains, reduce glare and create a high-quality indoor environment” (Tzempelikos, 2007).

2.3.1 Types of Passive Lighting Control Systems

The most popular form of blinds is Venetian blinds. These are commonly known are horizontal blinds and they typically contain metal, wood or plastics slats that can be tilted up to 180 degrees. These blinds allow for more or less light depending on the needs of the space. More commonly, these are typically installed with a chord so that they can be pulled up to allow for maximum daylight. Some examples of Venetian blinds can be seen below.

Figure 2.3-1: Examples of Venetian Horizontal Blinds (Smith, 2023)

Another type of blinds that are commonly found in residential spaces for glass doors or large windows are vertical blinds. These blinds consist of “tiltable vertical floor-to-ceiling slats that typically come in vinyl or fabric” (Smith, 2023). These vertical blinds can sometimes be called “panel blinds” depending on the size of the vertical slats. These have similar capabilities compared to the horizontal blinds that were previously discussed and the only difference is typically considered a visual preference. Examples of vertical blinds can be seen below.

Figure 2.3-2: Examples of Vertical Blinds (Smith, 2023)

While most passive lighting control systems are required to be operated by the home owner or space occupant, there has been an increase in motorized blinds for residential locations. These motorized blinds can be connected to smart home control systems and can be controlled by a remote. Most motorized blinds operate similar to horizontal blinds with the raising and tilting abilities, but they may be more appealing for individuals that don't want to adjust the blinds manually every time.

Figure 2.3-3: Examples of Motorized Blinds (Smith, 2023)

2.4 Active Lighting Control Systems

Active lighting control systems involve systems that are not typically controlled by the homeowner or space occupant. The most common active lighting control system is dimming. By dimming light fixtures, this will allow for a reduction in the load and will result in lower energy costs. "Active lighting demand response involves acting upon the capability to specifically reduce load during peak demand periods or periods of high pricing or upon utility request during times of grid stress. This capability requires the ability to measure lighting load at any point in time, accept a utility signal to start, stop and measure a load shed event; and temporarily reduce lighting load by a significant amount while respecting occupant lighting needs. While it's possible to manually shut off non-critical loads, automating the process and incorporating dimming can be more reliable and less disruptive" (DiLouie, 2017). Although most LED fixtures that are used in residential spaces today use a lower amount of energy, it is still important to consider dimming these fixtures when the full output is not needed. By utilizing an active lighting control system, dimming could be automatically controlled based on events that have happened within the space.

For spaces that have occupancy detection, "a demand response program begins by evaluating each space and determining whether the lights can be turned off or turned down. In spaces with regular occupancy, this may require dimming with a smooth fade between light levels to avoid disruption. Step dimming can be effective in transition and utility spaces such as corridors and lavatories" (DiLouie, 2017). With active lighting control systems, it is important to consider the amount of natural daylight that is entering the space in order to ensure that the occupants are still comfortable.

2.5 Lighting Control Modes

When developing a control system, it is important to consider energy efficiency, optimal system performance, and human comfort. Multiple control models can be considered to maintain the controlled variable at the desired set point. There are three basic types of control modes and they will be discussed below.

2.5.1 Two-Position Control

A two-position control system is the simplest and most common control mode that is used in most applications. This control mode applies to systems that only have two states (on or off). An example of a two-position control system is a small heating, ventilating, and air conditioning (HVAC) system that is located in a residence. The downside of this control mode is that the system will constantly fall below and rise above the set-point because there are only two states within the system. The controlled system would have to continually open and close to maintain a constant variable. In addition, it takes time for the sensing equipment to detect changes near the occupants which results in a delayed response between the measured value and the controller output signal.

2.5.2 Floating Control (Two-Position with Set-Point Adjustment)

A floating control system is very similar to a two-position control, but it is not limited to two states. This system must have a modulating-type controlled device that is driven by a motor. The controller within this control mode has three different modes that include drive open, idle, and drive closed. For this control mode, when the supply air temperature falls below the lower line of the differential, the controller starts to drive the control valve open and this will increase the flow. As compared to the previous control mode, floating control also has a delay in the control time and may take time to adjust the controlled variable within the space. Overshoot and undershoot are also common with these two control methods.

2.5.3 Modulating Control

A modulating control mode can be directly related to driving a car at a constant speed. While the road is flat or at a steady slope, you can maintain a constant speed while keeping the accelerator pressed down at a fixed position. When you begin to drive up a hill, the car will begin to lose speed so you press the accelerator down further to maintain the constant speed. This analogy can be directly related to the temperature within an HVAC system and the controlled valve being opened and closed.

This type of control mode would be used for dimming a light control system because it allows for a constant and consistent dimming process. Consistent dimming is very important for a lighting control system because it allows for a gradual increase or decrease in the provided light levels. A gradual change in the light levels within the space will be less noticeable to the occupants compared to a dramatic change. “The benefits of LED lighting can be further enhanced simply by dimming light to appropriate levels needed for the application, if the amount of energy consumed is reduced while dimmed. The dimmed LED lamp also operates cooler, which can save air conditioning costs. Dimming then further increases the operating life of the LED lamp. Daylight harvesting is the concept of using natural light to enhance indoor lighting and, thereby, reducing the generation of artificial light and saving energy. Proper daylight harvesting requires the artificial light to be dimmed at different level throughout a room and throughout the day. For example, more dimming of the light source near a window and less further away. Here, an automatic dimming function may save a tremendous amount of energy” (Phoebeli, 2018).

2.6 Existing Occupancy Sensors

2.6.1 Passive Infrared (PIR) Occupancy Sensor

PIR sensors operate by reacting to the movement of heat emitted by an occupant walking past the sensor. These sensors “detect motion within a coverage area that requires a line of sight; they cannot ‘see’ occupants behind obstacles or glass” (DiLouie, 2017). The detection mechanism of these sensors has a coverage area that has fan-shaped zones. When motion is detected within one of these zones, the sensor will send a signal to the light fixtures and they will operate accordingly. The disadvantage of this system is that the gaps between these fan-shaped zones increase as they move further from the sensor. This will result in decreased sensitivity as the occupant moves further away from the sensor. In addition, most PIR sensors are only sensitive to full body movement. The sensors can be sensitive to hand movement within a smaller radius from the location of the sensor. An illustration of the sensitivity locations of the PIR sensor is shown in figure 2.2.1-2 below.

Figure 2.6-1: Passive Infrared Sensor (PIR)

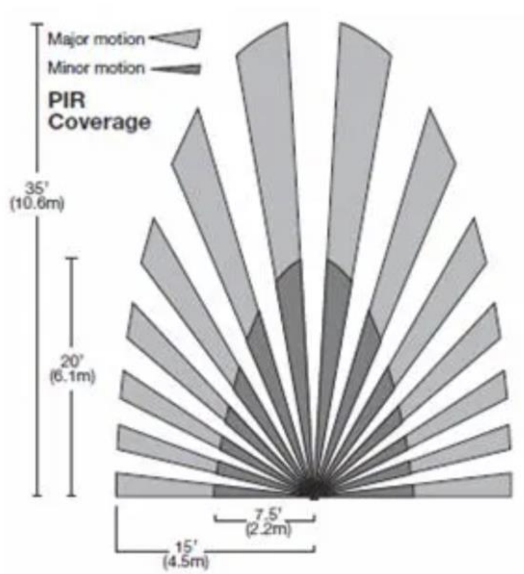


Figure 2.6-2: Passive Infrared Sensor Motion Coverage (DiLouie, 2017)

2.6.2 Ultrasonic (US) Occupancy Sensor

US occupancy sensors emit an ultrasonic high-frequency signal throughout the space and then monitor the frequency of the reflected signal. If there is a change between the emitted and received frequency, the sensor treats this change as motion. The advantage of these sensors is that they do not require a direct line of sight, compared to the PIR sensor (DiLouie, 2017). Although these sensors have been implemented in various spaces, it is still possible to receive false readings and distance limitations are a known disadvantage. An image of a US occupancy sensor can be seen in figure 2.2.2-1 below.

Figure 2.6-3: Ultrasonic Occupancy Sensor

2.6.3 Dual-Technology (DT) Occupancy Sensor

Dual-technology sensors combine the concepts from both of the sensors that were discussed previously. These sensors are used when a higher degree of detection is desirable. Classrooms are an example where these sensors would typically be used because there are long periods of time when the occupants may not be moving (DiLouie, 2017). Some DT sensors also include acoustic detection which will filter out white noise and focus on variations within the vocal activity in the space. An image of a dual-technology sensor and an example of the coverage area provided by a ceiling-mounted dual-technology sensor is shown below.

Figure 2.6-4: Dual-Technology Occupancy Sensor

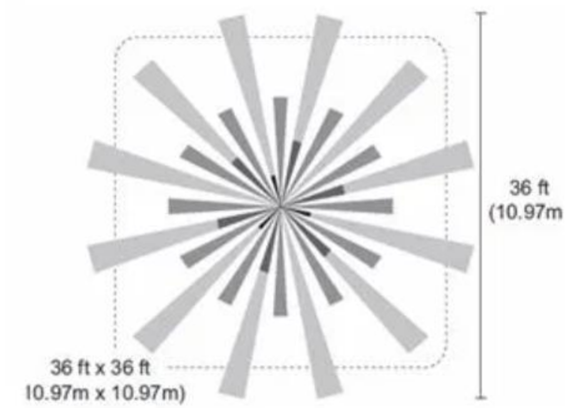


Figure 2.6-5: Dual-Technology Sensor Detection Range (DiLouie, 2017)

2.6.4 Artificial Intelligence Based Occupancy Detection using IR Array Sensor

Although PIR, US, and DT sensors provide results that work for occupancy detection, there are further opportunities to develop a system that can use artificial intelligence to detect the presence and absence of occupants within a building to maintain visual comfort and reduce energy consumption. Artificial intelligence will use machine learning and computer vision to recognize and distinguish objects within a space. These models that will be created will be able to report the position and orientation of these objects within their environment (Deok-Oh Woo et al, 2021). This system would be able to detect the human occupancy within the space and effectively adjust the light levels. This system would provide a space that is more comfortable to the occupants compared to existing lighting control systems. Shown below are illustrations of how the artificial intelligence occupancy detection system would be incorporated within the space.

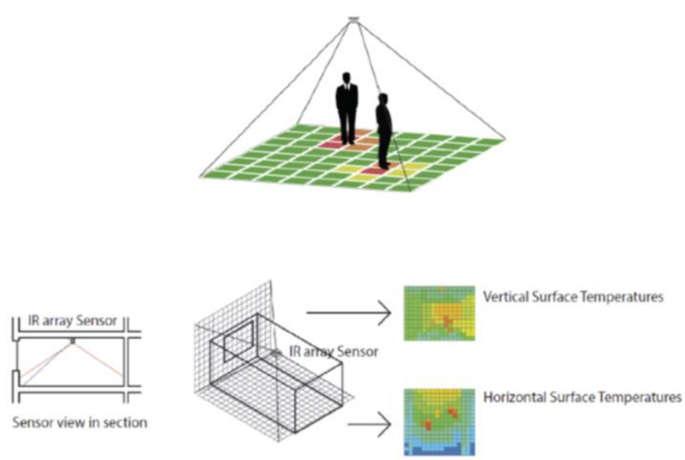


Figure 2.6-6: IR Array Framework (Deok-Oh Woo et al., 2021)

2.6.5 Occupancy Sensor and Detection Method Comparison

The following table is a comparison between the characteristics of the occupancy sensors and detection methods that were discussed previously. This table visually relates the advantages and disadvantages of each system.

Table 2.6-1: Occupancy Sensor Comparison

	Sensor Types			
	Passive Infrared	**Ultrasonic**	**Dual Technology**	**IR Array**
Detection Type	Infrared Radiation	Ultrasonic Sound	Ultrasonic Sound & Passive Infrared	Temperature & Thermal Properties
Range	3 ft – 15 ft 750 nm – 8 μm	50 kHz – 500 kHz	Coverage up to 200 square feet	-40°C - 300°C
Advantages	- Small - Inexpensive	- Do not require a direct line of sight	- Acoustic detection - Higher degree of detection	- Over 768 individual infrared readings - Compact for simple installation
Disadvantages	- Sensitive to movement - Small radius of coverage - Gaps between coverage at further distances	- Distance limitations - False readings are possible	- More expensive - Complex installation	- Requires machine learning & computer algorithm

2.7 Smart Home Lighting Control Systems

As technology has increased over the recent years, smart home technology has caught the attention of many home owners. “Smart Home is an application system that combines technology and services specific to the home environment with certain functions that aim to increase the efficiency, comfort and safety of its residents. Smart Home usually consists of control, monitoring and automation of several home devices or appliances that can be accessed via a computer” (Irawan, 2021). Most appliances and technology devices that can be purchased today come with smart technology and allows consumers to effectively monitor their energy usage and reduce their overall energy costs. Smart technology for lighting control systems typically consists of using smart light switches and dimmers that are embedded directly into the wall of your home. “Once it’s installed, a smart light switch lets you turn your lights on and off according to a schedule, with a smartphone app, and—with the installation of accessories—in response to voice commands, motion, or even your location (provided you have your smartphone with you)” (Brown, 2023). Although smart switches and dimmers allow for a homeowner to have wireless control over their lighting systems, it still requires the homeowner to interact with the system. The proposed IR Array system would allow for the lighting system to be controlled autonomously, meaning that the homeowner would not need to interact with the system after it is installed.

Since smart home technology has become a common addition for many every day home appliances, the proposed IR array lighting control system would be implemented in a smart home system to compliment with other smart home appliances. This coordination between the systems would allow for home owners to receive the maximum amount of energy savings by considering energy consuming appliances and lighting fixtures.

2.8 Energy Savings and Visual Comfort

According to previous research, “lighting of the environment, visual privacy, connection to outdoor and view are included in visual comfort. The architecture of the buildings and interior design of them affects the visual environment, therefore the visual comfort of the occupant directly. By determining visual comfort criteria and occupants’ frequent complaints, the study unfolds common reasons behind visual discomfort and consequences of poor visual performance. A methodology involving literature survey, expert interviews and a survey that includes a large population of office building occupants was adopted in the quest to present empirical results on visual comfort, as previous literature is lacking survey based empirical studies in this topic” (Tekce, 2020). This research paper was analyzed to determine which factors are most important for individuals within a space when it comes to artificial lighting. “As for importance, occupants find daylighting most important (4.5) followed by visual privacy (4.3) and artificial lighting (4.3). Glare, reflection and view are perceived as less important criteria (4.1 each). On the other hand, occupants are most satisfied with reflection (3.6), followed by artificial lighting (3.5), glare (3.4) and daylighting (3.4). Occupants are least satisfied by view and visual privacy (3.3 each) in the offices” (Tekce, 2020). According to this research, daylighting is considered to be the most important aspect for room occupants. With this information, it is important to develop a lighting control system that considers the amount of natural daylight entering the space so that the occupants can be as comfortable as possible. Refer to the figure below for survey data collected regarding what is considered to be important for visual comfort criteria according to room occupants.

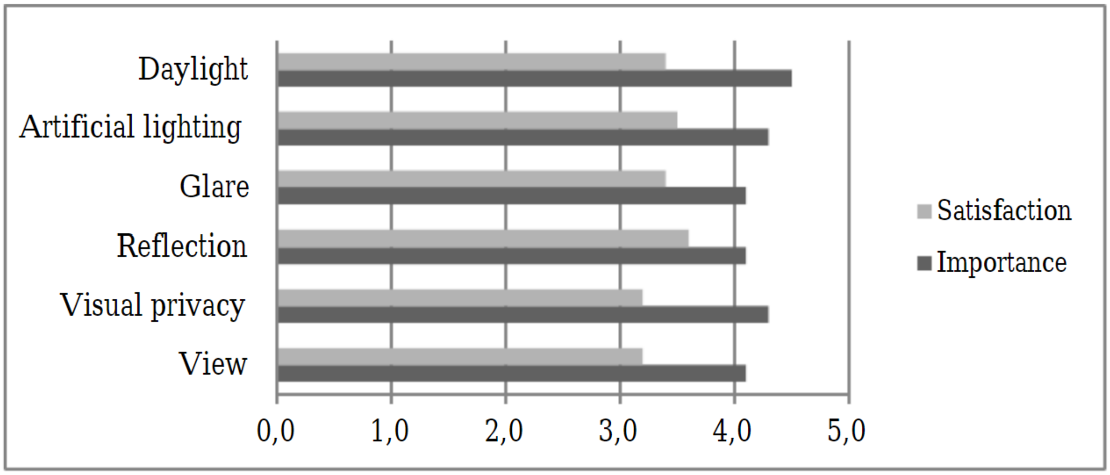


Figure 2.8-1: MLX90640 IR Array Cost (Tekce, 2020)

Most previous research does not fully consider visual comfort while considering energy savings. Many of the previous studies only considered the amount of glare that would be experience by the occupants within the space. Although this is an important consideration to ensure that the occupants are comfortable, there are more factors that need to be considered. For example, if the glare has been reduced within the space, it is important to ensure that the occupants still have a sufficient amount of light on their task surface to complete appropriate tasks. Listed below are the factors that should be considered in order to provide visual comfort (Calleja, 2011).

- Uniform Illumination – the distribution of light across a surface should remain consistent to allow for a proper perception by the human eye. The IES provides uniformity ratios that should be considered depending on the task that is being completed.
- Optimal Illuminance – each activity requires a different level illumination that is specific to the location and task. These guidelines are usually followed utilizing the IES standards.
- No Glare – it is important to have general illumination compared to localized illumination in order to reduce glare. Glare is present where there is a prominent light source visible by the human eye, this can come from an artificial light source or from the sun through the window. Glare is also a possibility from reflections in objects nearby the task surface.

- Adequate Contrast Conditions – it is important to provide contrast for the human eye. When there is no contrast visible, surfaces may become flat and unappealing.
- Correct Colors – not only do the colors surrounding a work surface impact the visual comfort for the occupant, but the color of the light also affects the perception received by the human eye. Warmer or cooler lights can be applied for many different applications depending on the task that is being completed.

2.9 Thermal Camera Limitations

Some previous studies involve using a thermal camera to detect motion within a space. Although this is an appropriate way to detect motion, a thermal camera is very expensive and not applicable for residential applications. "The average cost of thermal imaging cameras ranges from $600 to $2000. However, some high-end thermal imaging cameras can cost upwards of $5000. Most of the lower-cost thermal imaging cameras connect with smartphones – and are used as an extension to the mobile device. However, with lower price comes less reliable results" (HomeGauge, 2023). Due to the high cost of thermal cameras, not including installation and maintenance, this makes it out of reach for many homeowners and their lighting control needs.

Due to the high price of thermal imaging cameras, the need for the proposed IR array technology is increased. The proposed system will decrease the overall cost for components and installation making it more appealing to the homeowner. Currently, the MLX90640 IR Array Thermal Imaging Camera Module that is being proposed for this system can be purchased for less than $100. This is a significant decrease compared to the thermal imaging camera and will make this technology applicable to more residential locations.

QTY	UNIT PRICE	EXT PRICE
1	$74.95000	$74.95

Figure 2.9-1: MLX90640 IR Array Cost (DigiKey Electronics, 2023)

In addition to the relatively low cost for the MLX90640 IR array camera, they also have a short lead time which makes it ideal for residential homeowners. Some proprietary systems can take weeks to be delivered which is undesirable for many individuals. They MLX90640 IR array camera can be purchased from many distributors which makes it easier to obtain and install.

2.10 Lighting Control System with Smart Sensors

Although there are not currently any known lighting control manufacturers producing occupancy detection using IR array technology, there are manufacturers using smart sensors with PIR technology. This technology allows for accurate motion detection, daylighting control, and occupancy tracking. The updated technology from Enlighted Lighting Controls was investigated because this technology is considered to be part of the leading lighting control technology in the market today. "Built on the leading Internet of Things IoT Infrastructure, the system consists of a network of LED lights fitted with patented sensors, which are wirelessly connected in a mesh grid and an advanced analytics platform. The sensors collect data 65 times per second, to monitor environmental and occupancy changes, and make immediate, real-time lighting adjustments for occupant comfort and energy savings. Easily adjusted features like individual task lighting level and color temperature tuning let users enjoy ideal lighting conditions, while continuous automatic occupancy monitoring and daylight harvesting dramatically reduce energy costs" (Enlighted, 2022).

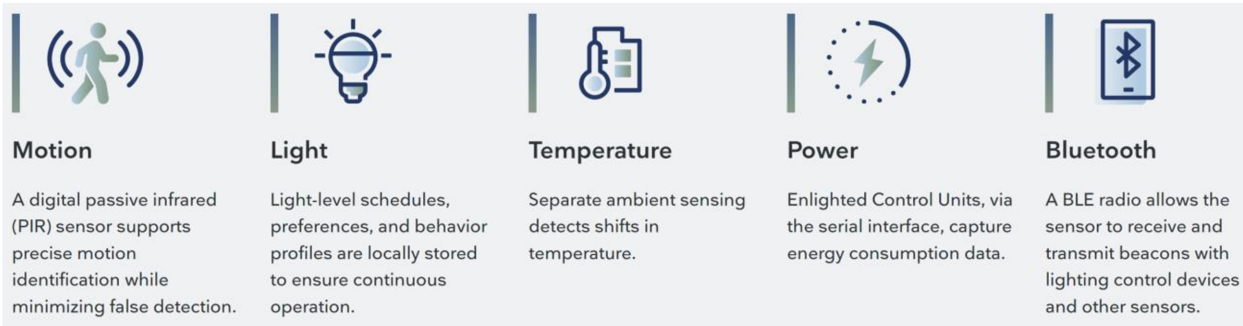


Figure 2.10-1: Smart Sensor Technology and Details (Enlighted, 2022)

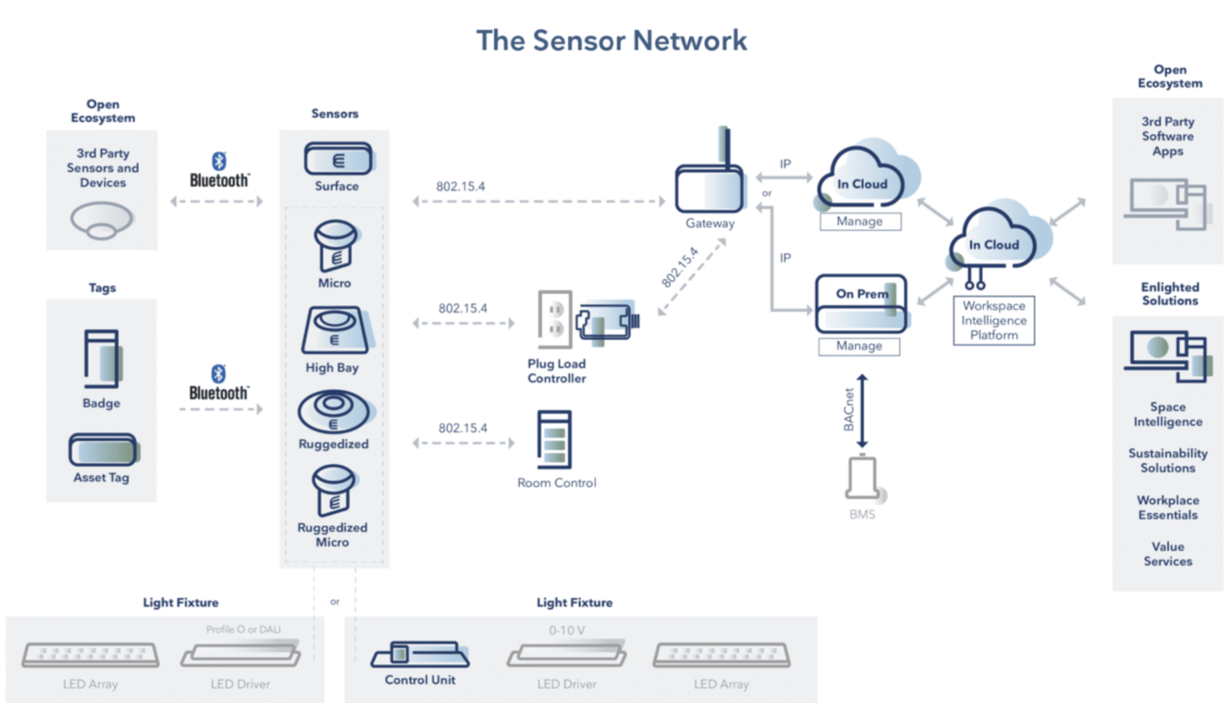


Figure 2.10-2: Smart Sensor Network Diagram (Enlighted, 2022)

A system with this technology is extremely advanced and would be very difficult to implement in a residential location. In addition to this system being complex, it is very expensive and out of reach for many homeowners. Although this system can produce results similar to the results that are hoping to be obtained from the proposed lighting control system, there is no direct alternative currently present in the market. This system also bases the light levels based on occupancy and time of day, rather than what the individual is doing within the space. The proposed IR array control algorithm has the ability to detect differences between equipment and humans. This will allow for future developments to be made that will allow for light levels to be adjusted based on what the occupant is doing within the space.

2.11 Research Objective

The objective of this project will be to study the effectiveness of existing lighting control systems and determine how well they can reduce energy costs. It is known that existing lighting control systems do not typically consider visual comfort for occupants; therefore, it will be important to study how well a new proposed lighting control system that utilizes machine learning can adjust the lights within a space while maintaining visual comfort. All of the previously discussed lighting control systems will be compared to determine which system can effectively reduce the most energy while maintaining visual comfort.

Due to lighting controls and energy efficiency becoming more prominent in residential locations, the data collected throughout this study will be collected in a residential setting. In addition, many residential spaces are not typically considered for lighting control systems which means that this proposed system has the ability to be widespread throughout newly built and newly renovated homes. Not only will this give homeowners the ability to reduce energy costs by effectively limit their lighting use, but this system will also give the homeowners the chance to limit energy use in other sectors including HVAC systems. For example, the lighting control system would be able to communicate with other building systems to detect where occupants are located and adjust levels accordingly. Outlined below are the research objectives of this technical study:

i. Determine the total number of cloudy days per month.
ii. Obtain and collect data utilizing sensors and occupancy detection methods that replicate existing lighting control systems.
iii. Obtain and collect data utilizing an illuminance sensor and IR array for occupancy detection for comparison with existing lighting control systems.
iv. Determine and analyze the effectiveness of all lighting control systems in terms of energy savings without compromising visual comfort.
v. Determine the total energy saved per hour for each existing lighting control system and compare to the energy savings for the proposed lighting control system.
vi. Determine total cost savings using the proposed lighting control system.
vii. Provide recommendations and conclusions based on findings.

CHAPTER 3: METHODOLOGY

The following chapter will outline the methodology that will be used to analyze the effectiveness of existing lighting control systems and the proposed lighting control system.

3.1 Overall Research Procedure

The figure shown below is a flow chart of the overall research procedure for this project. The workflow contains developing lighting control framework and occupancy detection algorithms that will be used to compare the energy consumption with existing lighting control systems.

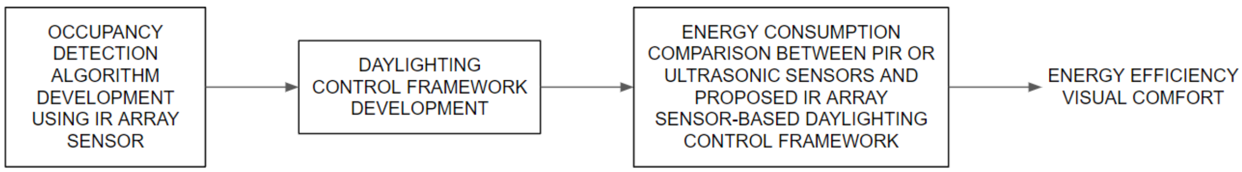


Figure 3.1-1: Research Workflow

3.2 Occupancy Detection

There are two types of occupancy detection models that were considered for this research project, the convolutional neural network and the YOYO (You Only Look Once) model. The convolutional neural networks are used for image or media data and typically consist of many different layers that may become very complex. In order to detect occupancy within a space, convolutional neural networks work by using artificial intelligence to identify the differences between an image. The base image is used and then separated into different subsections to scan for objects.

The YOLO model is a single stage model which allows it to be a lot faster compared to the convolutional neural network that was discussed above. Although there have been different versions of the YOLO model, the earlier models “divide the image into regions and predict bounding boxes and probabilities for each region. These bounding boxes are weighted by the predicted probabilities" (Redmon, 2018). In other words, the system can make predictions based on what it thinks will happen next.

In order to provide accurate occupancy detection, the YOLOv5 model will be used in coordination with active IR arrays and light sensors that will be connected to Raspberry Pi’s. The list of components used in this research project will be discussed in detail in further sections. Each system will work by running the machine learning model and use a centralized system to detect occupancy. Images will be captured at one-minute intervals and they will be used to differentiate between human occupancy, computers, and equipment. This machine learning system will allow for near real time detection of occupants within the space.

3.3 Control Logics

There will be four control logics that will be compared for this project. The four control logics include a simple manual switch control, illuminance sensor-based control, PIR sensor-based control, and the recommended IR array control. These control logics are being compared and studied because they are the most common lighting control systems used today.

Table 3.3-1: Studied Lighting Control Logics

CONTROL LOGICS			
Manual Switch	**Illuminance Sensor**	**Illuminance Sensor with PIR Sensor Occupancy Detection**	**Illuminance Sensor with IR Array Occupancy Detection**
- Simple On/Off Control - Assumes that the light fixture is on the continuously	- Uses illuminance detection to control light fixture - Does not consider occupancy	- Uses illuminance detection to control light fixture - Considers occupancy and control delay	- Uses illuminance detection to control light fixture - IR array camera for thermal detection

3.4 Occupancy Detection Algorithm Development

The occupancy detection algorithm that is anticipated to be used for the proposed lighting control system is currently being developed by the Lawrence Technological University E-Challenge 5 group. While this algorithm is being developed for a heating, ventilating, and air conditioning (HVAC) system, it can be directly related to a lighting control system with further research and development. The current development of the occupancy detection algorithm is outlined and summarized below.

The occupancy detection algorithm is developed by using an infrared (IR) array sensor that can develop a grid of surfaces temperatures within a space and determine the number of occupants in a room, their activity level, indoor surface temperatures, irradiation, and illuminance levels (Deok-Oh Woo et al, 2021). The algorithm will further be developed by collecting images from the thermal infrared (IR) array sensor within the space and these images will be used for training the framework of the system. The developed framework will then be tested with a heating, ventilating, and air conditioning (HVAC) system that can effectively adjust the provided levels based on the values collected and provided by the infrared (IR) sensor. The energy savings potential of the developed framework will be compared to conventional control systems. Initial data will be collected and will be used for further development of the artificial intelligence (AI) based system. A YOLO v5 model algorithm is used for the development of this algorithm because it maintains a good balance between speed and precision. With this proposed algorithm, the model achieved limited accuracy in training and verification but the accuracy should increase with additional number of images included and further development with inclusion of much varied data (Deok-Oh Woo et al, 2021).

3.5 Daylighting Control Framework Development

The layout and locations of the sensors is very important for the data collection portion of this study. The TSL 2591 sensor should be located close enough to an exterior window that it is providing accurate readings of the daylight that is entering the space. By locating the sensor close to an exterior window, this will allow the control system to determine if the space is bright enough for the occupants to work comfortably. Figure 3.5-1 shown below is a layout of the system that was used for data collection. This layout is used for determining the effectiveness and energy saving abilities of existing lighting control systems as well as the proposed system. Figures 3.5-2 through 3.5-8 show the various daylighting control systems within the testing space.

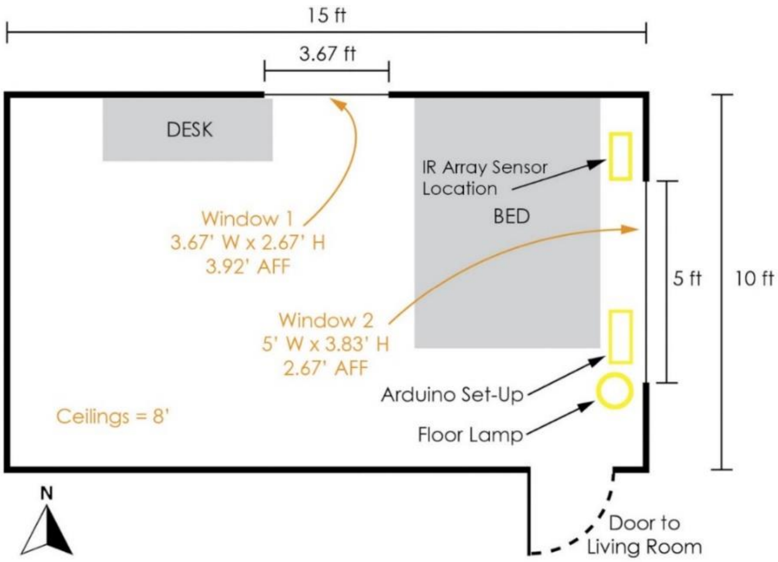


Figure 3.5-1: Floor Plan with Dimensions and Equipment Locations

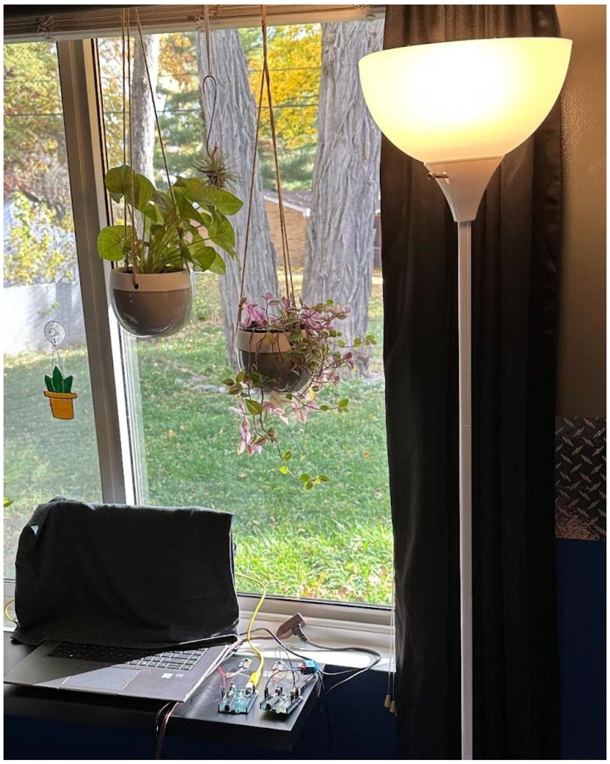


Figure 3.5-2: Daylighting Control System with Illuminance Sensor

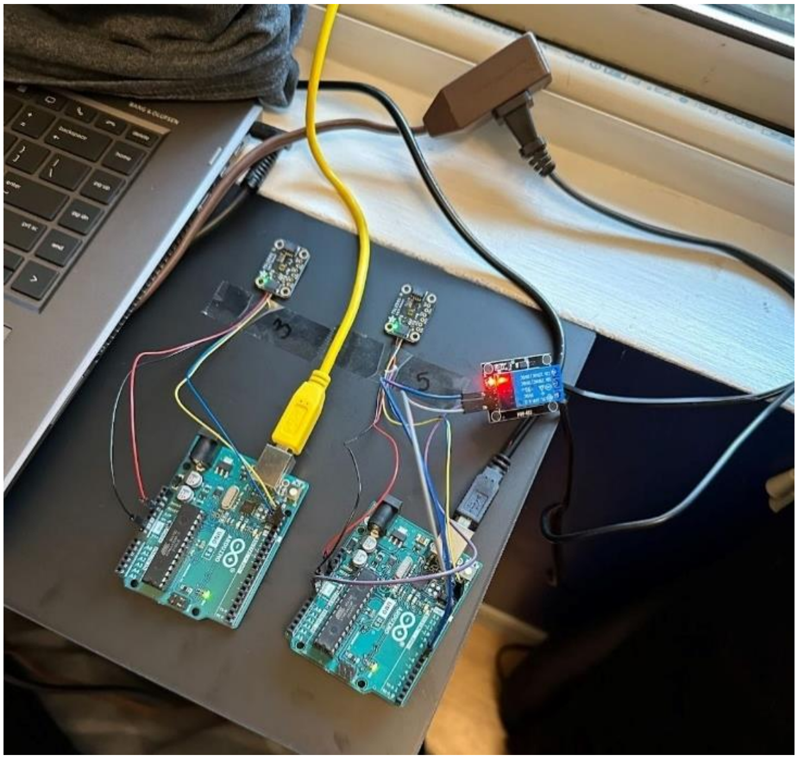


Figure 3.5-3: Daylighting Control System with Illuminance Sensor (Locations)

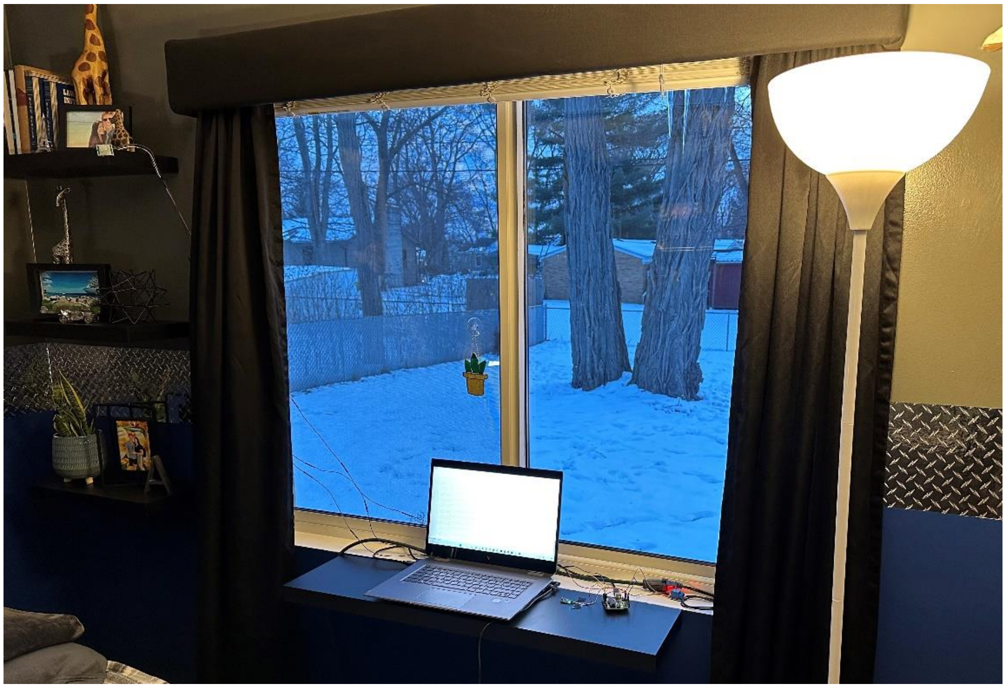


Figure 3.5-4: Daylighting Control System with PIR Sensor

Figure 3.5-5: Daylighting Control System with IR Array

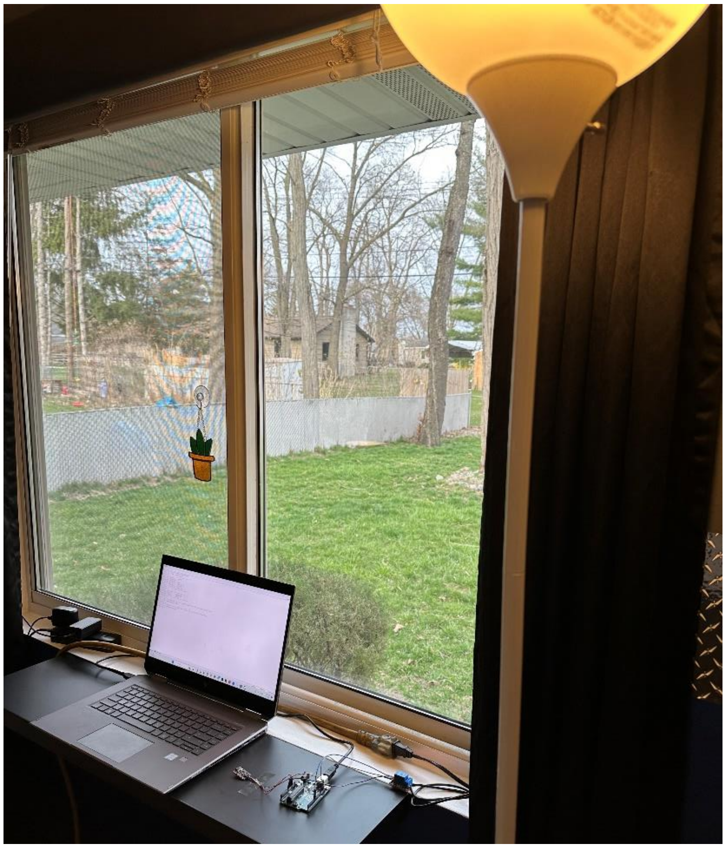


Figure 3.5-6: Daylighting Control System with IR Array (Illuminance Sensor Location)

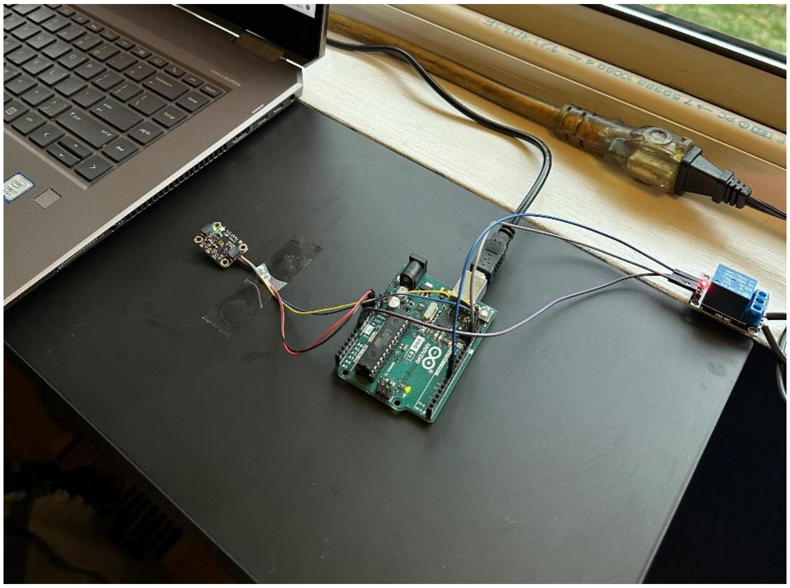


Figure 3.5-7: Daylighting Control System with IR Array (Illuminance Sensor)

Figure 3.5-8: Daylighting Control System with IR Array (IR Array Location)

The IR array camera also comes with different degree options which can be applied to a project based on different conditions. For this residential application, the 110-degree view range was used to detect motion entering the room as well as motion while sitting at the nearby desk. This allows for an accurate representation of the occupancy within the room because these are the two locations that are used the most often during an average working day. The visible range from the IR array sensor can be seen in the figure below, illustrated with an orange highlighted area.

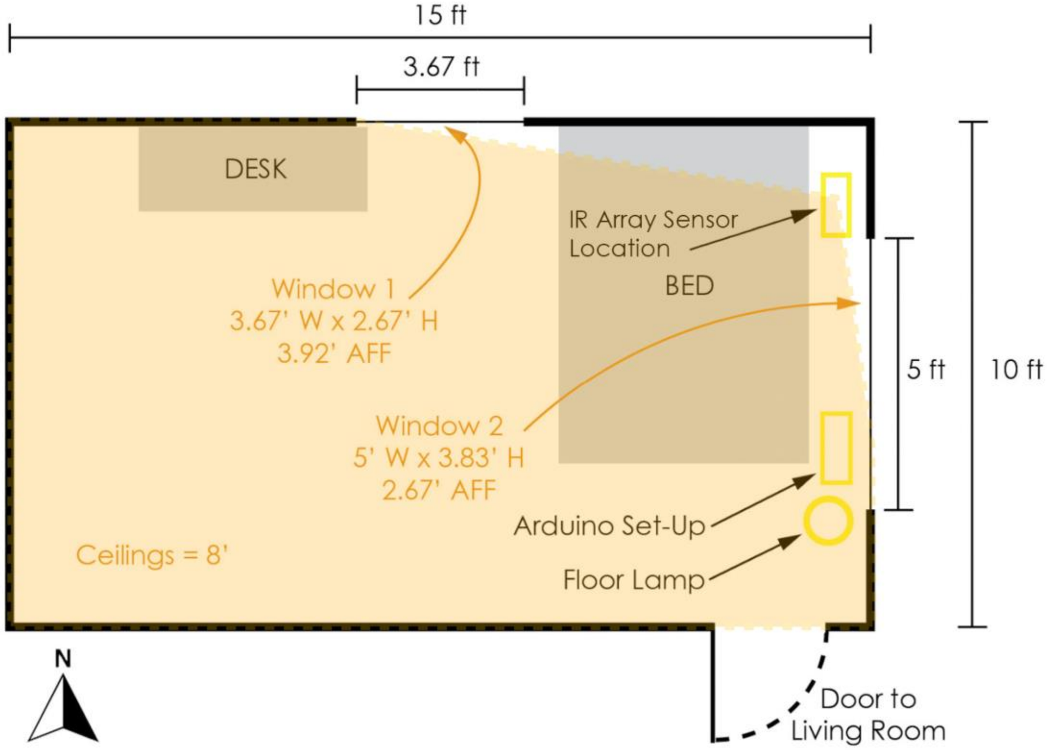


Figure 3.5-9: IR Array Visible Angle

3.6 Building Orientation

For this experiment, data will be collected using a large east facing window. It is important to consider that many homes and residential locations face different directions and have windows on different elevations. Although windows on different elevations of a house will provide different levels of illumination to a space, the proposed system using an IR array sensor will allow for adequate illumination to be provided to the space at all times. It is known that southern facing windows will provide the largest amount of light in the northern hemisphere, but heat gains can also be a concern with direct illumination. "For residents of the northern hemisphere, the top benefit a south-facing window offers is sunshine. During the winter, throw open the shades or curtains from south-facing windows to allow the sun to naturally warm the interior of the house. In the summer, shades and curtains help reduce solar gain and keep the room cooler. Year-round, south-facing windows are ideal for natural light" (UWCC, 2019). Although south facing windows will provide the most amount of light year-round, it is also important to consider windows that also face different directions. "When your home's windows face the east, it's easier to enjoy natural light and warming sunshine in the earlier hours of the day. Beams of sunlight streaming into a kitchen first thing in the morning can make the room, and its inhabitants, feel cheerier and more peaceful. The ambient warmth, especially during the winter months is another benefit. East-facing windows can have a downside. Windows facing east and west accept the very low angle of spring and fall sunlight, which can often be blinding—especially troublesome in a room used for watching television or working on a computer" (UWCC, 2019).

3.6 Sensors and Equipment

Outlined below is a list of the sensors and equipment that will be utilized to determine the effectiveness of existing lighting control systems:

i. Arduino IDE – a computer software that is used to communicate with sensors and collect data.
ii. TSL 2591 Light Sensor – a sensor used to determine the light levels present within a space.
iii. VCNL 4040 Proximity and Ambient Light Sensor – a sensor used to determine the light levels present within a space. This sensor has a higher temperature resistance compared to the TSL sensor.
iv. HC-SR501 PIR Sensor – a sensor used to detect human occupancy.
v. Floor Lamp – a light fixture used to house the light bulb and provide illumination to the space.
vi. Light Bulbs – a variety of light bulbs will be used to determine their effectiveness and energy consumption.

Outlined below is a list of sensors and equipment that will be used to determine the effectiveness of the proposed lighting control system:

i. MLX 90640 IR Array Sensor – an electronic device that emits infrared lights to sense aspects of the surroundings and can be employed to detect the motion of an object.
ii. Raspberry Pi 4 Micro Controller

Table 3.6-1: Sensors Used for Data Collection

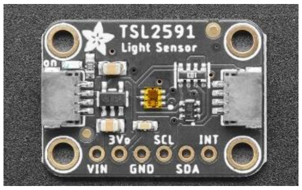
SENSORS	
	
TSL 2591 Full Spectrum Light Sensor Range: 188 µLux to 88,000 Lux Accuracy: +/- 10%	**VCNL 4040** Proximity and Ambient Light Sensor Range: 0.0125 Lux to 6553 Lux Accuracy: +/- 10%
	
MLX 90640 IR Array Sensor Range: -40°C to 300°C Accuracy: +/- 2°C	**HC-SR501** PIR Sensor Range: 3 m to 7 m Accuracy: Varies

Table 3.6-2: Equipment Used for Data Collection

EQUIPMENT	
	
Floor Lamp	**LED Light Bulbs**

Table 3.6-3: Microcontrollers Used for Data Collection

MICROCONTROLLERS

Raspberry Pi 4 Micro Controller

3.7 LED Lamp Considerations

Even though LED lamps are taking over the current lighting industry, it is important to consider their limitations and capabilities. "The operating life of a LED is unaffected by turning it on and off. While lifetime is reduced for fluorescent lamps the more often they are switched on and off, there is no negative effect on LED lifetime. This characteristic gives LEDs several distinct advantages when it comes to operations. For example, LEDs have an advantage when used in conjunction with occupancy sensors or daylight sensors that rely on on-off operation. Also, in contrast to traditional technologies, LEDs turn on at full brightness almost instantly, with no delay. LEDs are also largely unaffected by vibration because they do not have filaments or glass enclosures" (U.S. Department of Energy, n.d.). This information allows for the conclusion that there will be no limitations by implementing a system that may turn the LED lamp on and off many times during a short period of time. With this system, it is also important for the light source to turn on to full brightness as soon as the light is needed and LED lamps allow for this requirement to be met.

In addition, LED lamps have an estimated energy efficiency of between 80 and 90%. Along with the energy efficiency, "LED lights are widely acclaimed for their enhanced durability and cost-effective performance, making them, by far, the smartest lighting solution available today. With much to recommend LEDs, one of the overriding reasons to switch still remains their long operational lifespan" (Archer, 2021). LED lamps also provide approximately 50,000 hours of light and can last up to 14 years if you use them for 10 hours per day. All of these considerations assist with the selection of which lamps should be used when implementing these lighting control systems.

3.8 Experiment Date and Outdoor Conditions

The following table shows the dates of the conducted experiments and the exterior weather conditions. This table also shows the time intervals for data collection and how many times the experiments were repeated for calibration purposes. Although the experiments were conducted many times throughout the previous months, only a handful of experiments were selected to be analyzed based on the quality of data collected.

Table 3.8-1: Experiment Date and Outdoor Weather Conditions

Control System	Data Collection #	Conducted Date	Weather Conditions	Time Interval
Illuminance Sensor (ON/OFF Control)	1	1/12/2023	Cloudy	8:16 AM - 4:40 PM
	2	3/6/2023	Cloudy	8:33 AM - 3:49 PM
Illuminance Sensor and PIR Sensor (Motion Detection Control)	1	1/29/2023	Cloudy	9:00 AM - 5:04 PM
	2	2/15/2023	Cloudy	8:18 AM - 12:19 PM
Illuminance Sensor and IR Array (Occupancy Detection Control)	1	4/12/2023	Cloudy	8:26 AM - 4:24 PM
	2	4/19/2023	Cloudy	7:31 AM - 6:18 PM

Figure 3.8-1: Cloudy Outdoor Weather Conditions at Testing Location

For this experiment, cloudy days will be used in order to account for worst case scenario conditions. This assumption is being considered because artificial lighting is most commonly used when there is not a sufficient amount of daylight entering the space. Due to the fact that most of the days throughout the year in Michigan are considered to have an overcast sky, data collection during cloudy days will account for an accurate representation of the weather conditions throughout the year. The table shown below illustrates the cloudiest major US cities and what percentage of days throughout the year that have 75% or more of the sky covered by clouds.

Table 3.8-2: Cloudiest Major US Cities (Osborn, 2022)

City	Days of Heavy Cloud	% of Days
Seattle, Washington	226	62
Portland, Oregon	222	61
Buffalo, New York	208	57
Grand Rapids, Michigan	205	56
Pittsburgh, Pennsylvania	203	56
Cleveland, Ohio	202	55
Rochester, New York	200	55
Columbus, Ohio	190	52
Cincinnati, Ohio	186	51
Detroit, Michigan	185	51

In order to determine the amount of cloudy days per month, cloud coverage data was analyzed and studied based on the percentage of cloudy days for the months January, February, March and April. These months were analyzed because it was determined that they have the highest amount of cloud coverage throughout the year. “The month of March in Michigan Center experiences gradually decreasing cloud cover, with the percentage of time that the sky is overcast or mostly cloudy decreasing from 59% to 55%. The clearest day of the month is March 29, with clear, mostly clear, or partly cloudy conditions 46% of the time. For reference, on January 10, the cloudiest day of the year, the chance of overcast or mostly cloudy conditions is 66%, while on August 26, the clearest day of the year, the chance of clear, mostly clear, or partly cloudy skies is 67%” (WeatherSpark, 2023). The graphs shown below were used in determining the number of cloudy days per month. The graphs display the percentage of having sunny sky conditions, in order to determine the percentage wanted for the purpose of this project, the percentage of having sunny sky conditions was subtracted from one hundred percent to determine the cloudy sky conditions.

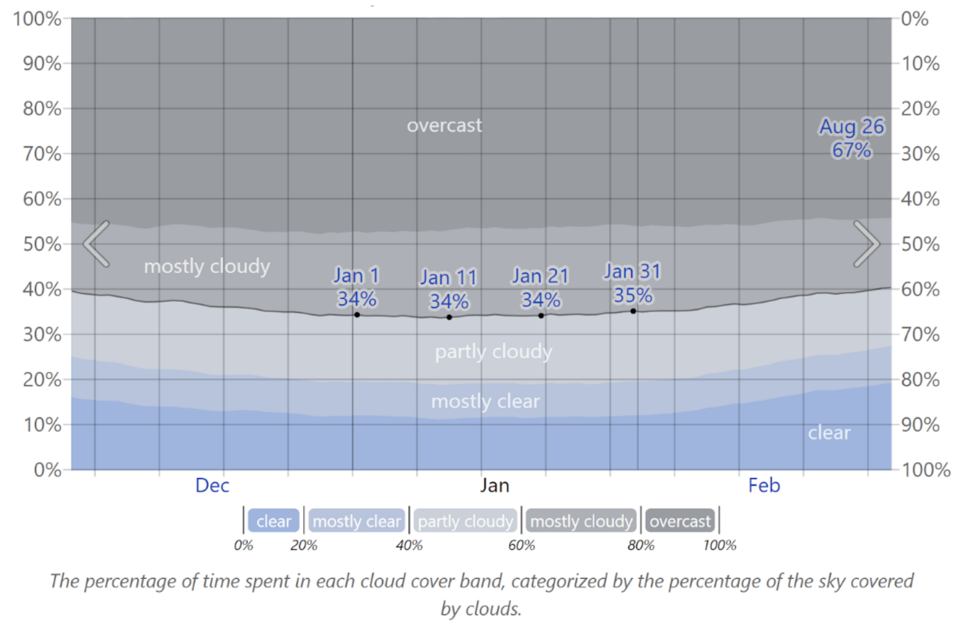


Figure 3.8-2: Cloud Cover Categories in January in Michigan (WeatherSpark, 2023)

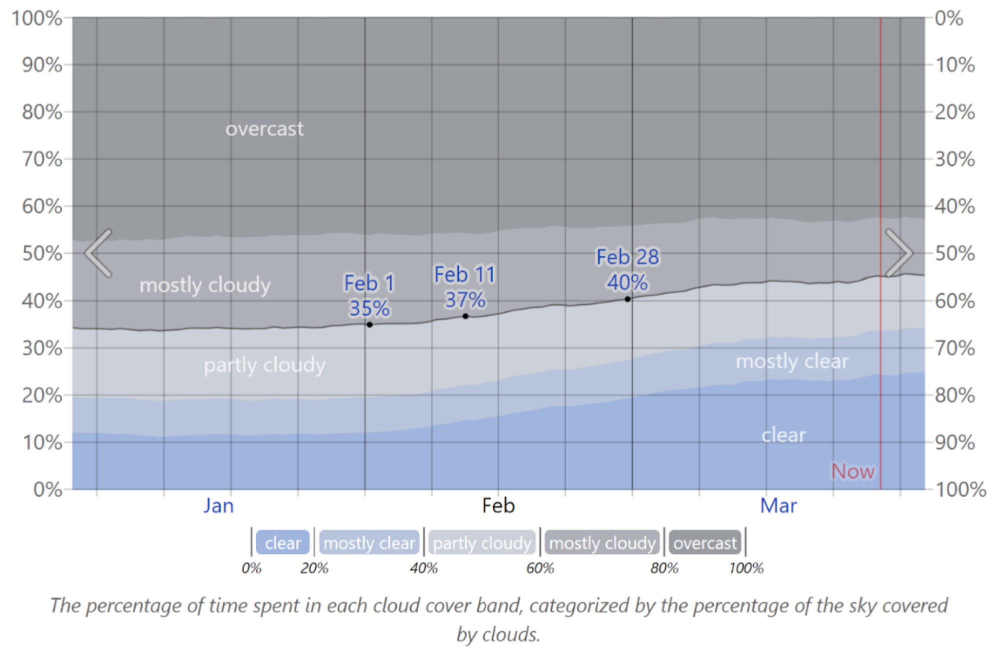


Figure 3.8-3: Cloud Cover Categories in February in Michigan (WeatherSpark, 2023)

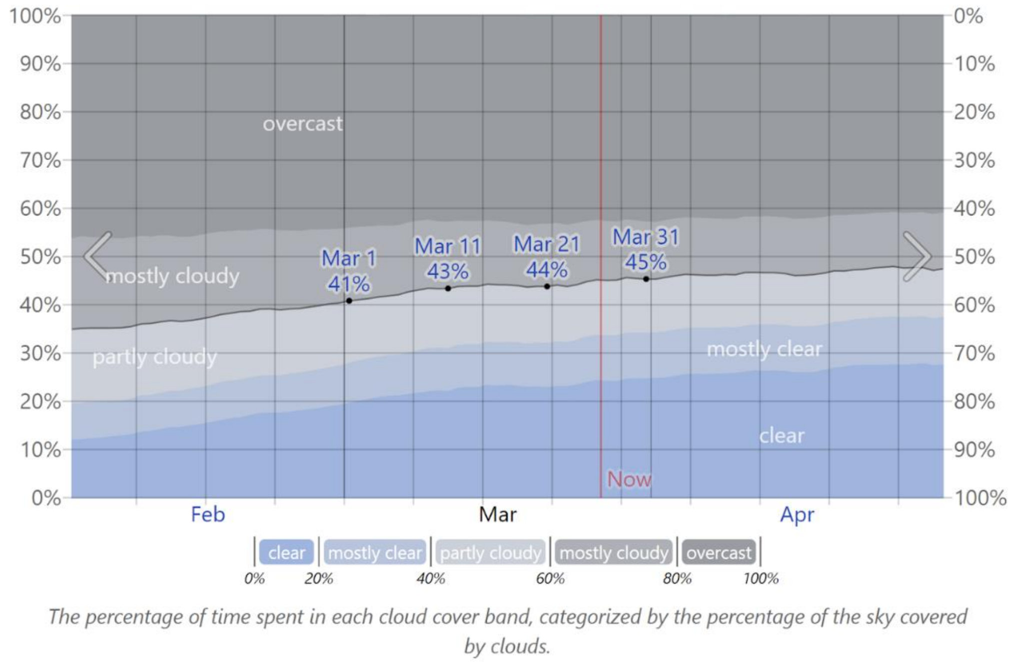


Figure 3.8-4: Cloud Cover Categories in March in Michigan (WeatherSpark, 2023)

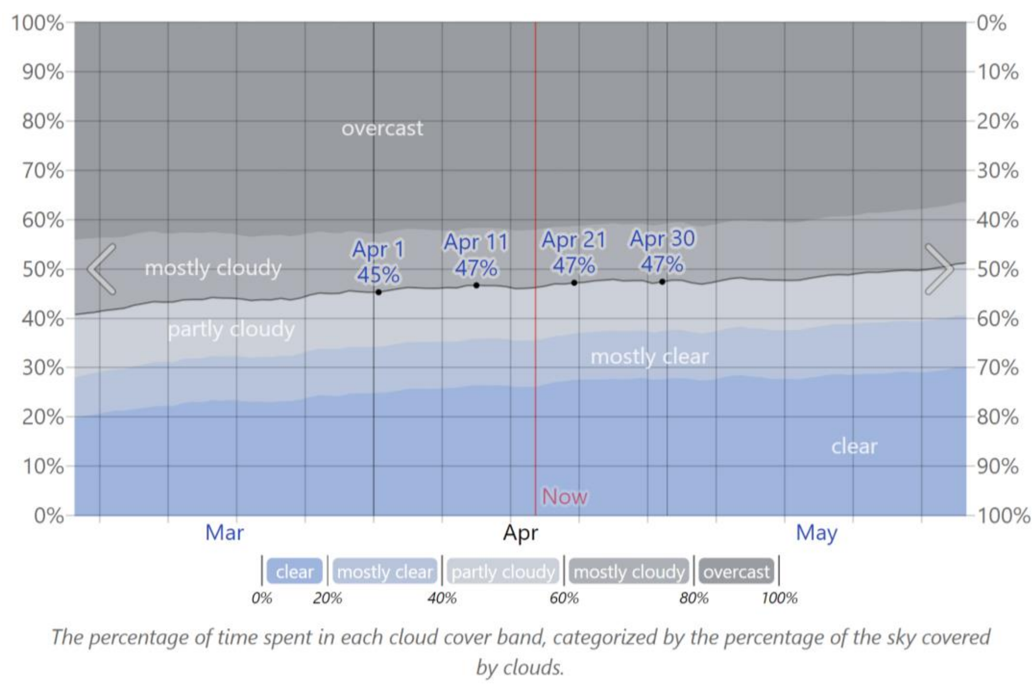


Figure 3.8-5: Cloud Cover Categories in April in Michigan (WeatherSpark, 2023)

After these graphs were collected, further data was analyzed in order to get an accurate number of cloudy days per month. This involved determining the average percentage of cloudy sky conditions and the multiplying this percentage by the number of days during each month. This data is shown in a table format below.

Table 3.8-3: Number of Cloudy Days Per Month

Month	Day	# of Days Per Month	Pertange of Sunny Sky Conditions	Average Percentage of Sunny Sky	Average Percentage of Cloudy Sky Conditions	Number of Cloudy Days Per Month
January	1-Jan	31	34	34.25	65.75	**20.38**
	11-Jan		34			
	21-Jan		34			
	31-Jan		35			
February	1-Feb	28	35	37.33	62.67	**17.55**
	11-Feb		37			
	28-Feb		40			
March	1-Mar	31	41	43.25	56.75	**17.59**
	11-Mar		43			
	21-Mar		44			
	31-Mar		45			
April	1-Mar	30	45	46.50	53.50	**17.03**
	11-Mar		47			
	21-Mar		47			
	31-Mar		47			

3.9 Result Analyzation Strategies

In order to analyze the results of this project, many different factors were taken into consideration. The main components to determine the effectiveness of the discussed lighting control systems included the amount of times the visual comfort was compromised for the room occupant and the total amount of energy used and/or saved. These factors were considered because they are major components and concerns for home owners. It is important for the room occupant to feel comfortable in their space while also saving energy.

In addition to the number of times the visual comfort was compromised and the total energy usage, cost is an important factor to be considered. However, this project utilized LED light bulbs which do not typically have high monetary costs to operate. This is taken into consideration during this project and any cost savings are considered to be a positive for that lighting control system. The overall cost savings will be discussed in the next chapter.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter will discuss the results obtained through the data collection process for all of the tested lighting control systems.

4.1 Data Analysis

Data was collected to determine the energy efficiency of using the different types of lighting control systems that have been previously discussed. Each subsection below will discuss the energy efficiency and visual comfort of the lighting control system using a system with two position control utilizing an illuminance sensor, an illuminance sensor with a PIR sensor to detect human occupancy, and an illuminance sensor with a thermal camera to detect human occupancy.

To maintain accuracy between each system while collection data, the baseline was set at 15 footcandles and the light fixture is assumed to be on the whole time. This allows for an accurate detection of how much energy is being saved with each system. Although the baseline has been set at 15 footcandles, it is important to note that there is a flexible range within the footcandle level that will not be noticeable by the human eye. This consideration will allow for a larger energy saving. “The change in lumens depends on the occupant’s eye. A change between 8-20% can be detected by the average human eye, where some people may not be able to notice a change up to 40%” (North, 2014). With this information, the baseline has flexibility and will be able to go slightly below or above 15 footcandles by up to 8%. In addition, the dimming change can be more severe when there is prevailing daylight within the space. “If lighting can be dimmed, a big question is how much can be tolerated before occupants notice the change and find it objectionable. A National Research Council-Institute for Research in Construction (Canada) field study found that lighting loads could be reduced 14-23% without significant numbers of occupants noticing. Dimming can occur rapidly, over as little as 10 seconds, by 20% with no daylight, 40% with low prevailing daylight, and 60% with high prevailing daylight. If dimming occurs slowly, over 30 minutes or more, and with no immediate expectation of dimming occurring, levels may drop by 30 percent with no daylight and 60% with high prevailing daylight” (DiLouie, 2017).

In addition to the baseline being followed, there will still be times when the illuminance values will fall below 15 footcandles. This can happen throughout the nighttime when the daylighting is not sufficient to provide adequate illumination within the space. These scenarios would require an additional light source or a lamp with a higher output. Although light levels falling below the baseline is a concern, it is also important to consider when the light levels surpass 15 footcandles. During the day, it is very common for the light levels to be above 15 footcandles in a residential space. When the system detects levels above 15 footcandles, it would be beneficial for the occupant to use daylight modifying systems to adjust the light levels to make them feel more comfortable.

To remain consistent throughout the data collection process, all of the data was collected using a 1500 lumen lamp. This allows for an accurate comparison between each control type as the fixture wattage has stayed the same for each data collection session.

4.1.1 Two-Position Illuminance Sensor Data Collection

The following ARDUINO algorithm was used to collect accurate data using an illuminance sensor. This code was programmed to detect the illuminance entering the space and adjust the position of the light fixture accordingly. Due to the fact that data is being collected in a residential location where computer work is being completed, the set-point has been placed at 15 footcandles. The delay has been set at 60,000 milliseconds so that illuminance data will be collected once every minute.

```
void loop(void)
{
  //simpleRead();
  advancedRead();
  // unifiedSensorAPIRead();
  if (Footcandle<15){
    Serial.println("Lighting Fixture ON");
    Serial.println("");
    digitalWrite(in1, HIGH);
  }
   else
  {
    Serial.println("Lighting Fixture OFF");
    Serial.println("");
    digitalWrite(in1, LOW);

  }
  delay(60000);
}
```

Figure 4.1-1: Arduino Two-Position Control Algorithm

The first lighting control system that was analyzed was a two-position control system that was only based on the overall illuminance provide by daylight. The sensor detects the illuminance entering the space from the exterior window and will adjust the light fixture accordingly. The first set of collected data shown below in Figure 4.1-1 is a plot illustrating the illuminance values collected on January 12, 2023 from 8:16 AM until 4:40 PM. The second set of data collected is shown in Figure 4.1-3 and was collected on March 6, 2023 from 8:33 AM until 3:49 PM. The baseline at 15 footcandles has been drawn on the graph to visual represent the amount of time that the horizontal illuminance falls below this threshold. When the horizontal illuminance falls below 15 footcandles, this is considered to be a moment in time when the visual comfort is compromised.

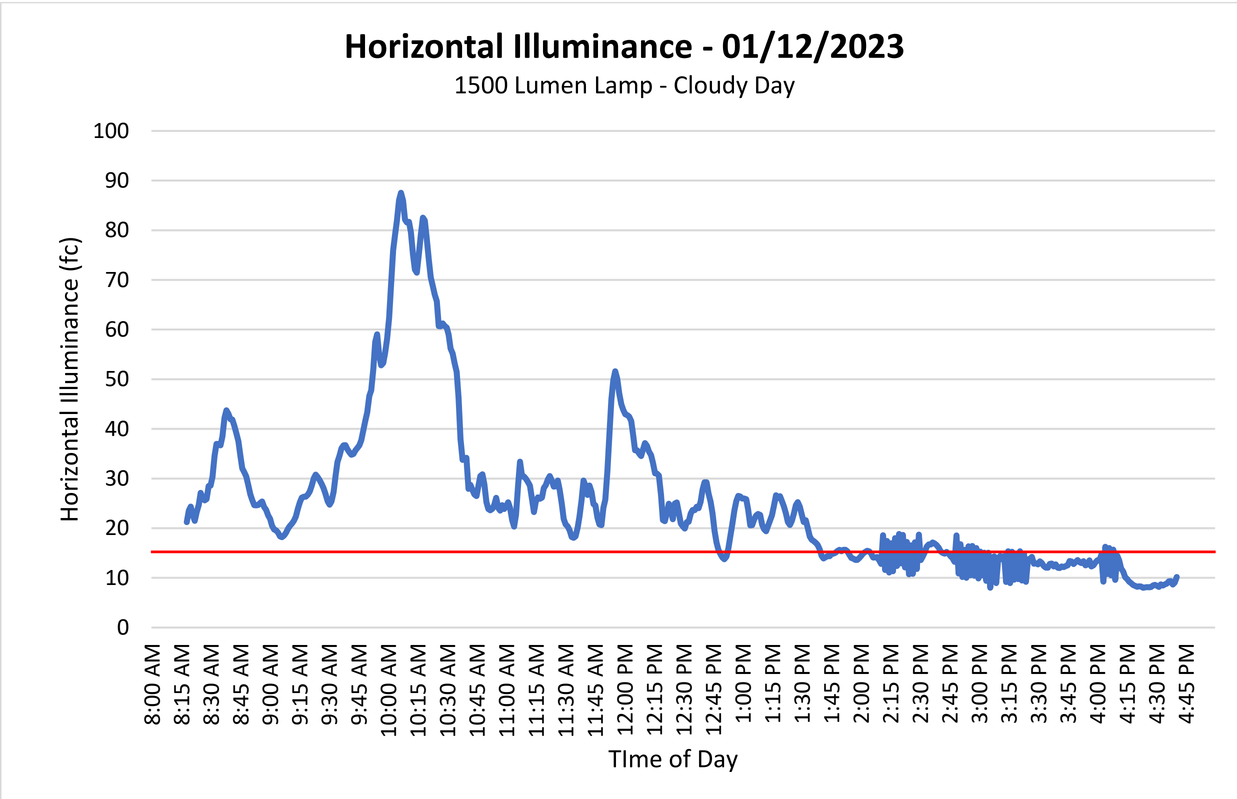


Figure 4.1-2: Two-Position Control Horizontal Illuminance Plot 1

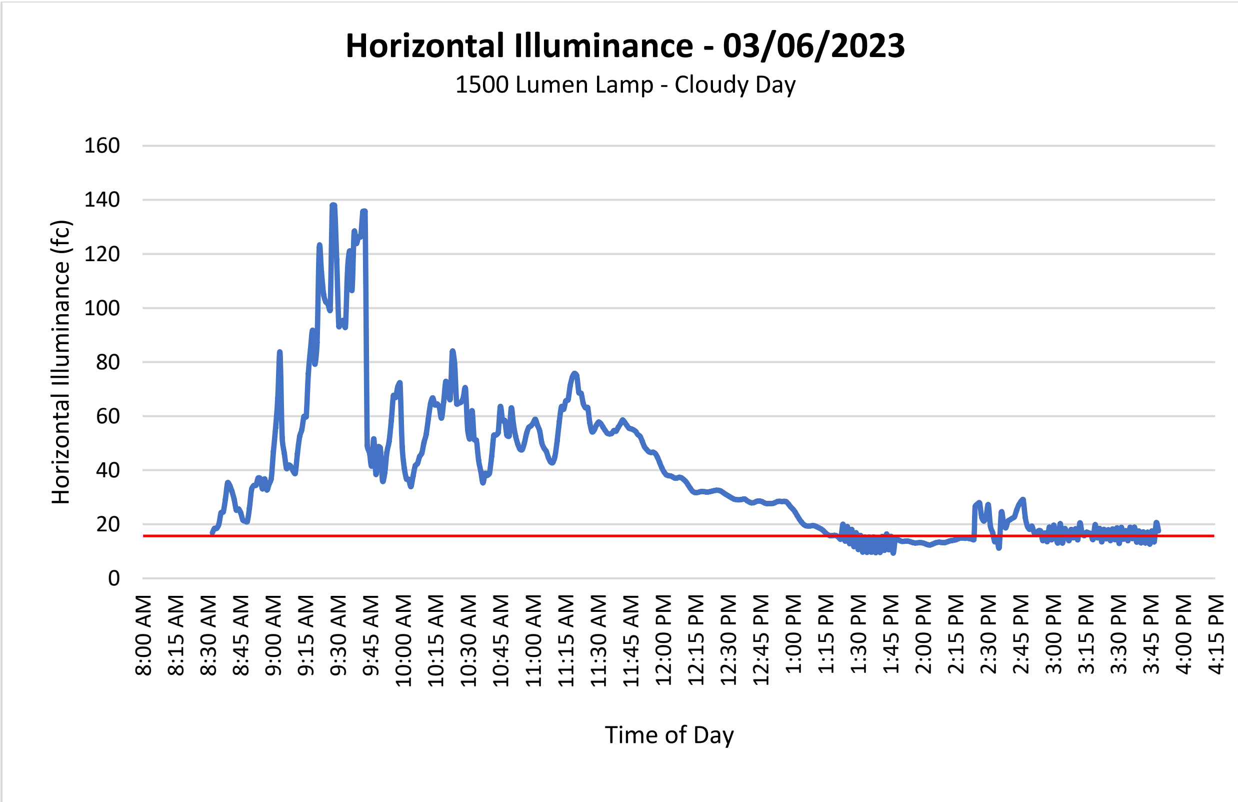


Figure 4.1-3: Two-Position Control Horizontal Illuminance Plot 2

After collecting the illuminance data, the total energy used and energy saved was calculated based on the amount of times that the light was turned on or off. If the illuminance value reading was below fifteen foot-candles at any time during the data collection, the light bulb was turned on. The tables shown below include the energy data found using the two-position lighting control system.

Table 4.1-1: Two-Position Control Energy Data Test 1 (01/12/2023)

TOTAL MINUTES FOR DATA COLLECTION	FIXTURE WATTAGE (PER HOUR)
504	14
TOTAL HOURS FOR DATA COLLECTION	**ENERGY CONSUMPTION (Wh) WITHOUT SENSOR**
8.40	117.60
TOTAL HOURS LIGHT IS ON	**ENERGY CONSUMPTION (Wh) WITH ILLUMINANCE SENSOR**
2.30	32.20

ENERGY SAVED USING ILLUMINANCE SENSOR (Wh)
85.40

ENERGY SAVED PER HOUR (W)
10.17

Table 4.1-2: Two-Position Control Energy Data Test 2 (03/06/2023)

TOTAL MINUTES FOR DATA COLLECTION	FIXTURE WATTAGE (PER HOUR)
436	14
TOTAL HOURS FOR DATA COLLECTION	**ENERGY CONSUMPTION (Wh) WITHOUT SENSOR**
7.27	101.73
TOTAL HOURS LIGHT IS ON	**ENERGY CONSUMPTION (Wh) WITH ILLUMINANCE SENSOR**
0.83	11.67

ENERGY SAVED USING ILLUMINANCE SENSOR (Wh)
90.07

ENERGY SAVED PER HOUR (W)
12.39

4.1.2 Illuminance Sensor and PIR Sensor Data Collection

The following ARDUINO algorithm was used to collect accurate data using an illuminance sensor to detect the horizontal illuminance and a PIR sensor to detect occupancy. This code was programmed to detect the illuminance entering the space and adjust the position of the light fixture accordingly when motion is detected. The algorithm works by simply detecting if there is motion within the space and then reading the horizontal illuminance value. If there is motion detected and the illuminance value is below 15 footcandles, the light fixture will be turned on. If there is no motion detected within the space and the illuminance value is below 15 footcandles, the light fixture will not be turned on and this is considered to be saving energy. Due to the fact that data is being collected in a residential location where computer work is being completed, the set-point has been placed at 15 footcandles. The delay has been set at 1,000 milliseconds so that illuminance data will be collected once every second. The delay has been placed at 1 second for this control algorithm because this will allow for accurate motion detection within the space. The control delay is set to 300,000 milliseconds when the footcandle level is detected to be below 15 footcandles. This control delay has been set so that the light level will be maintained even if the individual sitting in the space remains still for a certain amount of time.

```
void loop(void)
{

  pirStat = digitalRead(pirPin);
  //simpleRead();
  advancedRead();
  // unifiedSensorAPIRead();
 if (pirStat == HIGH) {            // if motion detected
        Serial.println("Motion Detected");
       if (Footcandle<15){
           Serial.println("Lighting Fixture ON");
           Serial.println("");
           digitalWrite(in1, HIGH);

           delay(300000);
           }
       else
  {
    Serial.println("Lighting Fixture OFF");
    Serial.println("");
    digitalWrite(in1, LOW);

  }
 }

  else {
    Serial.println("No Motion Detected");
    Serial.println("Lighting Fixture OFF");
    Serial.println("");
    digitalWrite(in1, LOW);

    delay(1000);

  }

 // delay(1000);
```

Figure 4.1-4: Arduino PIR Control Algorithm

The first set of collected data for the PIR based control system is shown below in Figure 4.1-5. This figure is a plot illustrating the illuminance values and motion detection collected on January 29, 2023 from 9:00 AM until 5:04 PM. The second set of data collected is shown in Figure 4.1-6 and was collected on February 15, 2023 from 8:18 AM until 12:19 PM. The baseline at 15 footcandles has been drawn on the graph to visual represent the amount of time that the horizontal illuminance falls below this threshold. When the horizontal illuminance falls below 15 footcandles, this is considered to be a moment in time when the visual comfort is compromised.

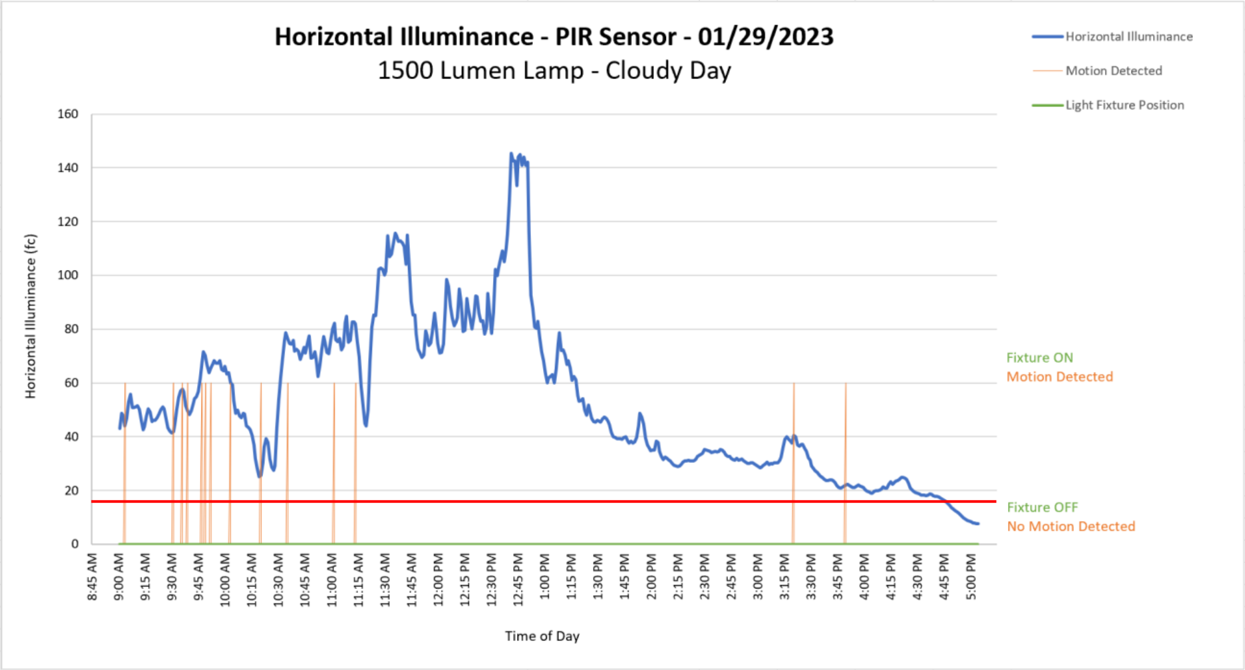


Figure 4.1-5: PIR Control Horizontal Illuminance Plot 1

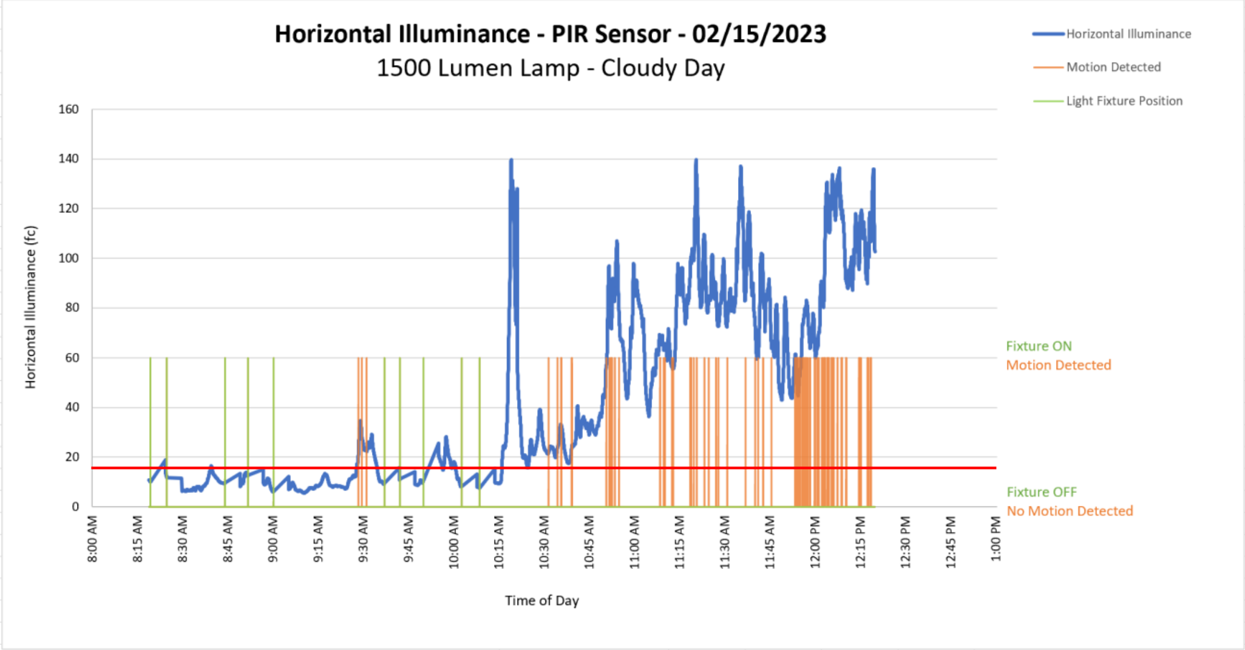


Figure 4.1-6: PIR Control Horizontal Illuminance Plot 2

After collecting the illuminance data, the total energy used and energy saved was calculated based on the amount of times that the light was turned on or off and the amount of times that motion was detected. If the illuminance value reading was below fifteen foot-candles at any time during the data collection when motion was detected, the light bulb was turned on. The tables shown below include the energy data found using the two-position lighting control system.

Table 4.1-3: PIR Control Motion Data Test 1 (01/29/2023)

TOTAL NUMBER OF TIMES MOTION WAS DETECTED
14
NUMBER OF INSTANCES WHEN LIGHT WAS ON
0
TIME LIGHT IS ON WHEN MOTION IS DETECTED CONTROL DELAY (MIN)
5
TOTAL AMOUNT OF TIME LIGHT IS ON
0

Table 4.1-4: PIR Control Energy Data Test 1 (01/29/2023)

TOTAL MINUTES FOR DATA COLLECTION	FIXTURE WATTAGE (PER HOUR)
484	14
TOTAL HOURS FOR DATA COLLECTION	ENERGY CONSUMPTION (Wh) WITHOUT SENSOR
8.07	112.93
TOTAL HOURS LIGHT IS ON	ENERGY CONSUMPTION (Wh) WITH MOTION DETECTION
0.00	0.00

ENERGY SAVED USING PIR SENSOR (Wh)
112.93

ENERGY SAVED PER HOUR (W)
14.00

Table 4.1-5: PIR Control Motion Data Test 2 (02/15/2023)

TOTAL NUMBER OF TIMES MOTION WAS DETECTED
257
NUMBER OF INSTANCES WHEN LIGHT WAS ON
10
TIME LIGHT IS ON WHEN MOTION IS DETECTED - CONTROL DELAY (MIN)
5
TOTAL AMOUNT OF TIME LIGHT IS ON
50

Table 4.1-6: PIR Control Energy Data Test 2 (02/15/2023)

TOTAL MINUTES FOR DATA COLLECTION	FIXTURE WATTAGE (PER HOUR)
241	14
TOTAL HOURS FOR DATA COLLECTION	ENERGY CONSUMPTION (Wh) WITHOUT SENSOR
4.02	56.23
TOTAL HOURS LIGHT IS ON	ENERGY CONSUMPTION (Wh) WITH MOTION DETECTION
0.83	11.67

ENERGY SAVED USING PIR SENSOR (Wh)
44.57

ENERGY SAVED PER HOUR (W)
11.10

4.1.3 Illuminance Sensor and IR Array Data Collection

The IR array control algorithm was designed to detect motion based on the temperature observed of the surroundings visible through the lens of the camera. This algorithm allows for an accurate detection of human occupancy and allows for differentiation between humans and equipment. Shown below are examples of what the occupancy images look like that are provided by the IR array control algorithm along with their corresponding heat map data.

Figure 4.1-7: IR Array Occupancy Image 1

Figure 4.1-8: IR Array Thermal Data 1

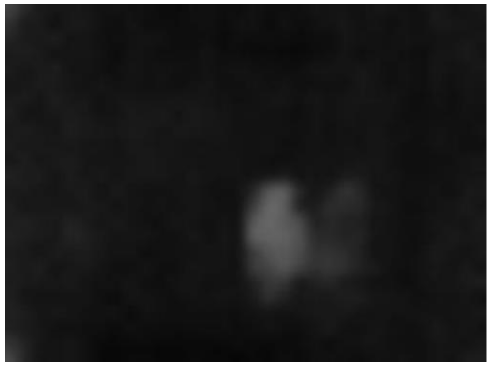


Figure 4.1-9: IR Array Occupancy Image 2

Figure 4.1-10: IR Array Thermal Data 2

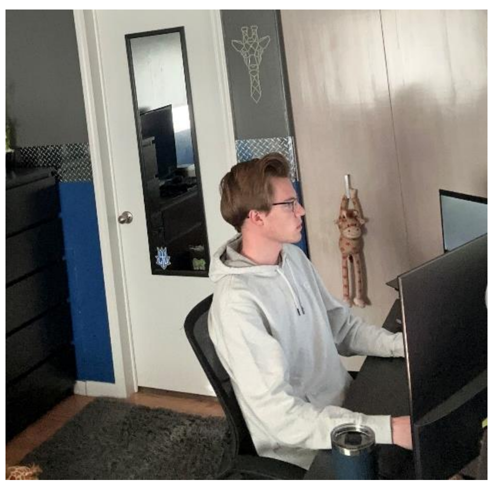


Figure 4.1-11: Occupancy Image Comparison

The first set of collected data for the IR array-based control system is shown below in Figure 4.1-12. This figure is a plot illustrating the illuminance values and motion detection collected on April 12, 2023 from 8:26 AM until 4.24 PM. The second set of data collected is shown in Figure 4.1-13 and was collected on April 19, 2023 from 7:31 AM until 6:18 PM. The baseline at 15 footcandles has been drawn on the graph to visual represent the amount of time that the horizontal illuminance falls below this threshold. When the horizontal illuminance falls below 15 footcandles, this is considered to be a moment in time when the visual comfort is compromised.

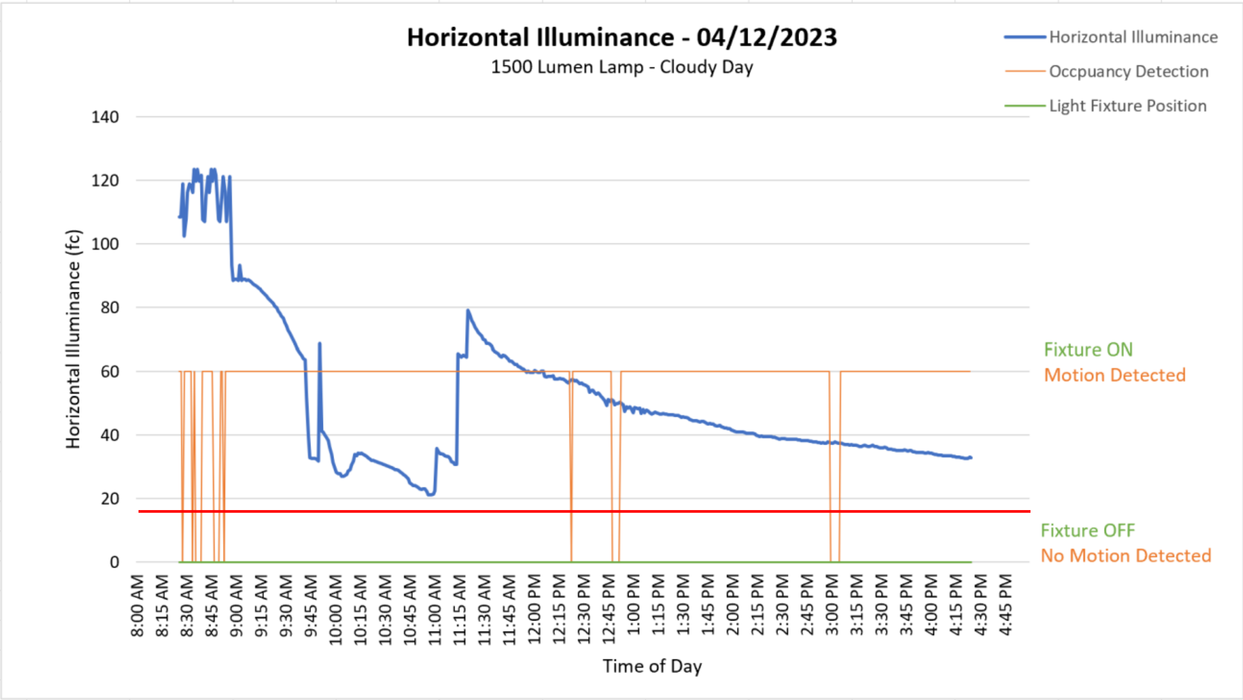


Figure 4.1-12: IR Array Control Horizontal Illuminance Plot 1

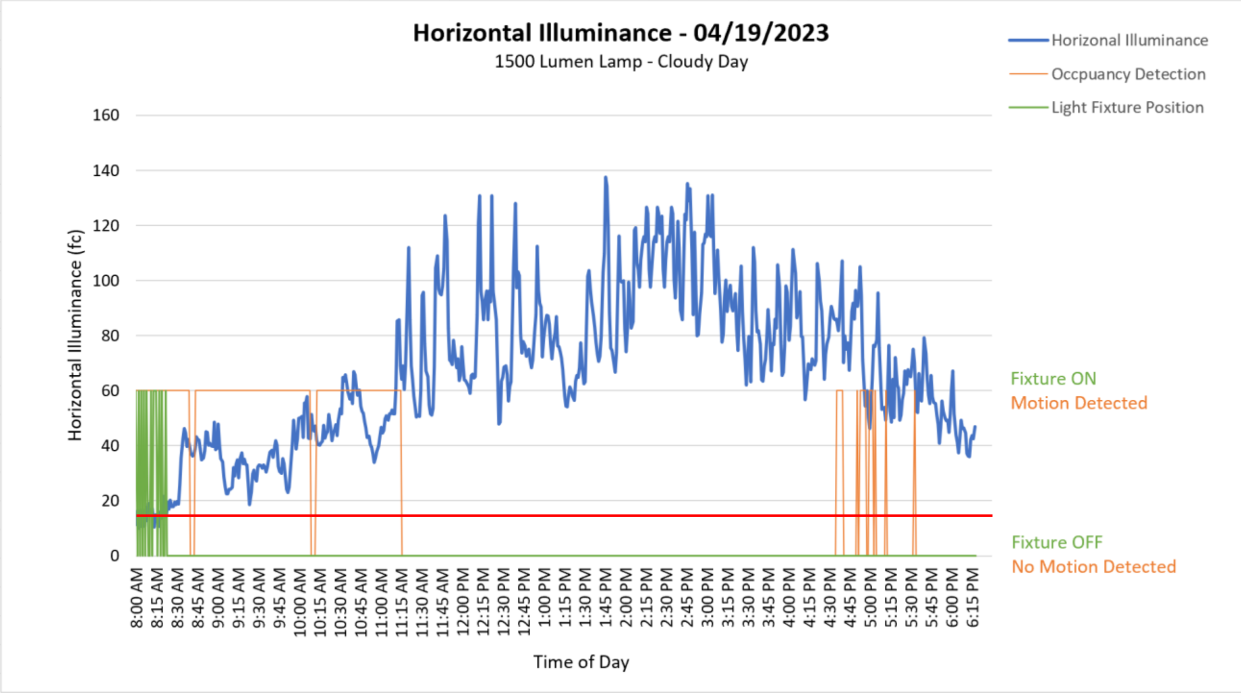


Figure 4.1-13: IR Array Control Horizontal Illuminance Plot 2

After collecting the illuminance data, the total energy used and energy saved was calculated based on the amount of times that the light was turned on or off and the amount of times that motion was detected. If the illuminance value reading was below fifteen foot-candles at any time during the data collection when motion was detected, the light bulb was turned on. The tables shown below include the energy data found using the two-position lighting control system.

Table 4.1-7: IR Array Control Motion Data Test 1 (04/12/2023)

TOTAL NUMBER OF TIMES MOTION WAS DETECTED
456
NUMBER OF INSTANCES WHEN LIGHT WAS ON
0
TOTAL AMOUNT OF TIME LIGHT IS ON
0

Table 4.1-8: IR Array Control Energy Data Test 1 (04/12/2023)

TOTAL MINUTES FOR DATA COLLECTION	FIXTURE WATTAGE (PER HOUR)
478	14
TOTAL HOURS FOR DATA COLLECTION	**ENERGY CONSUMPTION (Wh) WITHOUT SENSOR**
7.97	111.53
TOTAL HOURS LIGHT IS ON	**ENERGY CONSUMPTION (Wh) WITH IR ARRAY MOTION DETECTION**
0.00	0.00

ENERGY SAVED USING IR ARRAY SENSOR (Wh)
111.53

ENERGY SAVED PER HOUR (W)
14.00

Table 4.1-9: IR Array Control Motion Data Test 2 (04/12/2023)

TOTAL NUMBER OF TIMES MOTION WAS DETECTED
225
NUMBER OF INSTANCES WHEN LIGHT WAS ON
40
TOTAL AMOUNT OF TIME LIGHT IS ON
40

Table 4.1-10: IR Array Control Energy Data Test 2 (04/12/2023)

TOTAL MINUTES FOR DATA COLLECTION	FIXTURE WATTAGE (PER HOUR)
647	14
TOTAL HOURS FOR DATA COLLECTION	ENERGY CONSUMPTION (Wh) WITHOUT SENSOR
10.78	150.97
TOTAL HOURS LIGHT IS ON	ENERGY CONSUMPTION (Wh) WITH IR ARRAY MOTION DETECTION
0.67	9.33

ENERGY SAVED USING IR ARRAY SENSOR (Wh)
141.63

ENERGY SAVED PER HOUR (W)
13.13

4.2 Environmental Impact

An important aspect to consider when comparing the control systems was visual comfort. This factor was analyzed by quantifying the number of times that the light levels fell below fifteen footcandles. This was considered to be a compromise to visual comfort because the light levels were below the average value that is recommended by the Illuminating Engineering Society. Table 4.2-1 shown below includes the number of times that the visual comfort was compromised for each lighting control system. In order to accurately compare all of the systems equally, the total number of times that the visual comfort was compromised throughout the duration of the data collection was divided by the total hours for the data collection in order to get the number of times the visual comfort is compromised per hour.

Table 4.2-1: Visual Comfort Comparison

Control System	Data Collection #	Total Hours For Data Collection	Total Number of Times Visual Comfort is Compromised	Total Number of Times Visual Comfort is Compromised Per Hour	Average Number of Times Visual Comfort is Compromised Per Hour
Illuminance Sensor (ON/OFF Control)	1	8.4	138	16.43	**13.37**
	2	7.27	75	10.32	
Illuminance Sensor and PIR Sensor (Occupancy Detection	1	4.02	13	3.23	**1.62**
	2	8.07	0	0.00	
Illuminance Sensor and IR Array (Occupancy Detection Control)	1	7.97	0	0.00	**1.86**
	2	10.78	40	3.71	

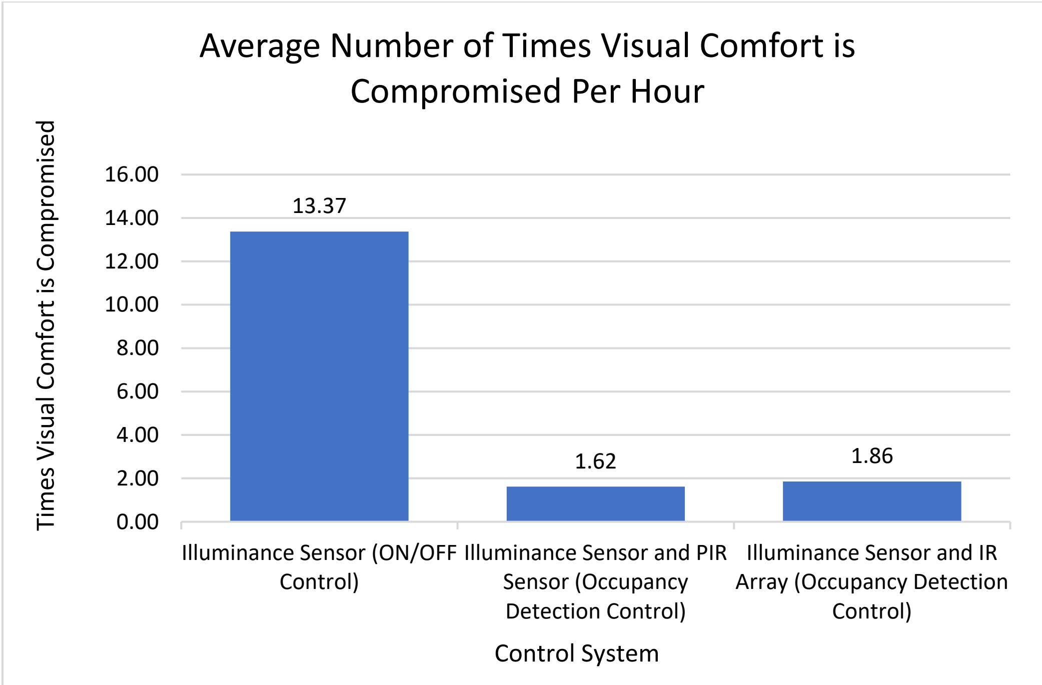


Figure 4.2-1: Visual Comfort Comparison

Based on this data, it can be determined that the PIR and IR array sensors are very similar when it comes to maintaining visual comfort for the occupant. With an average number of times the visual comfort is compromised per hour being less than 2, this means that the space occupant would need to find an additional light source to make them feel comfortable if needed. It is also important to consider that this data is very dependent on the preferences of the occupant. Everyone has different preferences when it comes to light levels, but this data is based on the recommended values from the Illuminating Engineering Society.

4.3 Lighting Control System Comparison

In order to effectively compare each lighting control system, the most accurate data collection sessions were used. The energy savings per hour were compiled for each lighting control system from the data that was discussed above. Once the energy savings per hour was inserted for each lighting control system, the average energy savings per hour was found for each system. Once the average energy savings per hour was determined, this value was then multiplied by the total hours for data collection. In this scenario, and discussed previously, the average work day of eight hours is assumed to be a baseline for the data collection. This is the time when lighting systems are most likely to be used within a home office and one of the areas with a larger potential for energy savings. Table 4.3-1 shows the data for each lighting control system and how much energy can be saved per day.

Table 4.3-1: Energy Savings Comparison

Control System	Total Hours (Average Work Day)	Data Collection #	Energy Savings Per Hour (W)	Average Energy Savings Per Hour (W)	Energy Savings Per Day (Wh)
Illuminance Sensor (ON/OFF Control)	8	1	10.17	11.28	**90.24**
		2	12.39		
Illuminance Sensor and PIR Sensor (Occupancy Detection	8	1	11.10	12.55	**100.40**
		2	14.00		
Illuminance Sensor and IR Array (Occupancy Detection Control)	8	1	14.00	13.565	**108.52**
		2	13.13		

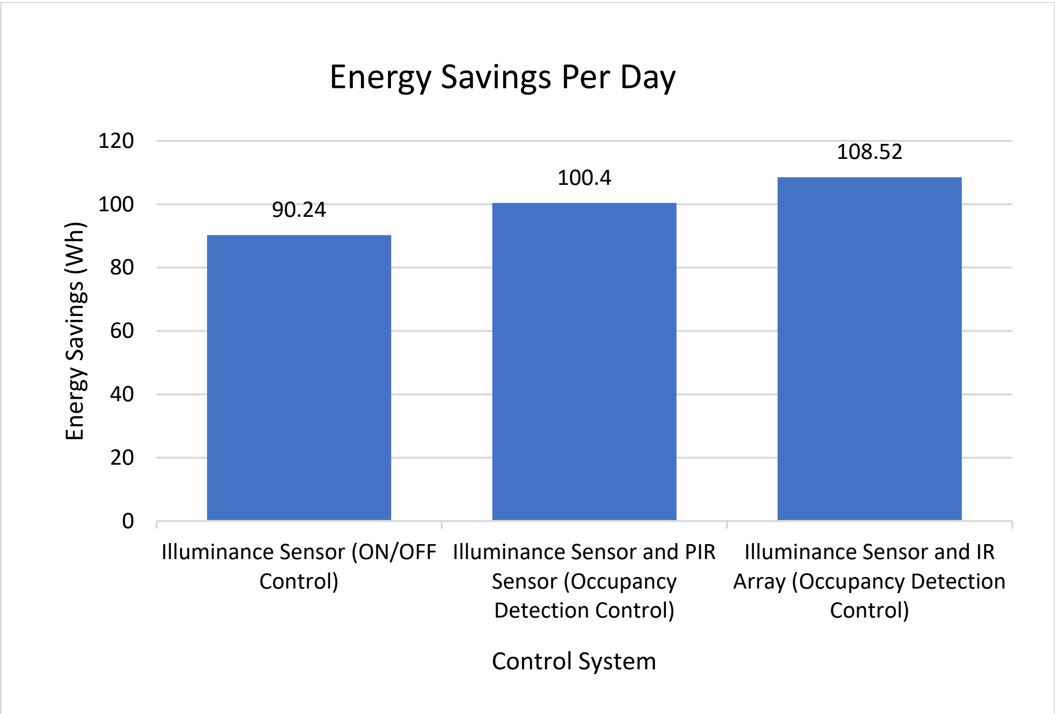


Figure 4.3-1: Energy Savings Comparison

It is important to note that this energy savings data is being compared to the standard lighting control switch of having the lighting system either on or off, controlled by a manual wall switch. In most cases, a room occupant will turn the light on as they enter the space and leave the light on for the entire time that they are working. This data is assuming a baseline of the lighting fixture being on constantly for the entire eight-hour work day.

It is noticed that they lighting control system utilizing the IR array sensor has the highest amount of energy savings per day; however, the other lighting control systems do not fall far behind. The decision between the different lighting control systems can be based on personal preference or can also be factored by the overall cost savings for each system.

4.4 Cost Savings

While considering the amount of energy that is being saved by using each lighting control system, it is also important to consider how much the cost will be decreased for the homeowner. In order to determine this value, the average energy cost was considered for the state of Michigan. "The average residential electricity rate in Michigan is 18.11¢ per kWh, which is the 10th highest average rate in the US. However, lower monthly electricity consumption keeps the average Michigan resident's electricity bill at 109.86¢ per kWh, which is lower than the national average of $117.46" (Electricity Rates, 2023). Shown below is the overall cost savings per month based on the different lighting control systems. This table should be considered when a home owner is more interested in the energy and cost savings compared to visual comfort.

Table 4.4-1: Monthly Energy Cost Savings

Control System	Energy Savings Per Day (Wh)	Month	# of Cloudy Days Per Month	Total Energy Savings Per Month (Wh)	Average Energy Savings Per Month (Wh)	Average Energy Savings Per Month (kWh)	Cost Savings Per Month ($)
Illuminance Sensor (ON/OFF Control)	90.24	January	20.38	1839.09	1636.73	1.64	0.30
		February	17.55	1583.71			
		March	17.59	1587.32			
		April	17.03	1536.79			
Illuminance Sensor and PIR Sensor (Occupancy Detection Control)	100.40	January	20.38	2046.15	1821.01	1.82	0.33
		February	17.55	1762.02			
		March	17.59	1766.04			
		April	17.03	1709.81			
Illuminance Sensor and IR Array (Occupancy Detection Control)	108.52	January	20.38	2211.64	1968.28	1.97	0.36
		February	17.55	1904.53			
		March	17.59	1908.87			
		April	17.03	1848.10			

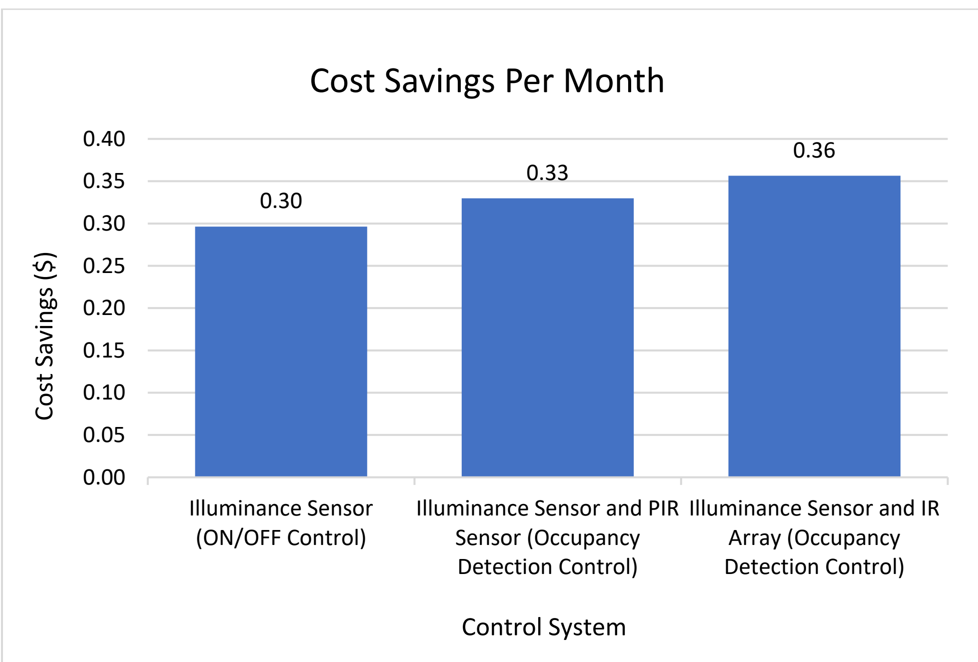


Figure 4.4-1: Monthly Energy Cost Savings Comparison

Although the lighting control systems to do not provide a large amount of energy savings per month, this is a positive approach to implement a system that mainly focuses on visual comfort while saving money at the same time. The low-cost savings is due to the fact that LED light fixtures are already energy saving alternatives compared to legacy light fixtures. “Taking an average 60 W incandescent light bulb, using the light bulb for 1 hour per day results in 0.42 kilowatt-hours (kWh) of electricity per week, 1.83 kWh per month, and 21.9 kWh per year. Two hours per day of light bulb usage comes to 0.84 kWh per week, 3.65 kWh per month, and 43.8 kWh per year” (Marsh, 2022).

4.5 Fitness Function

A visual comparison between all of the compared lighting control systems was created by using a fitness function and plot comparing the number of times the visual comfort is compromised with each system as well as the total energy savings per hour. Table 4.5-1 shown below includes the data that is plotted in Figure 4.5-1.

Table 4.5-1: Fitness Function Comparison Data

Control System	Total Number of Times Visual Comfort is Compromised	Energy Savings Per Hour (W)
Illuminance Sensor (ON/OFF Control)	138	10.17
	75	12.39
Illuminance Sensor and PIR Sensor (Motion Detection Control)	13	11.10
	0	14.00
Illuminance Sensor and IR Array (Occupancy Detection Control)	0	14.00
	40	13.13

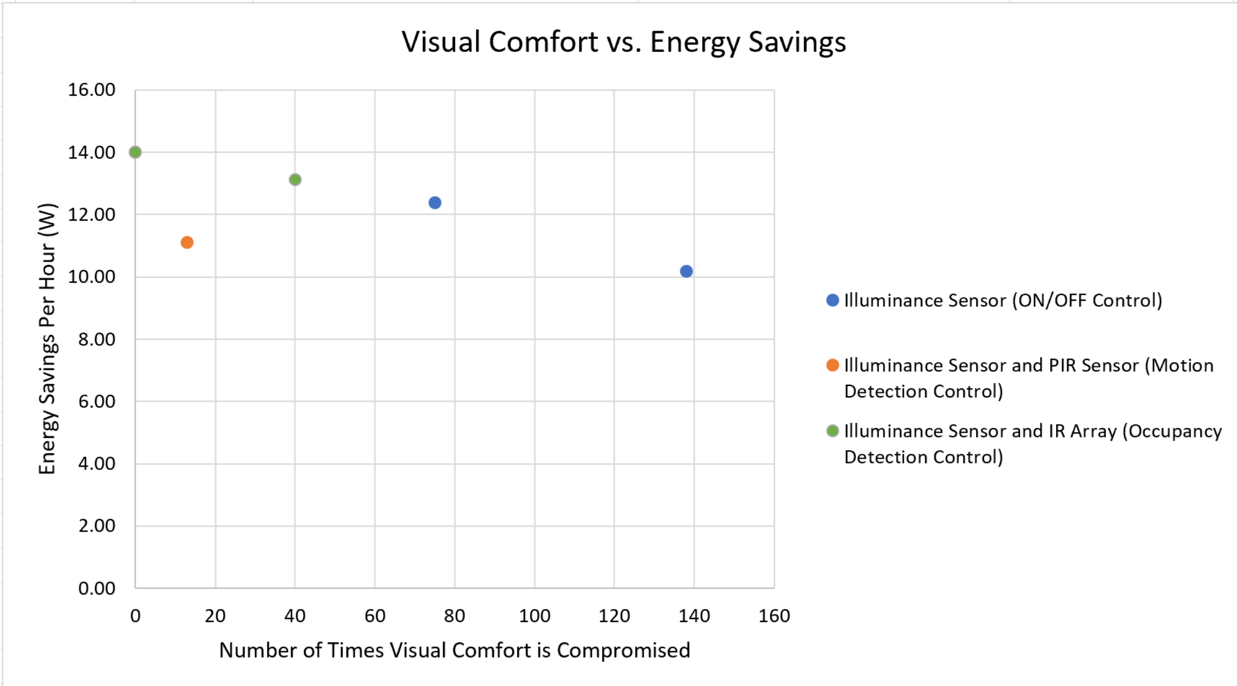


Figure 4.5-1: Visual Comfort vs. Energy Savings Plot

This fitness function is beneficial for this project because it allows for a visual comparison between the different lighting control systems. A fitness function works by changing weighting based on needs of homeowner. In other words, if a homeowner is more concerned in energy savings rather than visual comfort, they can use this plot to see which system best suits their needs.

Based on the plot shown above, it can be seen that the PIR and IR array sensor both have the lowest number of times the visual comfort was compromised as well as the same amount of energy savings per hour. Future considerations can be made between these two systems in order to determine which system will be the most suitable for a homeowner. The energy savings could also be increased depending on the wattage a fixture output of the lighting fixture being used.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

According to the analyzed results from the previous chapter, the proposed system with the IR array sensor was successful at reducing the energy consumption and limiting the amount of times that the visual comfort was compromised. The proposed system with the IR array also had the largest amount of cost savings per month. Regarding the cost savings of the proposed lighting control system, there is not a significant amount of cost savings that could make this system appealing to a homeowner looking to reduce their monthly costs. Since LED's are very inexpensive to operate, there will not be a considerable price decrease by incorporating a lighting control system within residential spaces. Although there are not large cost savings, the proposed lighting control system does perform well enough to reduce the number of times that the visual comfort is compromised while reducing the overall energy consumption. The installation of the proposed lighting control system utilizing the IR array sensor would be more beneficial to homeowners that are looking to make their home spaces more customizable and comfortable.

It is noticed that the lighting control system utilizing the PIR sensor performed very similar compared to the proposed system with the IR array. Although there are many considerations to be made, there are still negative outcomes if the PIR sensor is the chosen lighting control system. For example, this system typically requires motion to be activated. With the IR array sensor, the machine learning technology can detect when a human is sitting within the space even if they are not moving for a long period of time. It is beneficial to weigh out the benefits and challenges of each system when selecting the proper lighting control system.

Although lighting control systems are not typically used within residential spaces, machine learning technology that utilizes an IR array sensor may be the new technology to take lighting control systems within the residential sector to the next level. Based on the energy savings and benefits of being able to coordinate them with other cost saving technologies, this will be a positive way for homeowners to reduce their overall energy consumption. In addition, this system will allow for homeowners to feel more comfortable within their space while they are shifting to more remote work.

5.1.1 Considerations

While analyzing the results obtained for the various trials of data collection throughout the duration of this project, there are also some considerations that can be made by the homeowner to determine which system is the most beneficial for them. For example, there is a cost and installation required for all of these systems, so the selected system may be dependent on the experience of the homeowner and how well they can be educated on the system. In addition, this system is dependent on home location and window availability/direction. If a homeowner works in an office that does not receive a lot of daylight throughout the work day, they may not see benefits over time.

5.2 Project Limitations

Due to the time frame constraints of this project, much of the data was collected during different weather conditions. This is considered a limitation of this project because the weather and sky conditions have varied over the previous months which makes it difficult to directly relate the energy savings for each lighting control system. A solution to this limitation would be to install all of the lighting control systems that have been discussed and collect data with each system at the same time. This would allow for all of the data to be compared accurately and provide more definitive results.

5.2.1 Illuminance Sensor Limitations

During the preliminary data collection, it was determined that there are some limitations with the TSL 2591 sensor that is being used. For example, the TSL 2591 sensor was providing foot-candle readings below zero when exposed to direct sunlight. These false readings can be due to the plastic cover that protects the sensor from debris and damage. When this cover is exposed to direct sunlight for a long period of time, there is a possibility of the cover turning opaque which may lead to inaccurate data collection. Due to the limitations of the TSL 2591 sensor, all of the data collected for this experiment utilized cloudy days to avoid direct illumination. Not only will using cloudy days for data collection help with the sensor limitations, but it will also allow for data collection during worst case scenario conditions. Shown below in figure 5.2-1 is a graph of data collection that resulted in values close to zero foot-candles. This data was collected on October 24, 2022 between the times of 7:46 AM and 4:55 PM.

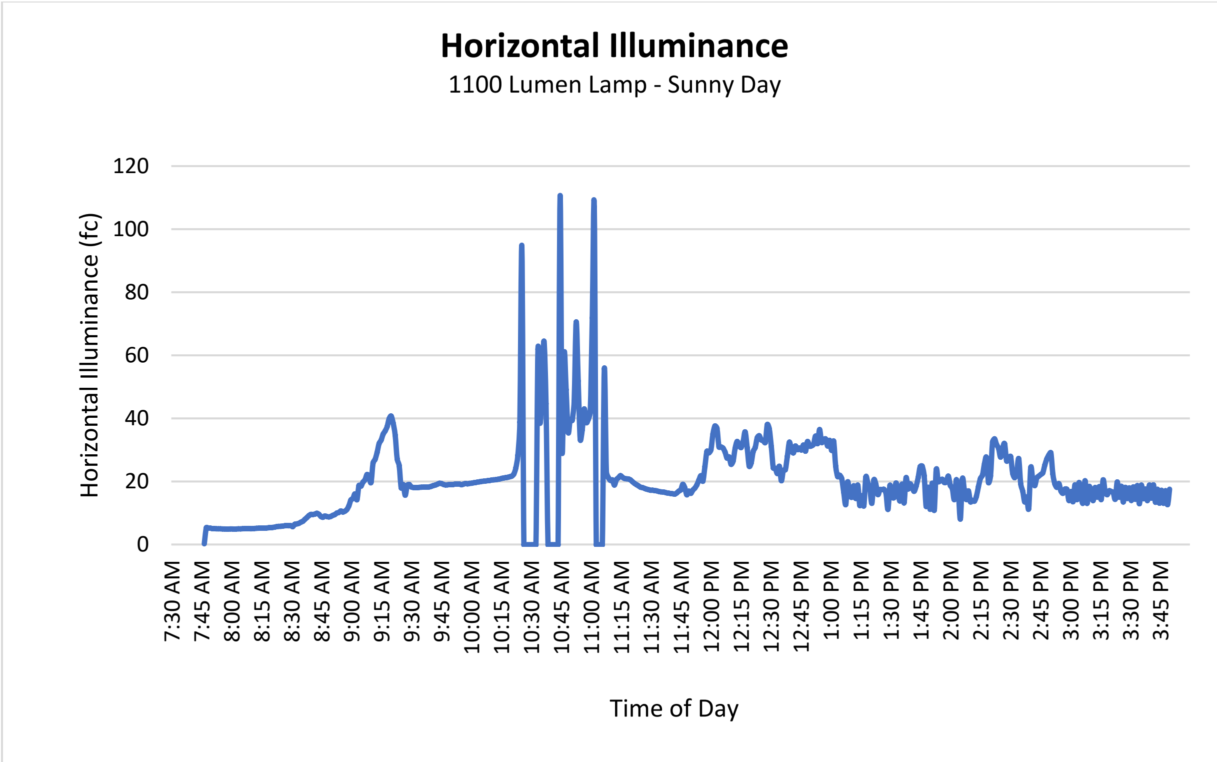


Figure 5.2-1: Horizontal Illuminance Data Collection - Sunny

5.2.2 LED Light Bulb Output

For the data that was collected during the experiments outlined in this report, only one light fixture was used for the entire space. Based on the size of this space, one fixture was acceptable, but this may not apply to all residential locations. It is also important to consider that many individuals place their home offices in different locations, which will result in different light conditions. Although this is considered a limitation of this project, future opportunities would include providing more light fixtures within one space that can provide more illumination based on the size of the room.

5.3 Future Opportunities

Based on the information that was discussed above, it will be beneficial to determine how to accurately collect illuminance data without experiencing complications with the TSL 2591 sensor.

Future opportunities of this study would include integrating an IR array algorithm within this control system to adjust the light levels based on human occupancy and human behavior. Once it is determined that this control system is able to reduce the energy consumption, dimming controls will be implemented in order to reduce the energy usage while maintaining visual comfort for the occupants. An accurate location of the occupants within a space will allow for the light levels to be adjusted accordingly depending on what tasks the occupants are completing. For example, someone walking through the corridor will need more illumination compared to someone who is working at their desk on their computer. Shown below is a flowchart of how a lighting control algorithm works based on light fixture zoning.

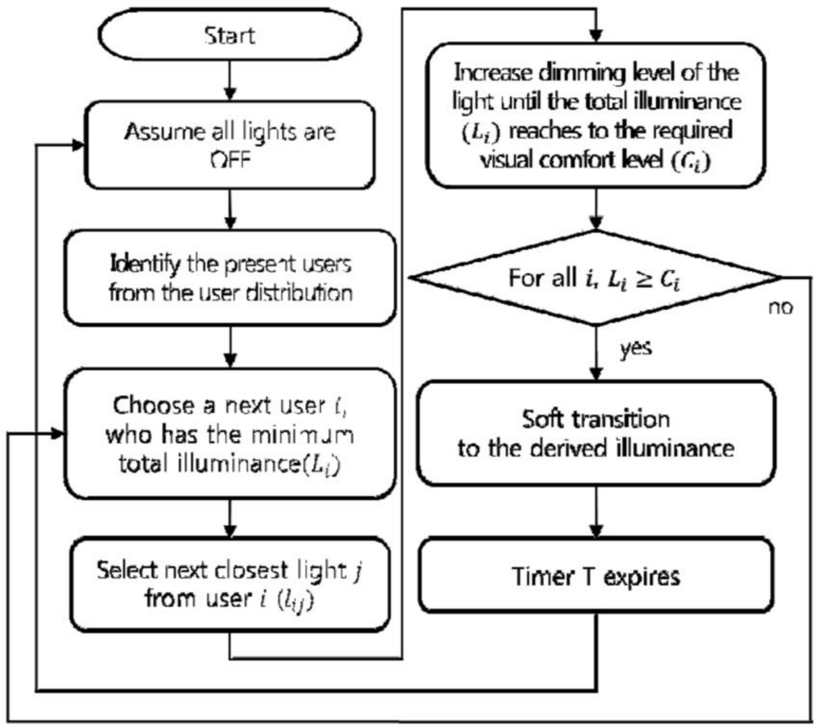


Figure 5.3-1: Lighting Control Algorithm Flowchart (Lee, 2018)

This system would also allow for future opportunities by incorporating automatic daylight modifying systems. Since the proposed system is detecting the illuminance values within the space, a baseline could be set for higher illuminance values and the daylight modifying system could be adjusted accordingly. Daylight modifying systems could include horizontal or vertical blinds. This opportunity would allow for the system to run completely autonomously and would eliminate the consideration needed by the room occupant.

5.3.1 Ease of Installation

One of the concerns with this lighting control system is that it can be very difficult for some individuals to install and operate the system without assistance. Since this is a system that shall be created for all residential spaces, it is important to develop the system to be easy to understand years after the initial installation. While keeping this in mind, future opportunities of this project could include developing a program that would provide ease of installation instructions for the individual that purchases the product. These instructions would include step-by-step instructions on how to install the system and how to troubleshoot any problems that may arise with the system. It would also be important to have a group of experts of the system be available when homeowners have any questions or concerns. Considering these future opportunities will allow this system to reach more customers and residential homes.

5.3.2 Fixture Integration

Future development of this system may allow for integral integration within light fixtures to allow for occupancy detection using the IR array control algorithm. This would allow for the system to be integrated with light fixtures and would eliminate the concerns of having equipment placed in random locations throughout a residence. In addition, if a homeowner is concerned with where to place the lighting control equipment, integral fixtures would eliminate that concern. This development is something that many lighting control manufacturers have been begin to implement in their systems so that lighting control systems do not have to be an eyesore placed randomly on the ceiling. Since lighting control systems are not commonly found in residential spaces, this would allow for an effortless integration into the home control system.

5.3.3 Computer Simulation

Since one of the limitations of this research project was the different weather conditions depending on the day, a computer simulation could be used to detect the illuminance on any given day throughout the year based on a specified location. This computer simulation could be used for calibration purposes across all of the different lighting control systems by determining the amount of available daylight throughout the whole year. This opportunity could be studied further in the future to have a better comparison between the lighting control systems.

5.3.4 Further Visual Comfort Considerations

Color Rendering Index (CRI) and glare are other important factors that contribute to healthy lighting and visual comfort that were not considered for this research study. These two factors should also be considered in the future to utilize passive lighting systems in order to make occupants feel more comfortable within their space. The proposed lighting control system could be installed to work in coordination with automated blinds that can automatically control the glare within the space.

In addition to glare, there have been many improvements in the lighting industry regarding CRI and many designers are beginning to use fixtures that have a highly rated CRI. A high level of CRI is important because this rating determines how well a light source can reveal the colors of an object compared to a natural light source. A lighting control system that is centered around making sure the space occupant is comfortable should also consider CRI as an important aspect in the future.

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