DESIGN AND IMPLEMENTATION OF A SENSITIVE CEILING BASED VISIBLE LIGHT SENSOR

by

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ABSTRACT OF THE THESIS

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Existing photoelectric, pyroelectric infrared (PIR) and camera based solutions for applications such as motion detection, activity detection, occupancy detection and localization in indoor settings require people to carry a device on their person or dense deployment of transmitters and receivers or raise privacy concerns. Some if not all of these shortcomings can be overcome by using visible light. Leveraging visible light in an indoor setting enables reuse of pre-existing light sources as transmitters. The short wavelength (nanometers) of visible light, properties of reflection and creation of shadows ensure that light is contained to the room and makes eavesdropping hard. Any system which aims to make use of these properties of visible light first requires a sensor which can sense and convert visible light to a voltage. The work presented in this thesis presents all the steps that go into designing a sensitive ceiling based photoreceiver that is able to detect light level changes occurring on any floor including dark carpeted surfaces. The photoreceivers are designed to be placed along with the existing lighting fixtures in a room to make deployment as easy as fitting a light bulb. The photoreceiver is designed as a module that can be used as the first component of any visible light based system that wishes to detect faint changes in light. The efficacy of the photoreceiver in terms of sensitivity and accuracy is shown by testing it in a conference room under realistic use case scenarios and different floor types. Experiments are conducted by deploying the photoreceiver in a conference room on the ceiling at a height of 9 feet along with an LED lamp. Sensitivity of the photoreceiver is found by slowly dimming a single LED lamp until the conference room is completely dark. Photoreceiver analog to digital converter (ADC) readings corresponding to dimming light at the ceiling are noted. Accuracy of the photoreceiver is found by first making people walk through the sensing area and collecting raw readings. The raw readings are then processed using a detection algorithm. The photoreceiver is able to detect light level changes of the order of tens of lux occurring on the floor and detect motion of a person walking with an AUC-ROC score of 0.9739 while pointed at a bright floor surface and an AUC-ROC score of 0.9276 when pointed at a dark floor surface.

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Chapter 1

Introduction

1.1 Motivation

The smart home sector is an area with interesting and unique open research questions. Indoor motion detection, activity detection, occupancy detection and indoor localization are domains that have had open research questions for the better part of the last two decades. Solutions presented to answer questions in these domains have depended heavily on radio frequency identity (RFID) sensors, pyroelectric infrared (PIR) sensors, cameras, and radio frequency (RF) technologies such as Bluetooth and Wi-fi. Invariably almost all of these proposed solutions have shortcomings which restrict their immediate widespread deployment. Mostly they either require special deployment of hardware and or changes to the environment intended to be sensed. There is a need for developing a solution which uses resources present indoors while reducing additional infrastructure deployment which can be readily deployed in a widespread manner.

In an indoor setting ceiling lights and the illumination they provide are ubiquitous resources that can be leveraged. Using visible light is an attractive solution for a few reasons; it reuses available lighting infrastructure which means widespread deployment is possible, the spectrum is unlicensed/unregulated which means designing and deploying a solution can be done quickly, the available bandwidth is nearly $10,000$ times more than RF spectrum bandwidth, it is privacy conserving (i.e. as the wavelength of visible light is in nanometers it does not penetrate through objects or obstacles. This means anybody wishing to eavesdrop cannot do so easily). Finally light in the visible light spectra is excellent for indoor motion detection, localization and tracking as the nanometer wavelength can detect even minor movements (any macroscopic object larger than the light's wavelength would block it).

Though there exist systems which use visible light to solve the aforementioned problems they do not use existing infrastructure enough, lack the potential for immediate widespread deployment, are too cumbersome to deploy or have high overhead costs to run and maintain. The properties of visible light along with an interest to find a more viable, widely deployable solution serve as motivation for this thesis.

Visible light when incident on objects creates shadows. This property of light is used to detect the presence of humans in a room. Visible light from ceiling lamps when incident on a person cast shadows on the floor. By accurately sensing these shadows, the presence and position of the person can be determined in real time. The challenge lies in sensing these shadows correctly and positioning the sensors to detect these shadows. Transmitters and receivers make up the first blocks in systems which operate in the visible light spectrum. Since the existing light sources act as transmitters this thesis focuses on building a sensitive photoreceiver.

1.2 Problem Statement

The research contribution made using this thesis is answering the following question:

Is it possible to design a sensitive enough ceiling based photoreceiver that is able to detect minute light level changes that occur on any floor, including dark carpeted surfaces?

This project intends to make use of shadows created when light is incident on objects to help provide a solution which can be used for motion, activity, occupancy detection and indoor localization all while using existing light sources in a room. It illustrates all the steps that go into building a new ceiling based photosensor / photoreceiver which can detect the light intensity of shadows.

1.3 Contributions

A ceiling based photoreceiver with the following capabilities is designed:

- Can be used to detect light level changes on different floor types (diffuse, specular, dark and bright surfaces) with minor changes to circuit component values.
- Ability to sense light level changes as small as tens of lux.
- Ability to detect shadows created by light sources from up to 8 feet away.
- An area under curve for receiver operating characteristic (AUC-ROC) score of 0.9276 for a dark carpeted floor and 0.9739 for bright carpeted floor.
- Small form factor enabling easy installation to existing infrastructure.

The ability to detect shadows on a surface depends heavily on the type of surface it is cast on. Specular surfaces reflect light better than diffuse surfaces. As the reflected amount of light is higher, detecting shadows cast on specular surfaces is easier. Diffuse surfaces as the name suggests diffuse the light incident on them making detecting shadows harder. Detecting shadows on bright surfaces is easier than on dark surfaces for similar reasons as before. Bright surfaces reflect more light than dark surfaces. It would be hardest to detect shadows cast on a dark diffuse surface. Hence it is important that the designed receiver work over a range of different floor surface types.

Light reflected from the floor reaches the photoreceiver at the ceiling. This means light has to travel twice the distance from the lamp source to the ceiling. This highly reduces the total amount of light the photoreceiver sees. The photoreceiver needs to be able to see shadows or dark areas on the floor, which means it needs to look for dark areas on the floor with little light incident on it. Hence the designed photoreceiver needs to have a high enough granularity or the ability to correctly sense minute changes in values of lux.

In addition to detecting small changes in light, the photoreceiver needs to be able to sense light from far away sources. As a sensor intended to be deployed in a room with multiple lights, it needs to be able to detect light from far away sources as well as differentiate between them. For applications such as indoor localization and activity detection reliable information from multiple sensors is required. Also, light from a far away source is dimmer and not readily distinguishable. Hence it is advantageous if the designed receiver is able to sense light from far away light sources.

As the photoreceiver is meant to be on all the time looking for shadows / changes in light level, merely detecting light level changes and having a metric of the photoreceivers sensitivity is insufficient. The final voltage / analog to digital converter readings need to be reliable and consistent over time. The output data should be as close to the actual ground truth as possible and there must be no drift in voltage with time. To determine the accuracy and reliability of the output data, a simple experiment is conducted by keeping the photoreceiver on for a long period of time and counting the number of times a person crossing the sensing area underneath the photoreceiver is detected correctly.

Finally, in order to be deployed readily as part of a LED lamp circuit the form factor of the final circuit must be small.

1.4 Thesis Outline

Subsequent chapters of the thesis are as follows:

Chapter 2 reviews various sensors / detectors developed to help solve indoor motion, activity, occupancy detection and localization. The solutions broadly include cameras (CMOS sensors), PIR sensors, photoelectric sensors and visible light based sensors. Specialized hardware parts; transmitter and receiver of each solution are discussed in detail.

Chapter 3 first presents a high level photoreceiver circuit design along with design considerations. Each block of the photoreceiver circuit is then explained in detail.

Chapter 4 discusses the implementation of the final designed circuit in its entirety. It discusses all the steps that go in to making of the final printed circuit board. The component values, schematic and layout of the circuit are shown.

Chapter 5 describes the conducted experiments, experimental settings and reasoning behind conducting a particular experiment to evaluate the designed circuit.

The sensitivity and accuracy of detection of the photoreceiver are tested.

Chapter 6 presents the results and inferences of the conducted experiments.

Chapter 7 gives the conclusions for the thesis and

Chapter 8 outlines the scope for future research.

Chapter 2

Related Work

2.1 Introduction

Many researchers have made use of photoelectric sensors, infrared radiation (IR) sensors and more recently visible light sensors to detect movement, blockages and interruptions. Sensors designed to detect motion using these stimuli typically have a line of sight (LOS) transmitter which emits a known signal and a receiver which collects this transmitted signal. A change in the received signal indicates that some change has occurred in the environment.

This chapter focuses on the transmitter and receiver designs of the aforementioned sensors that already exist for the purpose of detecting motion indoors. It discusses these sensors while taking into consideration constraints regarding the entire system such as: type of transmitter and receiver used, the number of transmitter and receivers needed to cover an area, sensitivity of the receiver, ease of deployment and whether the users have to carry a device on their person.

2.2 Photoelectric sensors

Photoelectric sensors consist of three parts: (i) a light source which acts as the transmitter, where the transmitted signal is usually a visible or invisible light (i.e. infrared light); (ii) a photosensitive receiver which receives this modulated light and is able to convert it to a current and (iii) an amplifying circuit that converts this current into a voltage while amplifying it [2] [4].

These sensors make use of the idea of light barriers. Essentially the transmitter transmits modulated light as a beam over an area which is either received by the receiver directly or after reflecting off a surface [18] [3].

The light source used can be a laser device for detecting very small motion, a red light source for detecting large objects, green / blue for detecting the color of a surface or can be infrared for other short range applications. The receiver is usually a photodiode or phototransistor with maximum sensitivity in the range of the wavelength of light being used. The signal from the receiver needs to be amplified before it can be used, this is accomplished using op amps. This amplified signal is then usually used to switch on or switch off other devices or processes.

These sensors are used over a wide variety of applications; they are used around heavy machinery on the shop floor, to detect something as small as a finger, to count the number of bottles passing through on a conveyor belt, to open doors, taps and flushes and to check color, contrast and light levels / luminescence of a particular target spot [3].

Depending on the type of sensor the receiver either expects to continuously receive the modulated light or doesn't expect to receive any light at all. An obstruction is detected when the reflected light fails to reach the receiver when it expects light or reflected light reaches the receiver when it doesn't expect to receive any.

In the opposed mode the transmitter and receiver are separate units and have to be installed opposite each other, with light being continuously transmitted to the receiver. If there is a break in the received light an obstruction is detected. When using this mode to sense motion it is imperative to make sure that the transmitter and receiver are properly aligned with each other when installing them opposite to each other [4].

In the retroreflective mode a single unit houses both the transmitter and receiver with light being continuously transmitted to the receiver. But the light beam is first made to reflect off a reflective material before reaching the receiver. Similar to the opposed mode an obstruction is detected when there is a break in the received light beam. A design consideration that needs to be taken into account before using this mode to sense motion is to identify locations where the reflective material can be stuck prior to installing the sensors. Also, in order to sense and detect movement over a large area multiple such reflective patches and sensors need to be deployed [5] [4].

In the proximity mode a single unit houses both the transmitter and receiver. The light beam is emitted into free space and no light is expected to impinge on the receiver. A detection is signalled when light bounces off an object and reaches the receiver. When using this mode to sense motion the sensor would need to be close enough to the object reflecting the light to be able to receive a strong signal [18] [4].

Each of these modes were developed to cater to a specific application requirement. The individual limitations of each sensor adds up if a large number of them are needed to perform motion detection on a room wide scale. In the case of opposed mode sensors, for every transmitter deployed a receiver would be required. Each retroreflective sensor would require its own reflective patch. And proximity mode sensors might not have the required range. Apart from this proximity sensors do not offer any range in motion detection sensitivity. They only provide one bit of information (i.e. obstruction or not). The deployment of these sensors would require individual sources of light (transmitters) which would entail additional infrastructure overheads.

2.3 PIR Sensors

The basic structure of a Pyroelectric Infrared Device (PID) sensor consists of a Fresnel lens, a pyroelectric infrared (PIR) sensor (typically LiTa03 crystal), an amplifier, a comparator along with a time delay circuit. Even though the PIR sensor is a component of a PID, the terms PIR and PID are often used interchangeably.

A Fresnel lens along with an IR filter is used to collect infrared radiation from a wide area and focus it onto the PIR sensor. The Fresnel lens makes the lens thinner. Infrared radiation incident on the pyroelectric crystal gets absorbed and results in a change in temperature of the crystal. This change in temperature can be measured in terms of the voltage generated across it. A PIR sensor has two such crystal slots. When a body emitting infrared radiation moves across the two slots there is a differential change generated between the two slots. First there is a positive differential change, when the body moves across the first slots sensing area; then, when the body leaves the sensing area, the sensor generates a negative differential change. When there is no change in infrared radiation in the sensed area both slots return the same value.

As the output voltage of the PIR sensor is low, it is generally passed through two stages of amplification each with an approximate gain of 100, effectively corresponding to a gain of nearly 10,000. Finally in order to declare a detection the output of the amplifier is compared to a threshold DC value using a comparator.

If the input voltage is higher than the threshold voltage a high voltage is given as the output (typically 5V).

Work by Jaeseok Yun and Min-Hwan Song [29] detects the direction in which people are moving using four PIR sensors. Since the voltage generated by the PIR sensor is low they use an amplification circuit. This setup is mounted to the ceiling and the data collected is used to train multiple classifiers (Bayes, Instance-Based, Decision Tree, Naive Bayes to name a few). The four sensors are each aligned towards W-E, N-S, NW-SE and WE-SW. After training the neural networks with experimental data, the authors were able to attain 89–95% accuracy in correctly identifying the direction of movement.

Xiaomu Luo et al. [20] simulated mounting five sensors modules on the ceiling with each sensor module containing four PIR sensors. Specific blocks on the floor were assigned to each PIR sensor to monitor and localize the movement of a person. They also used Webots and Matlab to simulate a cylindrical human being moving around and were able to simulate tracking a person to an accuracy of 0.486m.

Qi Hao et al. [10] and Ren Luo et al. [19] mounted PIR sensors to the wall instead of the ceiling. [10] deployed four sensor modules in a room each with eight PIR sensors and a synchronization module. The room was divided into grids which each node sensed to track humans. The angular velocity of a moving person was then extracted.

2.4 Visible Light based sensors

Light fixtures or luminaries that emit visible light are ubiquitous and are present in most if not all rooms. With minor modifications to these existing light sources they can be used as transmitters which can be deployed in various environments. It would then be easier to develop receivers which can work with these modified lights. This would not only reduce infrastructure overhead but make deploying motion sensors in varied environments far more feasible.

LiSense [16] and work presented by Chuankai An et al. [1] modified existing light fixtures in a room to act as transmitters. The setup then looked for shadows on the floor that were created by people due to the light incident on them from the ceiling. An array of receivers/sensors were deployed on the floor which collected/sensed the shadows incident on them. After processing these shadows a 3D human skeleton was reconstructed in real time.

The transmitters are modified commercial off the shelf (COTS) CREE bulbs. The receiver circuitry uses a cascade of photodarlingtons (SD3410-001) [24]. The SD3410-001 has a maximum spectral responsivity between 800 - 900nm lying in the infrared spectrum. The photodarlingtons are connected in series with a large resistor to convert current to voltage. They are then input to an Arduino Duemilanove. In order to reconstruct the person accurately while post processing, it is necessary that the receivers sense even small shadows. Hence, photodarlingtons with high gain and wide angular response are used at the expense of faster rise and fall time (75uSec) [24], response time and frequency response [9][8][12].

DarkVLC [26] provides a promising solution for visible light communication while using extremely small short and imperceptible pulses of light. It accomplishes data transmission of up to 1.77Kbps over a distance of 10cm. It uses a simple PIN photodiode (SD5421) connected in series to a 100kOhm resistor followed by a unity gain amplifier before connecting to an USRP. It demonstrates that data can be transferred between transmitter and receiver (both built using COTS components) over short distances in very low light conditions upto a maximum viewing angle of 50 degrees.

DarkLight [27] accomplishes transmitting data of up to 1.6Kbps over a distance of 1.3m using visible light. It builds upon DarkVLC [26] and expands its scope with a drastically faster and more sensitive receiver circuit. It presents many firsts and pushes the envelope in designing transmitters and receivers which are built using COTS components but are able to provide high gain and high speed. DarkLight demonstrates that not only data can be sent using extremely short imperceptible pulses of light, but can be received and demodulated as well. DarkLight was developed for communication purposes but inspiration can be taken from this work to design a highly sensitive receiver which is capable of detecting very faint light.

The receiver uses SD5421 [25] PIN photodiodes mounted with glass caps to narrow the acceptance angle, this is useful because the photodiode is looking for light coming from a certain direction only. The peak response for the SD5421 lies between between 800 and 900nm, just beyond red light (600 – 700nm). PIN photodiodes have a very fast rise and fall time (15ns) which make it ideal for a fast response. The current generated from the photodiode is sent to a transimpedance amplifier (TIA) which has a large feedback resistor (1MΩ) and suitable capacitance (10pF). The large resistance helps increase the gain and amplify the incoming current. They also use OPT101 [22] a monolithic photodiode and TIA. The OPT101 uses a photodiode with maximum spectral responsivity between 800 - 900nm. The TIA has an 1MΩ, 8pF feedback resistor and capacitor respectively.

Retro-VLC [17] accomplishes duplex communication using LEDs and photodiodes. The system consists of a reader (downlink source) called ViReader and a mobile tag (uplink source) called ViTag. The ViReader which has access to a power supply houses both the LED light used to generate the signal and the photodiode used to receive data together on the ceiling. Whereas the mobile ViTag consists of a photodiode, a retroreflective cloth, an LCD screen and a solar panel. The ViTag uses light incident on the solar panel to power the tag and uses the retroreflective material to opportunistically backscatter light. On the ViReader side since the received signal would be weak a pre-amplfier is first used followed by another tuned differential gain amplifier.

Paul Dietz et al. [7] and Stefan Schmid et al. [23] demonstrate and utilize the fact that LEDs when reverse biased can be used as photodiodes. LEDs and resistors in series are connected to microcontroller I/O pins which can be toggled between high and low states really quickly. LEDs can be changed from being forward biased photon emitters to reverse biased photon receivers by toggling the I/O pins. This technique enables the reuse of the same LEDs for both transmission and reception with complete control over toggling. The drawback being LEDs are not designed to be used as sensitive photoreceivers, hence the quality of received signal might be below par and sensing range of the photodiode would be much lower.

CeilingSee [28] uses the same technique as described above but modifies a few luminaries that are a part of the LED bulb deployed on the ceiling. Another significant difference is the distance between transmitter and receiver. In the case of CeilingSee the entire sensing and lighting unit is self contained and light reflected off the floor is sensed. [7], [23] use individual LEDs which are placed in close proximity (within a few inches) and have direct line of sight, while CeilingSee leverages a LEDs from an array of LEDs.

2.5 CMOS Based Sensors

The complementary metal-oxide-semiconductor (CMOS) sensors present in smartphone cameras have also been used as receivers for visible light communication purposes. A technique called 'Rolling Shutter' is made use of by Christos Danakis et al. [6]. It works as follows: a CMOS sensor consists of multiple rows of CMOS pixels arranged in a grid. Each pixel has color filters (red, green, blue) covering the photodiode beneath to filter incident light. Light incident on the photodiode through these filters gives rise to voltage. The camera works by sequentially activating each row of pixels and capturing light row by row. When a picture is taken, rows are activated one by one sequentially to capture light. Individual row data is then stitched to form the final image. Rolling Shutter coupled with LED lights flashing at a high frequency enables retrieval of data each time a row of pixels is scanned. This enables high speed data transfer.

Luxapose [14] attempts to modify off the shelf lights to act as transmitters while using the CMOS sensors present in smartphone cameras as the receiver. Luxapose is able to determine the location and orientation of the smartphone relative to the deployed lights by capturing a single image and identifying the positions of at least three light sources. Shinya Iwasaki et al. [13] and Toru Nagura et al. [21] also use rolling shutter for visible light communications. Epsilon [15] makes use of LED lights to act as beacons and light sensors present in smartphones as receivers. Received signal strength (RSS), incidence angle are found through these beacons and then used to localize the smartphone.

2.6 Summary

The limitations of the aforementioned systems are summarized as follows:

Photoelectric sensors require transmitters, receivers and / or retroreflective materials to be deployed. It might not always be possible and feasible to deploy these in an area (room, office space etc). They come with their own source of light and do not make use of existing light sources in the room. Visible light based systems whose receivers are deployed on the floor are cumbersome to install. Systems which use receivers on the ceiling depend on reflections from special reflectors which need to be carried or deployed again. Solutions which use LEDs as photoreceivers by reverse biasing them suffer from low sensitivity and response times. PIR sensors detect motion when the object moves across both the sensors. When the relative change seen by the sensors is same, no motion is detected. They tend to be more prone to errors and are likely to pick up other spurious IR signals as well. Camera based sensors are affected by light level changes during the day, they are computationally heavy and there are always fears of privacy violation. Most systems require dense deployment of sensors on the ground, or the user to carry a device or require direct line of sight (LOS) between transmitter and receiver. This limits the environments in which systems can be deployed.

An ideal receiver should be housed along with the transmitter on the ceiling and should be sensitive and fast enough to pick up light level changes on the floor. This would require minimum infrastructure overhead and would make deploying it in different environments easy.

Chapter 3

Approach

3.1 Introduction

The problem statement

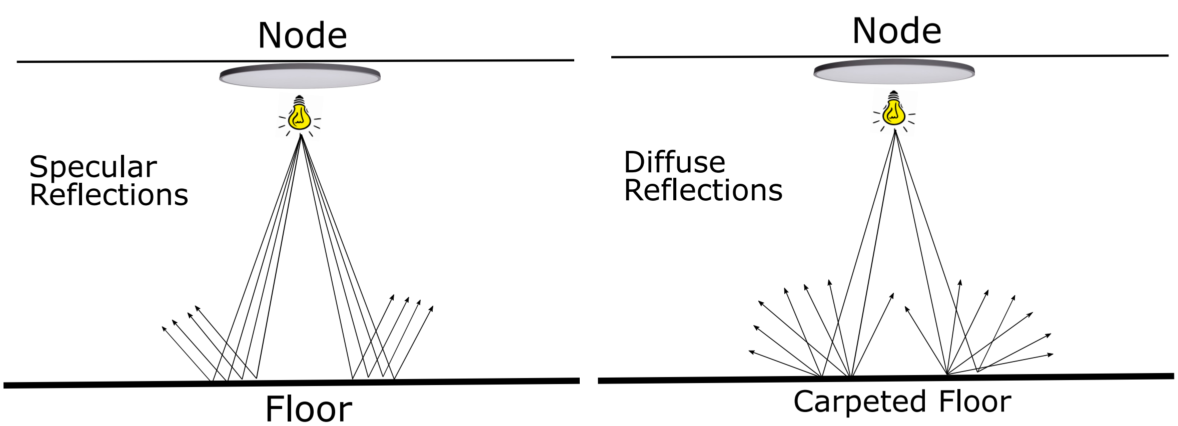
Is it possible to design a sensitive enough ceiling based photoreceiver that is able to detect minute light level changes that occur on any floor, including dark carpeted surfaces?

can be answered by considering it in smaller portions which are:

1. The photoreceiver needs to be located on the ceiling
2. The photoreceiver should be sensitive enough to detect light level changes occurring on any floor, including dark surfaces.

Given that the photoreceiver is located on the ceiling the total amount of light available at the ceiling can be estimated. It is known that light intensity decreases as a square of the distance travelled. This means the photoreceiver on the ceiling receives light which originates from the LED lamp, travels the distance from the ceiling to the floor and then reflects back to the sensor; effectively traversing the distance between the ceiling and floor two times (18 feet in this case). Even if various floor surfaces are assumed to be perfect reflectors which they clearly are not, at best a maximum of only one-fourth (light has to travel twice the distance between transmitter and receiver) of the initial light intensity can be received.

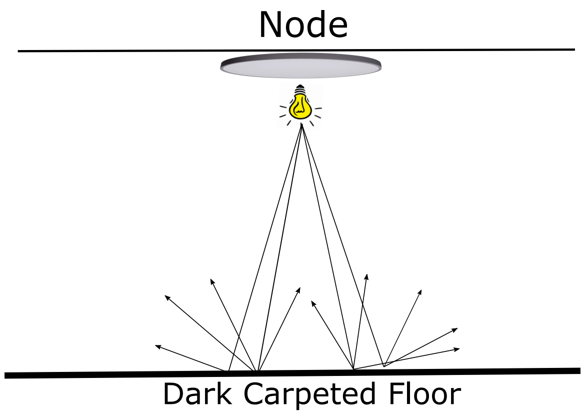
This naturally leads to investigating the reflective properties of the floor next. There are two types of reflective surfaces; diffuse and specular. Specular surfaces are smooth and reflect incident light in a definitive and concentrated manner as shown in Fig 3.1a. Diffuse surfaces are rough and reflect incident light in various directions as shown in Fig 3.1b. These observations are important as specular surfaces reflect more light than diffuse surfaces, making it harder to detect shadows on diffuse surfaces. The next detail to take into consideration would be the color of the floor surface; soft color tones closer to white (cream, beige, off white) reflect more light be it a diffuse or specular reflecting surface as shown in Fig 3.2b. Whereas, darker color tones close to black (dark blue, maroon) absorb more light making it harder to detect incident shadows on them as shown in Fig 3.2a.



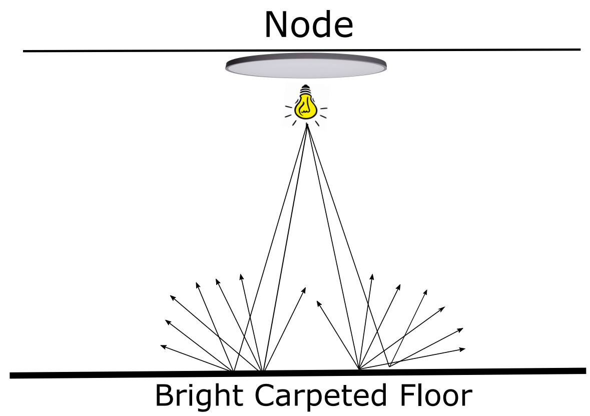
(a) Specular reflection (b) Diffuse reflection

Figure 3.1: Light reflections off (a) Regular specular surface (b) Regular diffuse surface

It can be said that it would be hardest for a photoreceiver located on the ceiling to



(a) Diffuse reflection



(b) Diffuse reflection

Figure 3.2: Light reflections off (a) Diffuse dark surface (b) Diffuse bright surface

be able to detect minute light level changes on a dark carpeted floor. The nature of carpet to diffuse light added with the dark carpet color makes it hard to sense shadows cast on an already dark background. Hence, any photoreceiver that is able to detect light level changes on such a floor surface should be able to sense light level changes on other more reflective surfaces.

Light levels / intensity is measured in terms of lux, where 1 lux is defined as 1 lumen per square meter. And lumen is a measure of total amount of visible light emitted from a source. The end goal is to design a photoreceiver which is located on the ceiling and is able to accurately detect and measure minute amounts of lux being reflected off even dark diffuse floors.

3.1.1 Circuit Design Overview

Key design ideas to enable light detection on dark carpets

- A sensitive transducer (photodetector) which is able to detect low light levels of reflected light (photons) and convert to current (electrons).

- An operational amplifier to convert this generated current to a usable voltage and amplify it.

- Instrumentation amplifier to measure exact changes in detected light with respect to a calibrated baseline light level. The amplifier has an optional gain to amplify the small voltage corresponding to light level change.
- Voltage divider and follower circuits to ensure that final voltage output is within acceptable range of the microcontroller I/O pin.

The front end of the circuit needs to be able to sense light or darkness. This can be accomplished with the help of photodiodes or phototransistors. Photodiodes and phototransistors convert incident light into small currents proportional to the incident light. The amount of light incident on the photodetector is a few lux (light has to travel from the ceiling reflect off a diffuse dark surface and reflect back to the photodetector) and the photodetectors generate one electron per incident photon. Hence the current generated is usually very small (in microamperes) and might need to be amplified before it can be used. Also, it is preferable to deal in terms of voltages rather than currents as different components (resistors, capacitors, amplifiers) in the circuit and analog to digital converters in the microcontroller use voltage inputs. But, since the generated current is small it needs to be amplified and converted to a voltage before it can be used.

The standard and well documented way of converting a small current to a voltage while having sufficient gain control is accomplished by using a transimpedance amplifier (TIA). A transimpedance amplifier is built using an operational amplifier (op-amp) with a feedback resistor and capacitor and a photodiode / phototransistor connected as input to the inverting terminal of the op-amp. The gain of the TIA is adjusted by tweaking the feedback resistor and capacitor values. The photodiode / phototransistor and TIA together form the sensing block of the circuit. They collect light and convert it to a large enough voltage that can be further processed.

The voltage being output by the TIA depends on the amount of light incident on the receiver. All changes in detected light levels are reflected as changes in the TIA output voltage (V_{op}). Hence to obtain a measure of change in light levels all that is needed is to measure the changes / fluctuations in the voltage output by the TIA. To calculate the delta amount of change in light, the voltage corresponding to the changing light levels due to additional light or shadow needs to be subtracted from the voltage corresponding to the existing light level. This means that there is need to assign a voltage to the existing light level as the TIA outputs voltages correspond to light conditions in real time.

An empirically calculated voltage is assigned to the existing light level. The real time output voltage generated by the TIA (V_{op}) is then subtracted from this empirically calculated voltage using an instrumentation amplifier. An instrumentation amplifier subtracts the voltages input to it while providing gain control and an option to bias the final output with a reference voltage. The voltage value obtained after subtracting the two voltages represents the change in light level. This voltage is usually in millivolts and is too small to be of practical use. The instrumentation amplifier further amplifies this voltage and adds a fixed reference voltage as well.

This voltage output from the instrumentation amplifier which represents the change in light levels is fed to a microcontroller. The voltage from the circuit is analog whereas the microcontroller works with digital values. Input voltage is converted to a digital value using an Analog to Digital Converter (ADC) present in the microcontroller at the input pin. Additionally voltage to the input pin of the microcontroller is fed through a voltage divider to provide higher control and to maintain the input voltage at the center of the ADC conversion range.

The overall circuit consists of a photodiode / phototransistor to sense light, a transimpedance amplifier to convert photocurrent to voltage, an instrumentation amplifier to calculate the change in light levels and a final voltage divider to clamp the final output voltage to within the voltage conversion range of an analog to digital converter (ADC). The final voltage output from the circuit is intended to be fed as an input to the analog to digital converter pin of a development microcontroller board (Arduino/MSP430/MSP432). The entire circuit is powered using a single 15V DC supply. Finally a 4cm tube is attached to the photodiode to make the sensor unidirectional. The overall circuit is as shown in Fig 3.3.

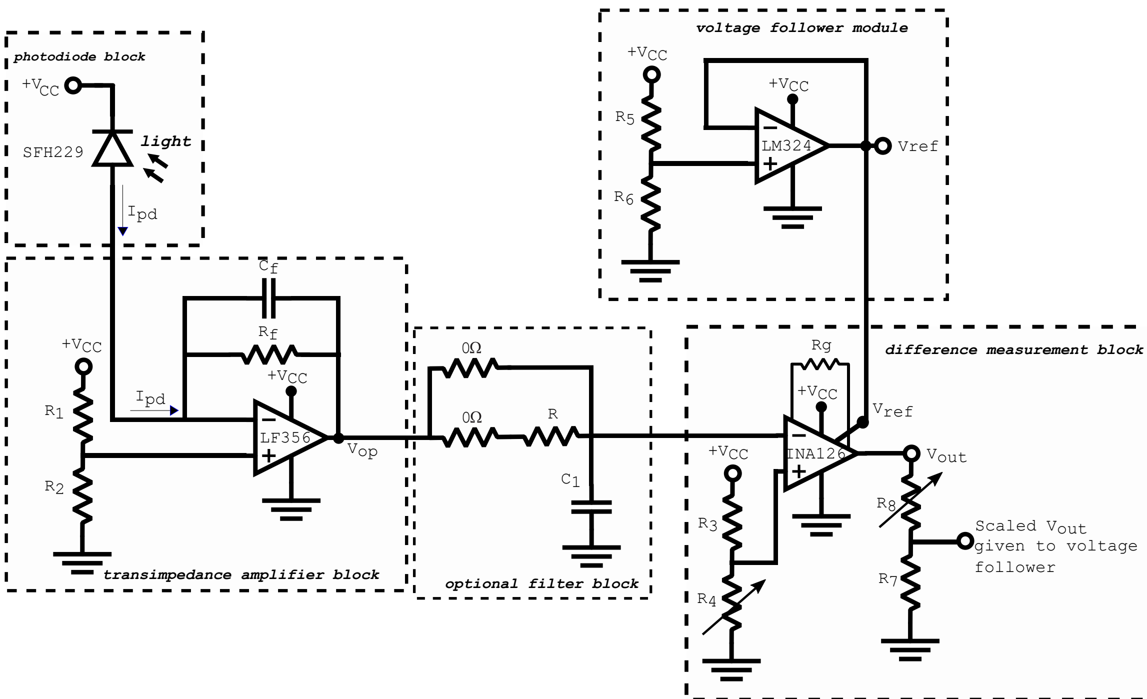


Figure 3.3: Complete circuit

With this understanding of what needs to be designed, this chapter delves into the specifics of the circuit design and discusses the required components, why they were chosen and how a particular design choice was finalized.

The following sections discuss the working and operation of the circuit in separate blocks while explaining how each block fits into the big picture.

3.1.2 Design Challenges

However before proceeding the following points are to be noted

- The LED lamp(s) which are used to illuminate the room flicker at a particular assigned frequency (i.e. the lights are not ON the entire time, but the LED lamp switches ON and OFF periodically), also, as there are multiple lights in the room, each light switches ON and OFF at its own assigned frequency.
- The designed sensor is intended to be used as part of a bigger indoor localization, occupancy and motion detection technology and being able to detect shadows in this flickering light scenario is a design requirement.

3.2 Block I: Photodetectors

3.2.1 Background

The first block of the designed circuit requires a sensor that is able to sense visible light and convert it to a current or voltage. This is accomplished by photodiodes or phototransistors.

Photodiodes are semiconductor devices which release electrons when photons (packets of light) are incident on them. Depending on the intensity, duration and frequency of light incident on a photodiode it displaces electrons in the semiconductor which produce current. This is the exact opposite of how light emitting diodes (LEDs) work; LEDs when provided with a voltage get excited and release photons at a particular visible light frequency, this is what gives the emitted light a particular color. LEDs can be reverse biased (connecting the positive terminal of power supply to the negative voltage terminal of the device) to make them act as

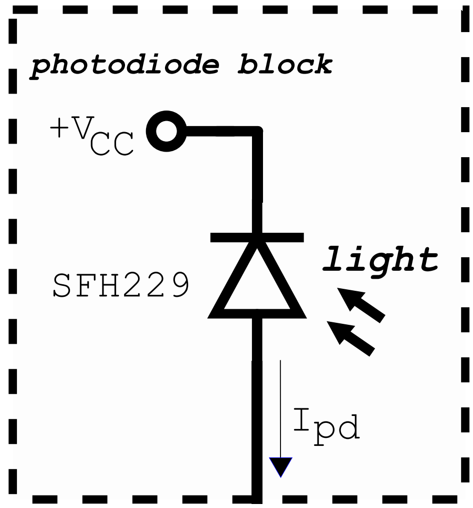


Figure 3.4: Photodiode generating photocurrent

photodiodes.

There are predominantly four types of photodiodes:

1. PN photodiodes which have doped p and n type semiconductors, they were the first photodiodes to be developed but are not used as widely today as other photodiodes provide better performance.

2. PIN or p-i-n photodiodes which have an intrinsic semiconductor (not doped) layer between the doped p and n type layers. They are the most widely used photodiodes today. PIN photodiodes have lower capacitance and are more efficient than PN photodiodes.

3. Avalanche photodiodes (APD) are ideally PIN photodiodes with higher gain and are designed to typically work in low light regimes. Though APD's provide high levels of gain they come at the price of high noise levels.

4. Schottky photodiodes offer very high speeds but are mostly used for large bandwidth communication purposes or in charged couple devices.

But as a general characteristic, photodiodes have fast response times (rise and fall times) but lower gain, (i.e. the time for the signal to rise to from 10% to 90% or fall from 90% to 10% of the final output voltage value is really quick, but the amplitude of the output signal is not high.)

Phototransistors on the other hand are semiconductor junction transistors (the semiconductor forms the base region of a transistor), this means that when light is incident on the semiconductor it releases electrons which completes the circuit and allows current to flow from the collector to the emitter pin while amplifying the current input at the base (transistor action). Phototransistors are almost a 100 times more sensitive than photodiodes and have an inherent gain/amplification as well. They have slower rise and fall times (large response time) but the amplitude of output voltage is higher.

3.2.2 Component Selection

Having discussed photodiodes and phototransistors, the exact design requirements are looked at to converge on a particular photodetector. The designed circuit is intended to be used along with commercial off the shelf LED lamps (Cree ECS BR30 Bright White) which emit white light at an intensity of 650 lumens / 65WE and flicker at a frequency of 1kHz. The photodetector needs to be able to detect (see) ON and OFF periods clearly from the light being reflected from the floor, while being able to detect(see) minor changes in light level on the floor. The amount of light that reaches the ceiling after being reflected off the floor lies in the range of 10 - 300 lux subject to the amount of ambient light present in the room (this was found empirically by conducting field experiments using a lux meter). The photodetector needs to be sensitive to light intensity in the above range and produce a satisfactory and usable output current or voltage.

From the discussion earlier, it is seen that a phototransistor or a PIN photodiode maybe a good fit. The design requires the photodetector to have a fast rise and fall time to be able to detect a flickering light, a high gain to be able to detect this flickering off the floor, and low noise levels to be able to distinguish minute changes in light levels. The photodetector should work in the wavelength range of 400 - 700 nm, the rise and fall time of the photodetector should be faster than 1kHz (1ms OFF time) to be able to correctly differentiate between different flicker times (slots) of light and the photodetector should introduce as little noise as possible during detection.

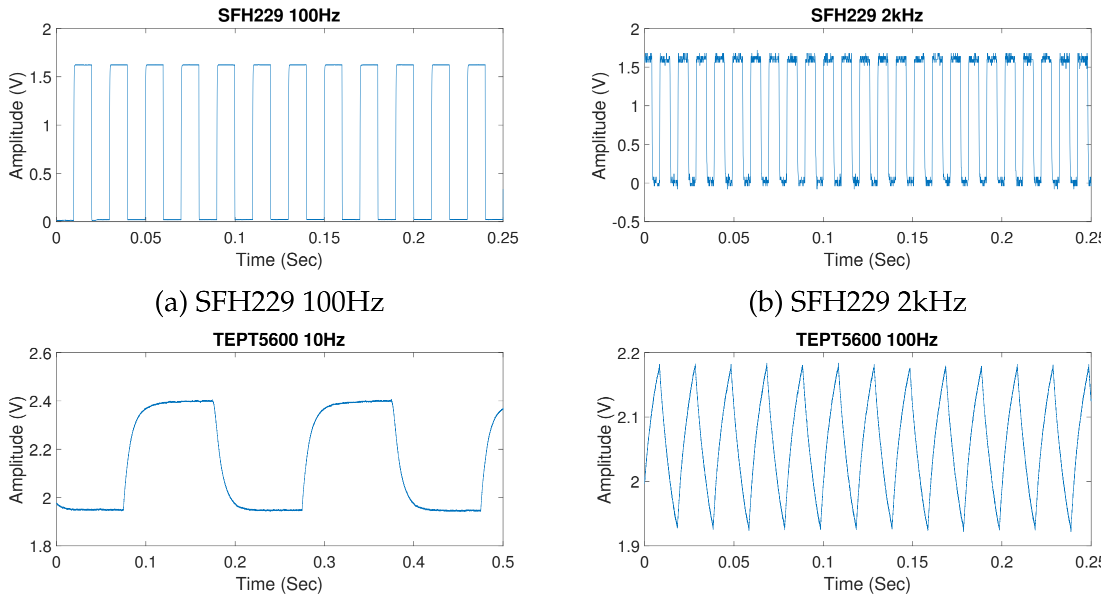
From the various products readily available in the market, the NPN phototransistor TEPT5600 and PIN photodiode SFH229 might meet these requirements and warrant deeper investigation. Table 3.1 summarizes the characteristics of the TEPT5600 and SFH229.

Characteristic	TEPT5600	SFH229
Operating range	440 – 800 nm	380 – 1100nm
Photocurrent at 400 lx (Max at 1000 lx)	1500 μA (Max 3500 μA)	10 μA (Max 28 μA)
Switching time	100ms (empirically calculated)	10ns
Angle of half sensitivity	$\pm$20 degrees	$\pm$17 degrees
Dimension	5mm	3mm

Table 3.1: Comparison of important photodiode and phototransistor characteristics

As can be seen from the table the TEPT5600 has a higher gain (more photocurrent for same amount of incident light) than the SFH229, but a slower rise and fall time. This is corroborated with our own experimental setup as seen in Fig 3.5a, Fig 3.5d. The TEPT5600 is unable to recover fast enough beyond 10 Hz, whereas the SFH229 works well even at 2 kHz. But a difference in the output amplitudes is seen.

Due to its faster rise and fall time, typically about 10ns the SFH229 is selected to be used. This faster response enables it to detect high rate flickering of light clearly



(a) SFH229 100Hz (b) SFH229 2kHz

(c) TEPT5600 10Hz (d) TEPT5600 100Hz

Figure 3.5: Rise and fall times corresponding to frequency of flickering light

which the TEPT5600 is unable to do. The downside to using SFH229 is that the maximum output current is 28 μA at 1000 lux. The amount of light incident on the floor ranges between 200 - 500 lux but after factoring in reflection loss and ambient light the output current can be expected to lie between 4 – 20 μA.

15V DC is used to power all the components of the circuit. Hence the SFH229 is operated under reverse bias using 15V DC as well. The current generated by the photodiode needs to be converted into a voltage for it to be of any practical use. The simplest way to convert a current into a voltage is by using a resistor as shown in Fig 3.6. Using a large enough resistor enables us to convert even a small current to a large voltage. According to Ohm's Law, $V = I * R$, a sufficiently large resistor in mega ohms (MΩ) can be used to amplify microamperes (μA) of current while converting it to a voltage. But this way of converting a current into a voltage has a slow response time (the output rolls off starting at $f = 1/(2 * pi * R_L * C_d)$ due to the large resistance and internal capacitance of the photodiode, whereby rendering such a setup to convert current to voltage in-feasible.

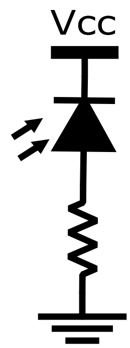


Figure 3.6: Single photodiode and resistor

3.3 Block II: Transimpedance Amplifier

To overcome the slow response time while converting the current to a voltage a transimpedance amplifier (TIA) is used. The transimpedance amplifier consists of an operational amplifier (op amp), a sufficiently large resistor (R_f) connected as feedback to its inverting terminal and a capacitor (C_f) connected in parallel to the resistor as shown in Fig 3.7.

But before delving into how a TIA converts current to voltage there are two important properties of operational amplifiers that need to be kept in mind:

1. the inputs of the op amp draw no current
2. the output of the op amp does whatever is necessary to bring the voltage difference between input terminals to 0V.

The transimpedance amplifier works as follows: the current generated by the photodiode is fed to the inverting pin of the operational amplifier, the LF356. Since the op amp terminals draw no current all the current passes through the feedback resistor R_f connected between the inverting and output terminals, in essence this resistor converts the input current to a voltage.

But the input current from the photodiode is AC in nature, this is because current

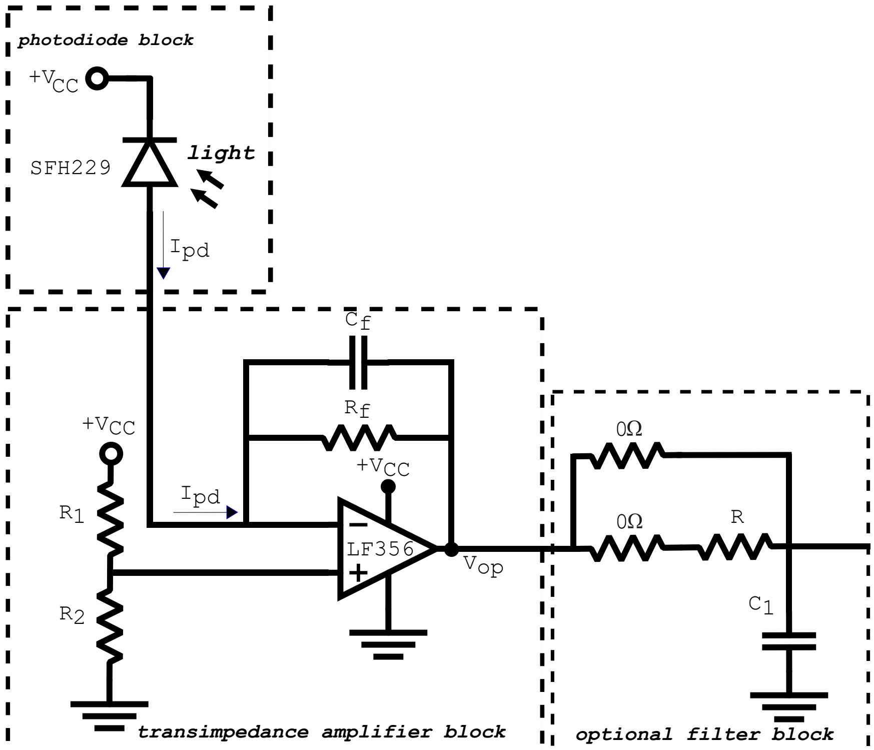


Figure 3.7: Transimpedance Amplifier

is generated only when light with sufficient energy is incident on it. Converting a continuously varying current to a continuously varying voltage has the potential to make the op amp output oscillate, noisy and unstable. Added to this op amps have the tendency to generate unwanted oscillations, so a capacitor C_f is connected in parallel to the resistor R_f as feedback to form a RC filter to avoid oscillations and to improve overall response time (with sufficiently small RC time constant). How the exact values of R_f and C_f are chosen is discussed in the implementation section.

The input provided to the non inverting terminal of the op amp is discussed next. The non inverting terminal is fed a bias voltage which is generated using a voltage divider. The non inverting terminal is fed a bias voltage for two reasons: (i) to ensure that even if there is no current being supplied by the photodiode, the op amp continues to produce the bias voltage as a stable output, (ii) to ensure that the output voltage from the TIA V_{op} always wiggles about this voltage. This is possible due to the second property of the op amp.

Recollect that the second property of op amps ensures that the output voltage tries to do whatever is necessary to make sure that the difference in voltages between its two input terminals is 0V. This means irrespective of the photocurrent I_{pd} input to the TIA the output voltage would always be maintained around the bias voltage. From the following equation it is apparent that a higher I_{pd} would result in a lower V_{op}. This is intuitive as well, a larger current produces a larger voltage across the feedback resistor, which means the op amp has to output a smaller voltage to ensure voltage between its input terminals is 0V.

The output of the TIA is given by,

$$V_{op} = V_{cc}/2 - I_{pd}R_f$$

The biasing voltage is generated using a voltage divider circuit supplied with 15V DC. To ensure output stability and maintain V_{op} around $V_{cc}/2$ the biasing voltage is set equal to $V_{cc}/2$. R_1 is set equal to R_2 to generate $V_{cc}/2$ from V_{cc}. An optional low pass filter is added after the TIA block to eliminate any unwanted AC noise before feeding V_{op} to the INA126.

3.4 Block III: INA126

After the TIA converts the incident photoreceiver light to voltage the next step is to distinguish between minute light level changes. Minute changes in light levels can be interpreted electronically as voltage changes or wiggling about (up or down) a particular TIA output voltage V_{op}. This magnitude of wiggle voltage would be equal to $[(ii) - (i)]$ where

- (ii) the voltage corresponding to when there is only ambient light and light being reflected off the floor with no shadows cast. This voltage can be thought of as the initial room setting calibration voltage.
- (i) the voltage corresponding to when there is ambient light and shadows are cast.

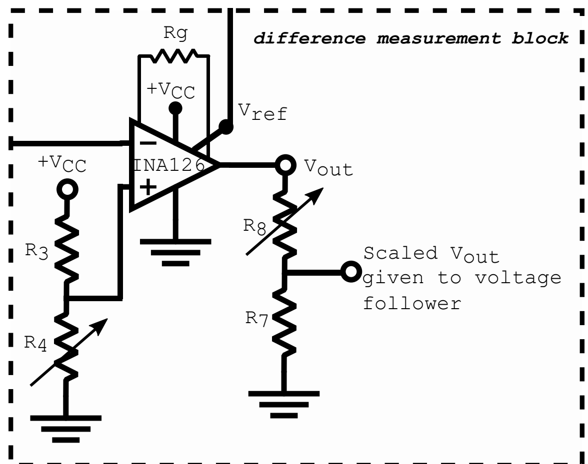


Figure 3.8: Difference measurement circuit

The idea is to calculate voltage values (i), (ii) separately and then calculate the difference. This difference would represent the minute light changes in volts. The value of (ii) is calculated empirically by switching on the light setup in a room with no people in it and finding the mean of values collected by the photoreceiver over a brief period of time. It is expected to be a steady output voltage with no drastic variations. The floor surface type and height of deployment are also noted. The value of (i) is the TIA output voltage being generated in real time. The magnitude of these wiggles $[(ii) - (i)]$ were experimentally determined to lie in the order of millivolts.

Another useful design observation is that in electronic circuits it is easier and less erroneous to measure a change in voltage with respect to a non-zero voltage rather than 0V (i.e. calculating 5.2V - 5.1V would be more accurate and less error prone that calculating 0.1V - 0V, even though the final value of both would be 0.1V.) So the need to find a calibration voltage and then subtracting the sensed real time light level voltage from it is fortunate. Next, how this difference in voltages is calculated using an instrumentation amplifier INA126 is discussed.

The INA126 is an instrumentation amplifier which amplifies the difference between two input signals and suppresses any voltage common to the two inputs. The idea is to find the difference between the calibrated voltage and actively sensed voltage, and then amplify this voltage difference as needed. This is akin to magnifying or zooming in on just the subtle and minute light level changes, to obtain more information and control over the sensed light. The INA126 is chosen because of its low noise $35nV/Hz^{(1/2)}$, wide range of gains $(5-10000)$ and the option of being operated on a supply voltage of 15V.

The output of the INA126 is given by,

$$V_{out} = G * (V_{in}^{+} - V_{in}^{-}) + V_{ref}.$$

Where G is the variable gain, which is set using a resistor. The value of G can be calculated using the formula $G = 5 + 80k\Omega/R_g$. V_{in}^{+} is a fixed voltage fed from a voltage divider whose voltage is set to (ii) and is calculated as discussed earlier. V_{in}^{-} is the real time output V_{op} from the TIA and V_{ref} is a DC reference voltage. The V_{ref} pin (pin 5) must either be grounded or driven by a low impedance source.

As V_{ref} needs to be supplied from a low impedance source it is supplied through a voltage follower circuit whose output has a low impedance. The desired reference voltage is generated using a voltage divider circuit. This voltage is fed to a voltage follower circuit built using the op amp LM324 (quad op amp). The output of the voltage follower is connected to the V_{ref} pin (pin5). The voltage follower is built as follows: Output from the voltage divider is fed to the non inverting terminal

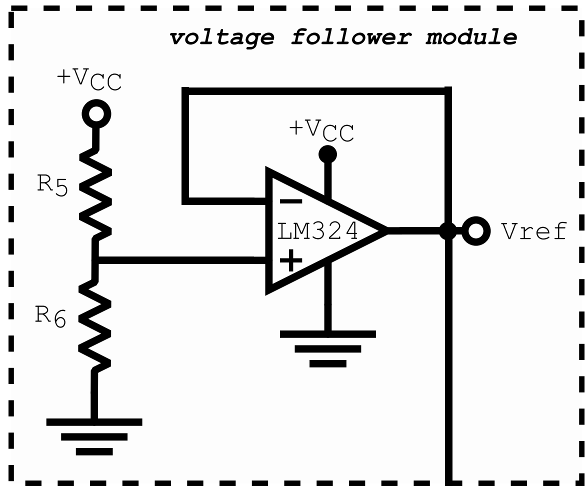


Figure 3.9: Voltage Follower

while the inverting terminal is connected to the output pin as negative feedback as shown in Fig 3.9.

Finally, the value of R_g used to set the gain depends on the amount of ambient light, type of floor surface and how much the difference between voltages needs to be magnified by. The selection of R_g is discussed in the implementation section.

3.5 Block IV: Output to Microcontroller

Output from the instrumentation amplifier V_{out} needs to be fed to an I/O pin on the microcontroller. There are two facets to this:

1. Ensuring that the final output voltage from the voltage follower is in the center of the Analog to Digital Converter (ADC) conversion range of the microcontroller.

   This is useful as there is more wiggle room for sensing values over a wider range. Also, analog to digital conversion at the center of the conversion range would be less prone to conversion errors. The ADC maps input voltages between 0-3.3V with a 10 bit resolution in MSP430 and 14 bit resolution in MSP432. That means a 1.67V input would be converted to 512 with each step equal to 0.003V for a MSP430 and 8192 with each step equal to 0.0002V for MSP432. But apart from the fact of having to maintain the final output voltage around the center of the ADC range, it is imperative that the voltage given as input to the ADC pins does not exceed the maximum voltage rating of the pin to avoid damaging it. To avoid such a situation the ever handy voltage divider is used. As the range of possible output voltages from the INA126 is known, a simple voltage divider whose output is limited to the maximum permissible I/O pin input voltage is built.

2. In order to drop maximum voltage across the I/O pin of the microcontroller the final output voltage should be from a low impedance source. This is accomplished using a voltage follower circuit built using the LM324, just as previously discussed. The scaled V_{out} from the voltage divider is fed to the non inverting terminal of the LM324 (the LM324 has 4 op amps) while the inverting terminal is connected to the output pin as negative feedback. This converts V_{out} from a high impedance source to a low impedance. This low impedance analog voltage is converted to a digital value at the microcontroller's ADC

3.6 Summary

This chapter explains how a ceiling based photoreceiver circuit can be built by breaking down the circuit design into four easy to understand blocks.

Block I describes the front end, namely the semiconductor devices (photodetectors) that can convert visible light to electrical signals along with their their pros and cons. It then narrows down the search based on certain design constraints such as rise and fall time and photodetector gain.

Block II describes the transimpedance amplifier used to speed up the response time of the photodetector, convert the current generated to voltage and then amplify this voltage to bring it to a usable level.

Block III describes and explains how an instrumentation amplifier is used to detect light level changes. Changes in light level are detected by comparing voltage corresponding to existing light level on the floor to the light level when a shadow is incident on the floor. A constant reference voltage assigned to the light level on the floor is compared to the real time voltage generated at the TIA.

Finally Block IV describes the properties of the Analog to Digital Converter (ADC) pin and the constraints that need to be satisfied to be able to send the final output voltage from Block III to a microcontroller.

Chapter 4

Implementation

4.1 Introduction

This chapter presents the final design of the photoreceiver along with the values of the individual components used. It then briefly discusses the process, component additions and design rules followed to realize the photoreceivers' final printed circuit board (PCB) form. The last section explains the working of the detection algorithm used to calculate the number of times the photoreceiver raw data detects a person crossing beneath it.

4.2 Overview of circuit

The final circuit as shown in Fig 3.3 has the following parts:

- A PIN photodiode SFH229. The SFH229 is chosen for its fast response time. The current generated is fed to the inverting terminal of the operational amplifier LF356.

- A transimpedance amplifying circuit built using the op amp LF356. A 10 MΩ resistor is connected between the output and inverting terminals as feedback. A 1pF capacitor is connected in parallel to the 10 MΩ resistor. The SFH229 is connected to the inverting terminal and a fixed voltage of 7.5V generated using a voltage divider is connected to the non inverting terminal. The output voltage V_{op} from the TIA is connected to the V_{in}^{-} pin of the INA126.

- An optional low pass filter is added between the TIA and the INA126.

- An instrumentation amplifier INA126. Output from a voltage divider circuit with the potentiometer tuned to $50K\Omega$ is connected to the V_{in}^{+} pin. Real time output voltage from the TIA is connected to the V_{in}^{-} pin. The gain resistor R_g is set to $3.6k\Omega$ when the floor is a dark carpeted surface and is left empty when the floor is a bright carpeted surface. The reference voltage V_{ref} is supplied from a low impedance source. It is generated using a voltage divider and passed through a voltage follower circuit built using a LM324 (quad op amp).

- Output from the INA126 is first passed through a voltage divider circuit built using a $10K\Omega$ resistor and a $50K\Omega$ potentiometer. This voltage is clamped to a maximum of 3.3V and the potentiometer is tuned to $36k\Omega$. The scaled V_{out} is fed to a voltage follower circuit built using a LM324 (quad op amp) to ensure the final output is from a low impedance source. The voltage from the follower circuit is fed to an I/O pin on the microcontroller.

4.3 Parameter Selection

The SFH229 is selected for its fast response time. The LF356 is selected to be used as the op amp for the TIA circuit because of its low noise, low source impedance, low $1/f$ noise corner and can be powered using a 15V DC supply. The feedback resistor of the TIA needs to be a large value to be able to provide a usable gain. Since the generated photocurrent is in microamperes a resistor that is at least a mega ohm is needed to generate a volt. Using a TIA enables the use of a larger R_f value without slowing the circuit down. But this presents new challenges such as: (i) increased Johnson thermal noise ($v_n = \sqrt{4k_BTR}$) (ii) low input roll off frequency (since $f_{RCin} = \frac{1}{2R_FC_{in}}$).

As the photodiode capacitance reduces feedback signal at high frequencies, the feedback loop needs to be phase compensated by a suitable feedback capacitance C_f placed in parallel with the feedback resistor. This feedback capacitance value is also constrained: too large a value would make the front end slow to respond, but too small value would create large overshoot and long ringing. Following design guideline [11] the bandwidth of interest is set to 10KHz to find a suitable amplifier and optimal values for R_f and C_f. Feedback resistor is set to $R_f = 10M\Omega$, and feedback capacitor is set to $C_f = 1pF$.

The output of the TIA is intended to be kept around $V_{cc}/2$ or 7.5V for output stability. Hence 7.5V is generated using a voltage divider circuit is fed to the non-inverting terminal of the op amp. Two 10 kΩ resistors supplied with 15V are used to form the voltage divider.

The voltage output from LF356 is fed to the inverting terminal of the INA126 which is an instrumentation amplifier. The INA126 is selected due to its low noise differential signal acquisition and wide range of gain which can be set using a resistor and option of adding a reference voltage. The output of the INA126 is given by

$$V_{out} = (5 + 80k\Omega/R_g)*(V_{in}^{+} - V_{in}^{-}) + V_{ref}$$

The non inverting terminal V_{in}^{+} is fed a voltage that represents the ambient light level. This voltage is fed through a voltage divider consisting of a 50 KΩ potentiometer and a 50 KΩ resistor. The potentiometer is tuned to 50KΩ. The tuning of the potentiometer is done empirically by first observing the output voltage from the TIA over a fixed period of time with the sensing environment, ambient lighting kept fixed and ensuring no light level changes occur. The average voltage over this time period is calculated and the potentiometer is tuned to produce this voltage.

A reference voltage is provided so that the output voltage from the INA126 is at least V_{ref}. It is preferable to have the final output voltage V_{out} move about a fixed reference voltage. This is to ensure that output voltage is not 0V (when ambient and sensed light are equal) or a negative voltage. To keep the output stable V_{ref} is selected to be $V_{cc}/2$ or 7.5V. It is generated using two 10KΩ resistors as voltage dividers.

The reference voltage input to the INA126 and the final output from the INA126 need to be from a low impedance source. In order to accomplish voltage follower circuits are built using the op amp LM324. The LM324 comes with four internal op amps.

Next the value of the gain resistor needs to be set. This is accomplished empirically and depends on the floor type. For dark surfaces the value of $(V_{in}^{+}$ - $V_{in}^{-})$ is not large and would need a higher gain value. This is done in an iterative manner by looking at the output voltage from the INA126 and then back calculating the required gain using the formula $G = 5 + 80\text{k}\Omega/\text{R}_g$ in order to bring the voltage into the desired range. For dark carpeted floor a gain of 27 is used. A 3.6KΩ resistor is connected between pins 1 and 8 on the INA126. For a light carpeted floor such a high gain is not necessary and a gain of 5 is sufficient. Hence, no resistor is connected and the connection between pins 1 and 8 is left empty.

Finally, V_{out} from INA126 should be a value between 0 and 3.3V and from a low impedance source before it can be fed to the ADC on the microcontroller. A voltage divider circuit with a 50 KΩ potentiometer and 10 KΩ resistor are used with the potentiometer tuned to 36kΩ. This scaled voltage is fed to a voltage follower circuit.

This circuit is first constructed on a breadboard to understand the workings of individual components, voltages at each step, interaction between different components their power requirements and to debug the circuit. It is then soldered onto a vector board in a more concise and space efficient manner. Finally after ironing out all the kinks and unknowns in the circuit design a printed circuit board (PCB) is developed.

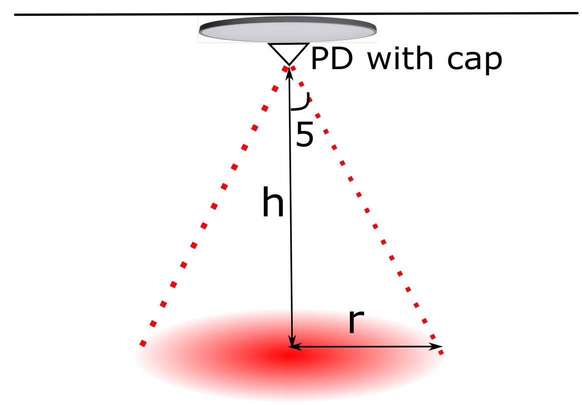


Figure 4.1: Sensing area under the photoreceiver

These PCBs are then deployed on the ceiling along with LED lamps. The PCBs point downwards and sense light level changes (shadows) of the floor. A final addition is a 4cm long cylindrical tube placed on the photodiode to make it directional. This makes sure that only light from where the photoreceiver is pointed will fall on it. It has an added effect of reducing the 17 degree half angle of the SFH229 to 5 degree half angle.

What is left is to calculate the area that is sensed by the photodiode after the cylinder is placed. This is accomplished using basic geometry. As shown in Fig. 4.1

the sensing area is circular, the radius can be found using, radius (r) = tan(sensing angle) * height (h). And area using, πr^2. The height of the conference room is 9 feet and sensing angle is 5 degrees. Radius (r) is found to be 0.7866 ft and area sensed 2.47 $sq.ft$.

4.4 Component Values

Component Name	Component Value
R_1	10kΩ
R_2	10kΩ
R_g	floor dependent
R_F	1MΩ
C_F	1pF
R_3	50kΩ
R_4	50kΩ pot
R_5	10kΩ
R_6	10kΩ
R_7	10kΩ
R_8	50kΩ pot
V_{CC}	15V
V_{op}	$\sim 7.5V$
V_{out}	$\sim 1.67V$

Table 4.1: Component values

The potentiometer R_4 is tuned to $50k\Omega$ and the potentiometer R_8 is tuned to $36k\Omega$. The gain resistor R_g is set according to the environment and floor type. It is set to $3.6k\Omega$ when using a dark carpeted surface and is left empty when using a light carpeted surface

4.5 PCB Design

4.5.1 Schematic

The PCB is designed using EagleCAD, the first step is to draw the schematic layout of the entire circuit as shown in Fig 4.2 The following additions are made to the final designed circuit to enhance its performance, increase flexibility and to follow good design practises:

1. A 0.01μF source capacitor (i.e. the source voltage is first connected to a capacitor which is connected to ground before being supplied to an IC) is connected to each integrated circuit (IC) to eliminate any source noise and protect IC's against sudden voltage spikes. These capacitors are placed as close to the IC as possible. Three test points (exposed copper pads connected to specific points of the circuit) are added to help check the voltage at the output of (i) the LF356 (ii) the filter connected to LF356 (iii) and the INA126.

2. There are two paths added for the output voltage from the LF356 to the INA126, (i) the option of using a RC filter after the LF356 or TIA stage. This low pass filter (a resistor and capacitor in series with the capacitor grounded) can be used to filter out any unwanted oscillations or noise that might have crept into the signal because of the op amp. This filter is added for flexibility for the future.

   (ii) A path of not using the filter for the output voltage from the LF356. Both paths have a 0 Ω resistor in series. A path is selected by soldering a 0 Ω resistor to form a connection. All the grounds are connected to a single GND and all the source voltages are connected to a single V_{cc}.

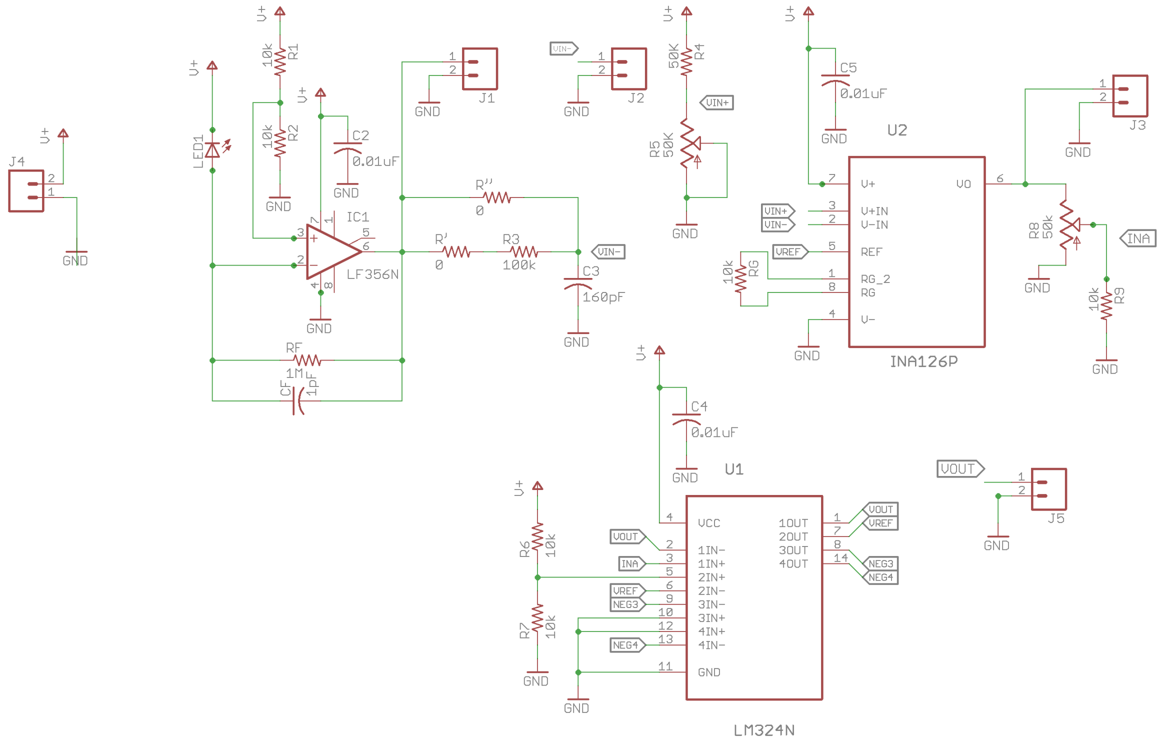


Figure 4.2: Schematic

4.5.2 Layout

EagleCAD generates footprints for all of the components in the schematic along with their connections. It is up to the designer to choose the number of layers in the PCB. This PCB as two layers; top (red) and bottom (blue) as shown in Fig 4.3. The bottom layer is defined as ground and top as V_{cc}. Components are placed (dragged and dropped) in a way such that the traces (connections) do not form right angles, the AC and DC parts are isolated and the source capacitors are as close as possible to the IC's. Component placement must ensure that they are easy to solder, easily accessible to add or remove and the entire circuit occupies as little space as possible as cost of the board goes up with more surface area.

Resistors and capacitors of 0805 package size $(2mm * 1.25mm)$ dimension are used as they are not too small nor too big to place and handle. Through hole (dual inline package (DIP) IC's are used. Sockets (6 or 8 pin) are soldered into the through holes to enable swapping out of faulty IC's if any. Each pad and component footprint is marked with the value of the component to help place and solder components. The final layout is exported layer wise as .gerber files. These files are sent to a fabricator to print out the PCB as shown in Fig 4.4.

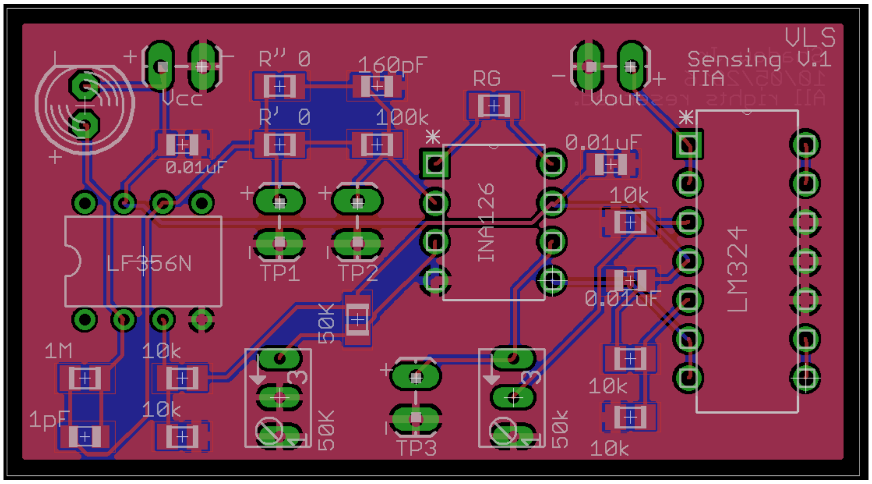


Figure 4.3: Layout

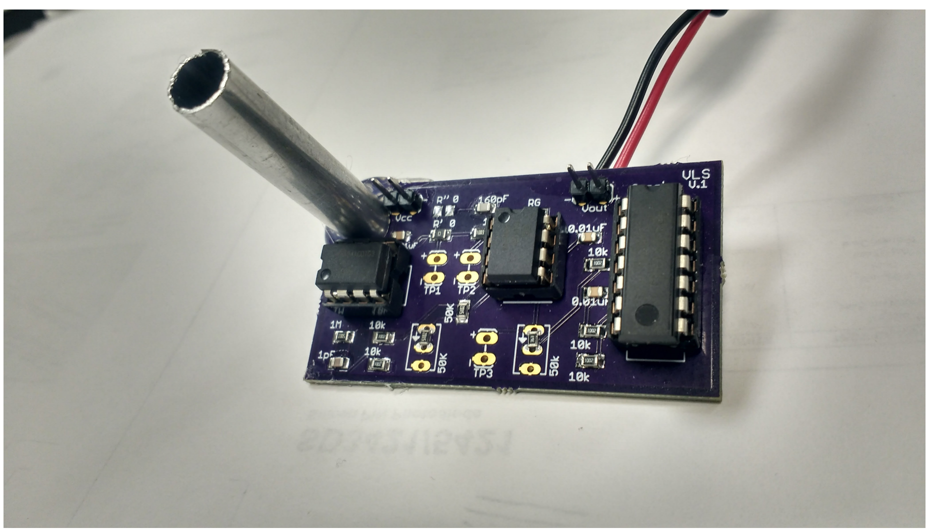


Figure 4.4: Final printed circuit board (PCB)

4.6 Detection algorithm

Input : Data: photoreceiver *raw reading* from node

Output: Detection: Number of detections

setWindowSize;

setThreshold;

setConfidence = WindowSize;

for $i = 1 \rightarrow length(Data) - WindowSize$ **do**

  if *mean (Data(i to i + WindowSize)* $\geq$ *Threshold* **then**

    set $count(i)$ to 1;

  else

    set $count(i)$ to 0;

  end

end

for $i = 0 \rightarrow length(count)/Confidence - 1$ **do**

  if *sum(count(window*$_i$*)* $>$ *Confidence/*2 **then**

    increment Detection by 1;

  end

end

Algorithm 1: Detection algorithm

A detection algorithm is used to count the number of detections seen by a photoreceiver based on its raw readings. The intuition behind the algorithm is to check for a significant change from the ambient light level over a fixed number of samples (i.e. window size). If there is indeed a change it is likely that a person caused this change. The algorithm works as follows:

The average ADC reading over a sliding window is compared to a threshold. If the average over this window is greater than the threshold, then the index corresponding to that window in a counter array is set to 1 else it is set to 0. Repeating this process yields an array of 1's and 0's in the counter array corresponding to each window (i.e. suppose a window size of 200 is chosen, the average value of samples 1 to 201 is compared to a threshold, if the average value is greater than the threshold, the index 1 in the counter array is set to 1. This window then slides right to compare the average value of samples 2 to 202 to set1 or 0 in index 2). The final length of the generated counter array is: *(total number of samples - window size)*

In essence a value of 1 or 0 is generated and stored in the counter array for each data point of the raw data. The 1's and 0's in the counter array are further processed to count the number of detections. The counter array is divided into chunks each the size of the previously selected window size. A confidence vote is taken over each of these windows to declare a detection or not (i.e. if the number of 1's is greater than half of the window size a detection is declared).

Chapter 5

Experiments and Results

5.1 Introduction

This chapter describes the conducted experiments, experimental settings and reasoning behind conducting a particular experiment to evaluate the design of the photoreceiver. All experiments are conducted in a conference room 19′ by 24′ with all the elements of the conference room kept static (i.e. table and chairs are not moved or shifted during or after an experiment). Experiments are repeated for two different floor surfaces; diffuse dark carpet and diffuse bright carpet. This is to ensure that the receiver works satisfactorily under conditions that are conducive to detecting shadows (bright floors with good light reflectivity) and under hostile conditions (dark diffuse floors with poor light reflectivity). Any changes made to the room are described along with the particular experiment.

As the aim of the thesis is to design a sensitive photoreceiver, the following parameters of the sensor are tested:

- **Response of the photoreceiver in low light conditions**

Finding how the photoreceiver behaves in low light regimes is a good indicator of its sensitivity. It provides information of output values corresponding to low light and the minimum amount of light in lux that can be sensed.

- **Change in measurement value with change in distance from a light source**
  As a source of light is moved away from the photoreceiver the total amount of light incident in the sensing area decreases. Finding the photoreceiver response for increasing distance from a light source is useful in gauging sensitivity of the photoreceiver as a function of distance.

- **Accuracy in detecting number of crossings**
  Merely being able to sense shadows on the floor does not provide the complete picture of photoreceiver performance. The photoreceiver needs to reliably and consistently sense shadows hence the accuracy of the photoreceiver is important as well.

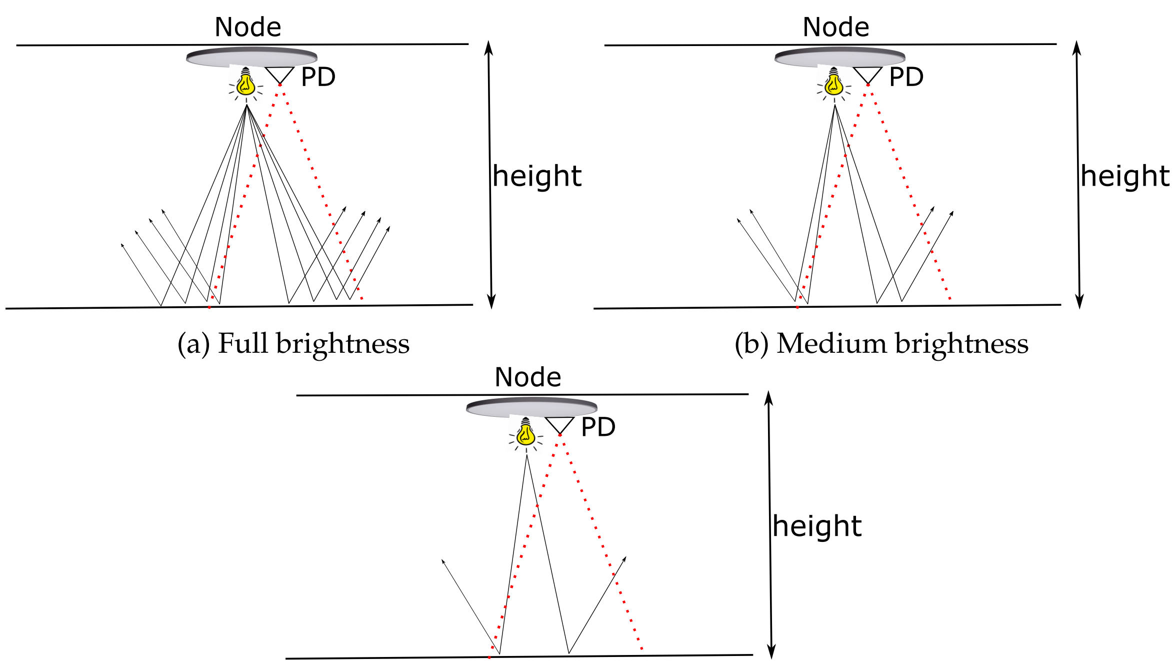
Each individual light source in the conference room contributes a certain amount of light. All of these individual contributions together can be considered as the ambient light present in the room. When all the lights are switched on this ambient light floods the entire room and can be thought to provide a constant light level value on the floor. For the first two experiments which evaluate the sensitivity of the photoreceiver the ambient lights are switched off. For the last experiment shadows are detected with ambient lights switched on.

The last section of this chapter discusses a detection algorithm used to count the number of times a person walks beneath a particular photoreceiver based on raw input data.

5.2 Response of the photoreceiver in low light conditions

The aim of this experiment is to map ADC Readings to light levels (lux) on the floor and to ascertain the minimum amount of light the photoreceiver can sense when pointed at different floor surfaces. It is important to note that light levels at the floor are reported, which means even fewer lux of light reach the receiver at the ceiling.

To conduct this experiment a single node is deployed on the ceiling of the conference room with a single photoreceiver pointed directly down towards the floor as shown in Fig 5.1. A single 65W Equivalent LED lamp which can produce up to 650 lumens is made to glow at full brightness. It is then slowly dimmed until there is complete darkness in the conference room. No other light in the conference room is switched on.



(a) Full brightness

(b) Medium brightness

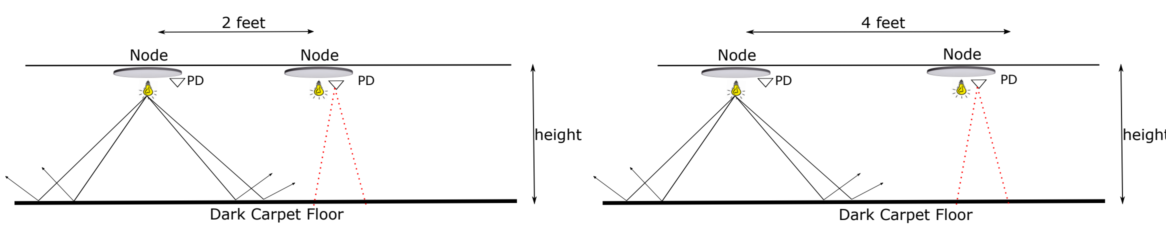
(c) Dim light

Figure 5.1: Dimming light

ADC readings input to the microcontroller by the photoreceiver on the ceiling are noted corresponding to the light levels (in lux) on the floor directly below the LED lamp. Light levels in lux are measured using an Amprobe Digital Light Meter. The experiment is repeated by changing the floor surface from a diffuse dark carpet to a diffuse white carpet.

5.3 Change in ADC readings with distance from light source

As discussed in the Implementation section the area sensed by a single photoreceiver is 2.47 $sq.feet$. Only light incident in this area can be sensed by the photoreceiver. A key factor that affects the amount of light or shadow incident on the sensing area is the distance of the light source from the receiver. This experiment is used to quantify that relationship.



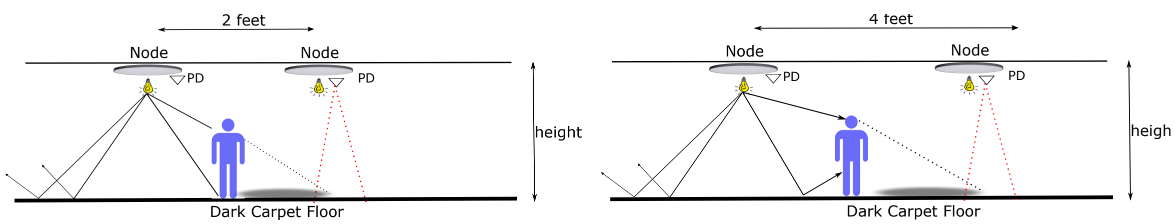
(a) 2 feet distance

(b) 4 feet distance

Figure 5.2: Increasing distance between nodes

Similar to the previous experiment a single node is deployed on the ceiling of the conference room with a single photoreceiver pointed directly down towards the floor. A single 65W Equivalent LED lamp which can produce up to 650 lumens is made to glow at full brightness. This photoreceiver node is then placed 2, 4, 6, 8 feet away from the light source and the corresponding ADC Readings with increasing distance are noted. The LED lamp present with the photoreceiver is switched off for this experiment. The experimental setup is as shown in Fig 5.2. Only diffuse dark carpeted surface is tested.

Next, to calculate the amount of change in light level the photoreceiver can sense with increasing distance from a source of light a person is made to walk across the sensing area similar to Fig 5.4. This is done each time the receiver is moved by 2 feet and is illustrated in Fig 5.3.



(a) 2 feet distance (b) 4 feet distance

Figure 5.3: Shadows with increasing distance between nodes

5.4 Accuracy in detecting number of crossings

The main requirement of the designed receiver is to sense shadows to enable applications such as motion, activity, occupancy detection and indoor localization. The first step towards all of these applications is being able to detect the presence of a human being accurately. This experiment is designed to test the accuracy of the photoreceiver in correctly detecting the movement of a person. The experimental setup is as shown in Fig 5.4.

A single node is deployed on the ceiling with a single photoreceiver made to point directly towards the floor. A single 65W Equivalent LED lamp which can produce up to 650 lumens is made to glow at full brightness. The node is deployed roughly at the half way mark along the 24′ side of the room. Other lights in the conference room are switched on as well. Six people of different heights, wearing different

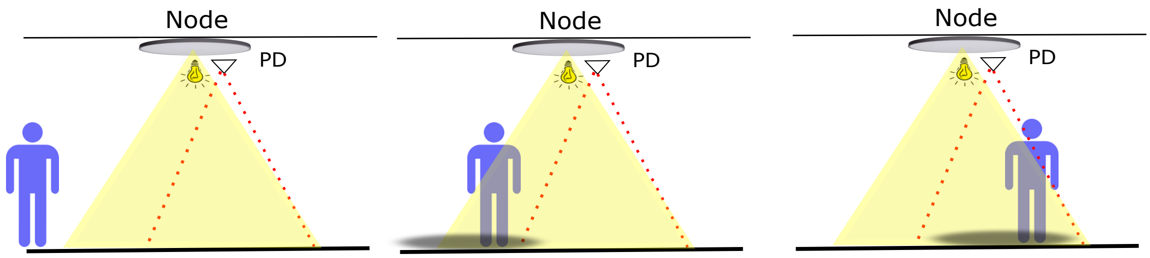


Figure 5.4: People crossing under the photoreceiver

colored clothes walk across this length of the conference room from one end of the conference room to the other while ensuring that they walk beneath the node through the sensing area of the photoreceiver. The experiment is conducted with diffuse dark and bright carpeted surfaces.

5.5 Results

5.5.1 Introduction

Sensitivity testing is done by changing ambient light conditions and floor surface types along with the distance between the transmitter and receiver light nodes. The accuracy in detecting moving people is tested by calculating the true positive and false positive rate. Testing is carried out in a standard conference room 19′ by 24′. People of varying heights were asked to walk under the node along a 24′ line to conduct detection.

All results are collected using a single photoreceiver mounted along with a LED light on the ceiling and which is made to point at a particular spot on the floor.

5.5.2 Raw Sensor Reading

Fig 5.5 shows real time readings collected by the photoreceiver over a small amount of time. These readings are raw readings which are sent to the server by the microcontroller on the node. By pointing the sensor towards the floor and collecting data over a small window of time, the ambient light level present in the room is obtained. This is also known as the base light level. Any changes occurring in the light level on the floor get reflected about this base light level.

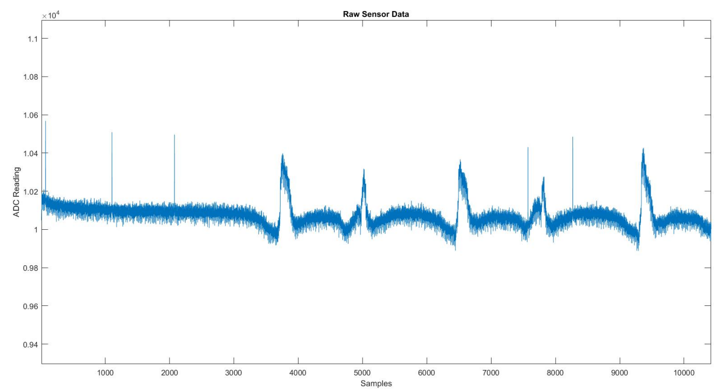


Figure 5.5: Raw readings for a dark floor

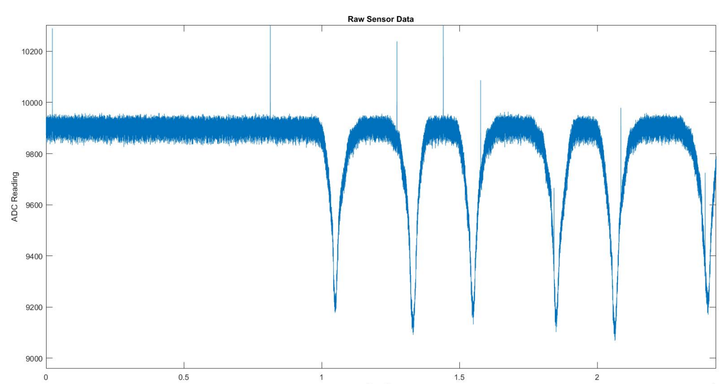


Figure 5.6: Raw readings for a bright floor

When a person walks past or their shadow is cast on the sensing area there is a change in light level sensed by the sensor. These changes are reflected as changes in ADC readings as shown in Fig. 5.5. The amount of change in ADC reading depends on the floor type, intensity of shadow and amount of ambient light present in the room. There is a reduction or dip in ADC reading if the light level detected is lesser than the ambient (base) light level and an increase or spike in ADC reading if the detected light level is greater than the ambient (base) light level.

5.5.3 Metrics

The performance of the designed photoreceiver is assessed based on its sensitivity and accuracy in detecting light level changes. These two parameters provide the most insight regarding the performance of the sensor and quantify its dependability.

5.5.4 Sensitivity under low light conditions

For a fixed change in light level the photoreceiver produces a similar change in ADC reading irrespective of the floor type. As shown in Fig. 5.7 the photoreceivier has a similar slope for both a dark carpeted surface and a bright carpeted surface. There is a change of 200 ADC readings with respect to the base light level for a change in 35 lux in light level. That is once a particular gain resistor is set according to the floor surface type, the performance of the sensor remains same.

To give the reader a better understanding of what a change of 35 lux on the floor means the following numbers are presented; the light level on the floor directly beneath a light source, when all the lights are switched on in the conference room, is about 420 lux. So a change of 35 lux means a change of 8.33% of light level at the floor. Which means an even smaller amount of absolute change of light is seen at

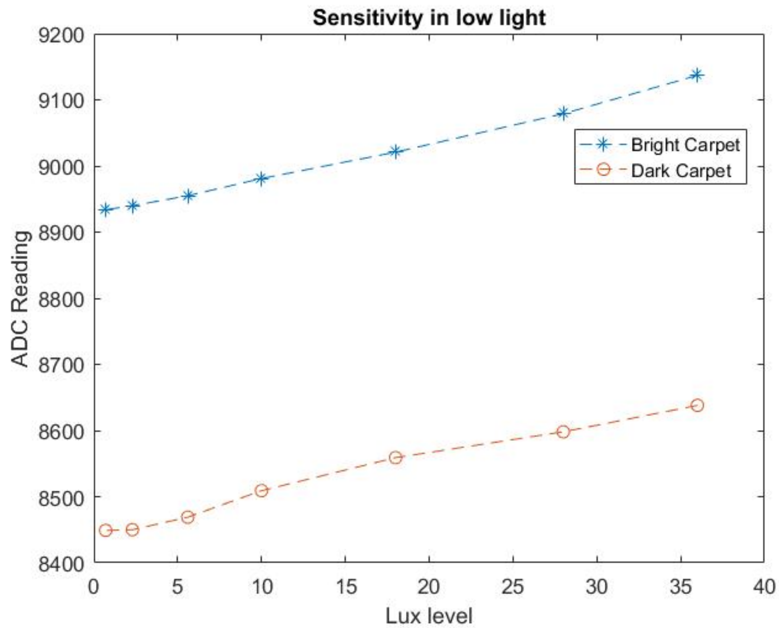


Figure 5.7: Receiver performance under low light and different floor surfaces

the photoreceiver at the ceiling which the photoreceiver is able to sense.

5.5.5 Sensitivity with increasing distance

The amount of light observed by the photoreceiver decreases with an increase in distance from the source of light. The absolute value change in ADC readings also goes down with distance. Hence detecting light or shadows from a far away source gets harder with increase in distance. The designed sensor is able to detect light from a source as far as 8 feet.

Even under low light conditions with a dark carpeted floor the photoreceiver is able to produce a change of up to 20 ADC readings. For the same distances the photoreceiver fares much better with ambient light on.

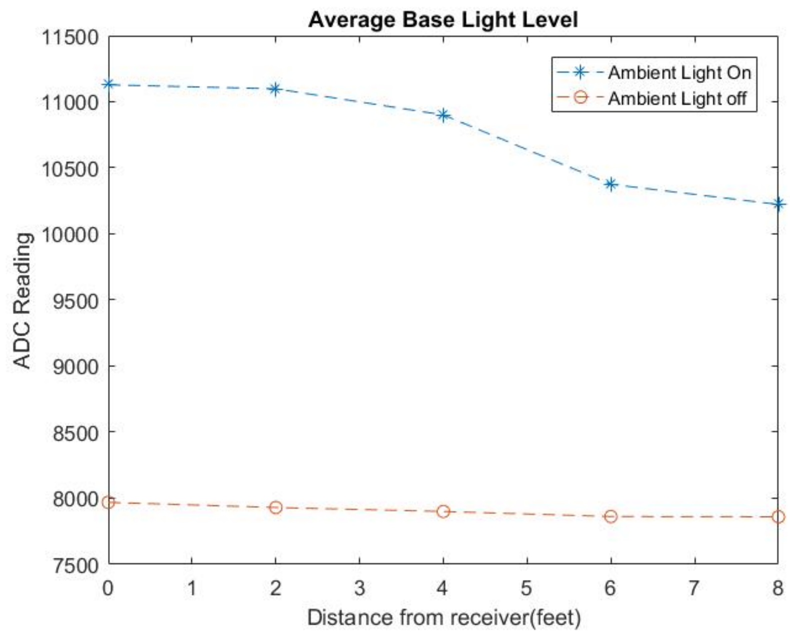


Figure 5.8: Changing baselight levels as light source moves farther away

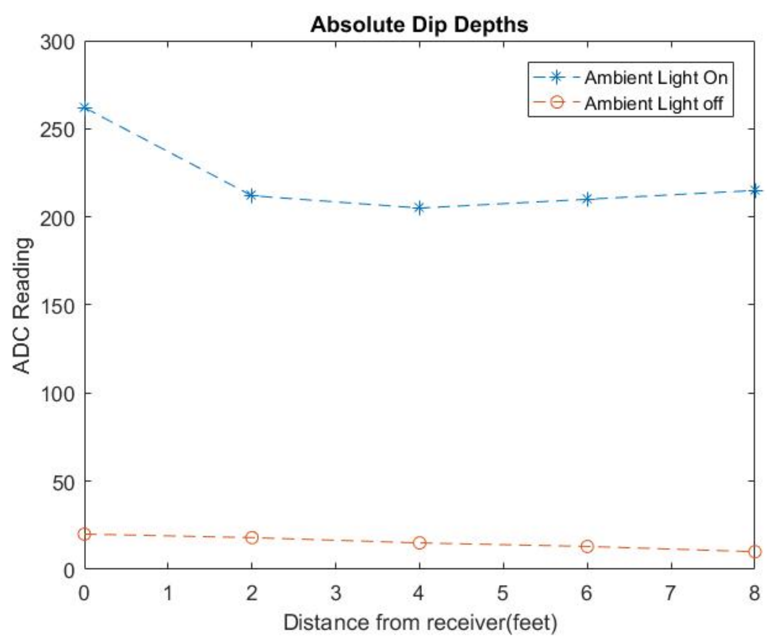


Figure 5.9: Absolute value of dips detected with distance from receiver

5.5.6 Accuracy

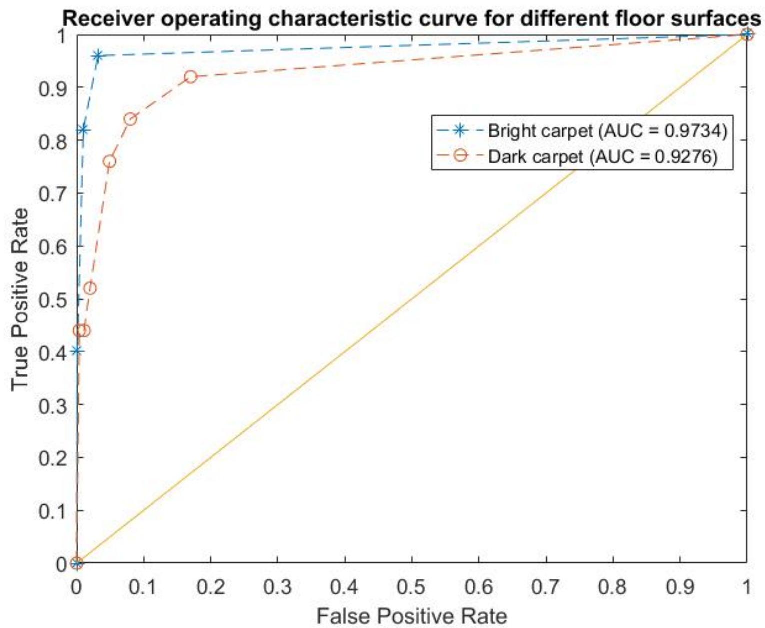


Figure 5.10: Receiver operating characteristic curve

The collected data of people crossing underneath the sensing area is fed to the detection algorithm described earlier in section 5.5 which gives a binary output; 1 for detection of a crossing and 0 for no detection. The output is analyzed by marking each output as follows:

1. **True Positive (TP)** when a person crosses under the photoreceiver and is correctly detected.

2. **False Positive (FP)** when a person doesn't cross under the photoreceiver but is reported to be detected.

3. **False Negative (FN)** when a person crosses under the photoreceiver but is not detected.

4. **True Negative (TN)** when a person has not crossed under the photoreceiver and is not detected.

These values are recalculated for different thresholds. From the values obtained for each of these, True Positive Rate (TPR) = TP/ (TP + FN) and False Positive Rate (FPR) = FP/(FP + TN) are calculated and plotted to generate a receiver operating characteristic (ROC) curve as shown in Fig 5.10. Accuracy of detection is measured by calculating the area under the ROC curve. An area of 1 represents a perfect detection.

The area under the ROC (AUC-ROC) curve for the bright carpeted floor is found to be 0.9739 and the the area under the ROC curve for the dark carpeted floor is found to be 0.9276 showing that the photoreceiver is more accurate for a brighter colored floor.

Chapter 6

Conclusions

A novel ceiling based photoreceiver which can sense light level changes occurring on the floor has been designed. The purpose of this thesis was to investigate whether it was possible to design such a ceiling based sensitive receiver to work with any floor. To accomplish this, a circuit was designed incorporating a photodiode with a transimpedance amplifier as the front end to sense light intensity and convert it to a voltage. The voltage was then compared to a calibrated base light voltage using an instrumentation amplifier and the final voltage output was fed to a microcontroller. This circuit was then fabricated as a printed circuit board which could be deployed. The photoreceiver was placed alongside a light bulb on the ceiling and tested. The research problem of whether or not such a receiver can be realized was solved. It was possible to realize such a receiver that can detect shadows of people crossing under the receiver on a diffuse dark carpeted floor with an AUC-ROC of 0.9276 and on a diffuse light carpeted floor with an AUC-ROC of 0.9739. It was also shown that the receiver was able to sense lux level changes of the order of tens of lux on a dark carpeted floor.

Chapter 7

Future Work

Currently the voltage that represents the existing light levels needs to be calibrated manually by tuning a potentiometer. As the photoreceiver is connected to a microcontroller this can be automated by using a digital potentiometer. The microcontroller can have a calibration step which runs which is executed at different times of the day. An automatic gain control circuit can be added to set the value of R_g according to the floor that the photoreceiver looks at. A lens can be added to the photodiode to increase sensitivity and specificity. The lens would collect light from a wider angle and focus it onto the sensing part of the photodiode. The output of the receiver is inferred as a detection (1) or not (0). Finer granularity can be added to the algorithm to infer the range of shadows better. Surface mount device (SMD) components for the IC's and smaller passive components (0402,0201) can be used to reduce the size of the photoreceiver further.

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