ECE 445

Senior Design Laboratory

Project Proposal

Illuminate

Multi-sensor Motion Detector for Reliable Lighting Control

Team No. 21

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1 Introduction

1.1 Problem

In offices, classrooms, and lecture halls worldwide, motion sensors are commonly used to automate lighting control. While convenient, these systems share a critical flaw: lights often switch off when people remain in the room but are relatively still, such as when typing, reading, or watching a presentation. This leads to frustration, disrupts productivity, and creates an inefficient work environment. The root of the issue lies in the reliance on Passive Infrared (PIR) sensors, which detect the infrared radiation emitted by warm bodies. Although effective for detecting large movements, PIR sensors struggle with micromotions, are prone to false triggers, and rely on fixed timeout settings. As a result, they fail to consistently recognize human presence.

1.2 Solution

Our approach introduces a two-stage verification system to improve reliability while preserving the strengths of current technology. The first stage utilizes a PIR sensor, which remains valuable for its fast response to initial entry and detection of larger body movements; this sensor will specifically capture when a person first enters the room. The second stage integrates a millimeter-wave (mmWave) radar sensor, which excels at detecting fine micromotions such as breathing or subtle hand movements. This stage ensures continuous detection of occupants even during periods of low activity. Together, the PIR sensor triggers the system upon entry, while the mmWave sensor maintains accurate presence detection until all occupants have left.

In addition, our design incorporates a multi-level lighting system to both conserve energy and enhance user comfort. Upon initial detection, the lights will gradually illuminate to the target brightness, avoiding abrupt transitions and providing a smoother user experience. When occupants remain in the room, the lighting will hold at the appropriate brightness level, informed by ongoing verification from the mmWave sensor. If no presence is detected for a designated interval, the system will first dim the lights to an intermediate level to signal a potentially empty room. Upon confirmation of vacancy, via an additional verification stage, the lights will go completely off.

1.3 Visual Aid

We have attached a high-level diagram for our sensing system in Figure 1. The PIR Sensor is used to turn on the light, while the mmWave sensor is used to either keep the light on or turn off the light.

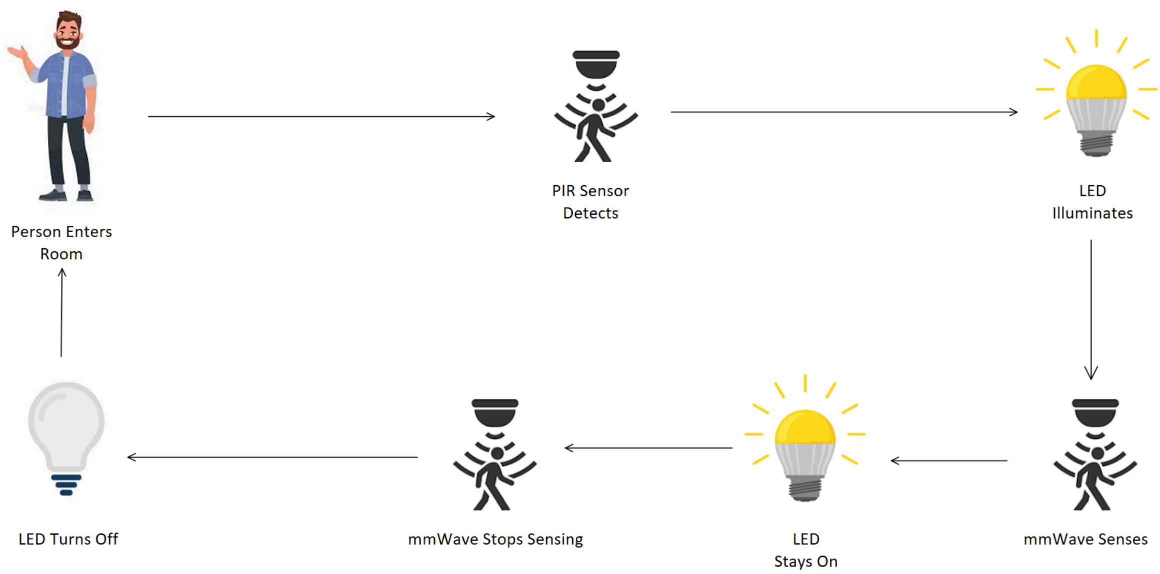


Figure 1: Overview of the Illuminate System

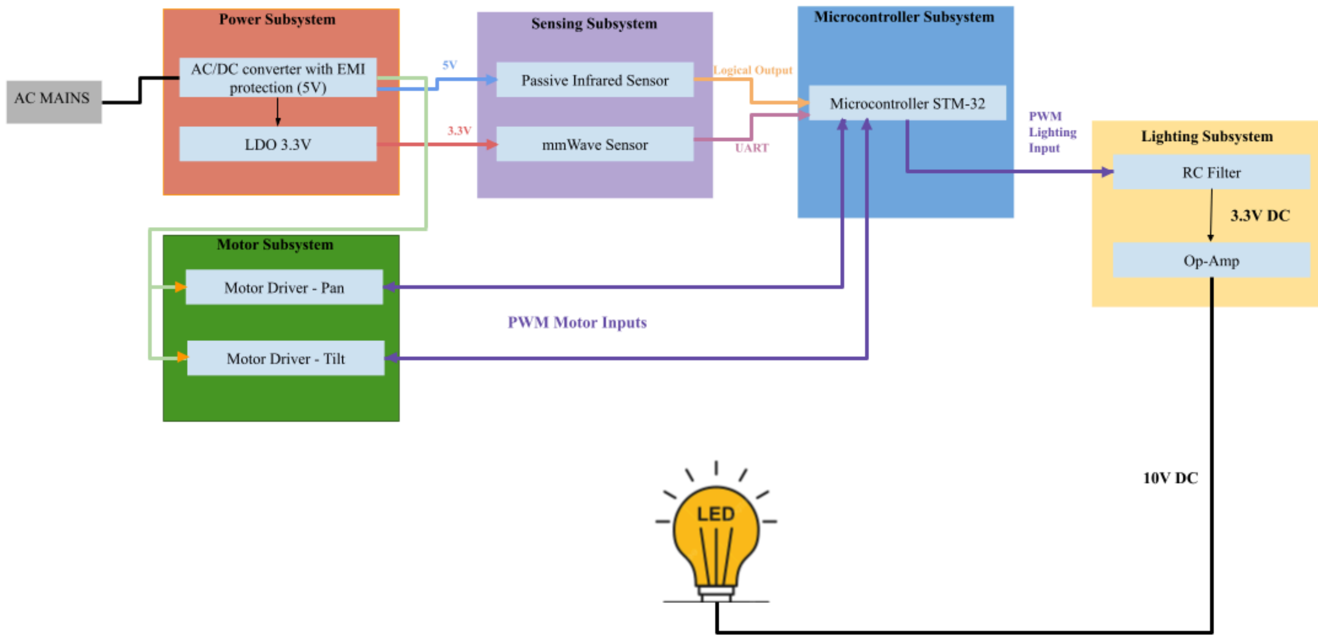
1.4 High-Level Requirements

To be considered successful, our project must meet the following objectives:

1. The light must begin to illuminate within 1 second of someone entering a room, stay on for 30 minutes with someone being in the room, and begin to turn off after 1 minute of not detecting anyone
2. Capable of detecting people in all parts of a 25’x40’ Room (or smaller).
3. The motor that controls the direction of the sensor should be able to sweep 180 degrees horizontally and 90 degrees vertically at the same time.

2 Design

2.1 Block Diagram



2.2 Subsystem Overview

Our Project is split into 5 subsystems, each of which is implemented in both hardware and software.

2.2.1 Power Subsystem

Our entire system will be powered by AC mains. We will require 5V for the motors, 5V for the PIR sensor, and 3.3V for the mmWave sensor. Thus, we will feed our AC mains into an AC/DC 5V converter with EMI Protection. EMI Protection is necessary since we deal with AC mains. This 5V will be fed into a 5V to 3.3V buck converter.

2.2.2 Motor Subsystem

The motor subsystem is powered from the system's regulated 5 V DC rail and drives two servo motors that together form a two-axis gimbal for the mmWave radar sensor. The pan servo provides rotation about the vertical axis, enabling horizontal sweeps across the room, while the tilt servo provides rotation about the horizontal axis, allowing the sensor to scan vertically downward from its ceiling-mounted position. By combining these motions, the subsystem expands the effective coverage area of the mmWave sensor beyond its inherent field of view.

To ensure reliable operation, the motors are powered through a dedicated supply rail capable of handling their peak current draw, isolated from the sensitive logic rails. Optional limit switches or built-in servo feedback can be incorporated to provide positional awareness and safe homing routines during startup. Mechanically, the servos are integrated into a compact gimbal mount that rigidly supports the mmWave sensor while minimizing vibration and backlash.

2.2.3 Sensing System

The sensing subsystem integrates both the Passive Infrared (PIR) sensor and the C4001 mmWave radar sensor, along with the necessary interface circuitry to ensure reliable operation. These two sensors work together to provide a two-stage verification system: the PIR sensor offers fast response to initial entry and large-scale movement, while the mmWave sensor provides continuous presence detection by recognizing fine micromotions such as breathing or typing of occupants within the room.

This subsystem requires two regulated power rails: a 5 V supply for the PIR sensor and a 3.3 V supply for the mmWave sensor, each routed from the power subsystem. The PIR sensor outputs a digital logic signal that connects directly to the microcontroller's GPIO, while the mmWave sensor communicates with the microcontroller over a UART interface for transmitting detailed presence and motion data. An optional interrupt line from the mmWave module can also be used to flag immediate detection events.

2.2.4 Microcontroller Subsystem

The microcontroller controls the movement of the two Servo motors by generating PWM signals to the motor drivers, which translate these signals into motor currents.

The microcontroller controls the LED through 6 states: OFF, Illuminate, Bright, dim1, Standby, and dim2. OFF is self explanatory: the LED is off. Illuminate means that the LED is gradually turning on after detecting motion. In the Bright State, the LED stays at its max brightness. In dim1, the LED begins to gradually turn off. In Standby, the microcontroller analyzes whether any extra movement is seen before fully turning the light off, and once it finds that there is still no movement, it sends a signal to turn off the light.

2.2.5 Lighting Subsystem

Our lighting subsystem's primary responsibilities are to keep the lights on and to gradually turn the lights on and off. The microcontroller generates a PWM proportional to the desired brightness, and we will employ a PWM to DC filter, which uses an RC circuit to pass through the DC and filter out the high-frequency waves. This will output a 3.3V DC signal, and we will use an op-amp to boost the voltage from 3.3V to 10V and feed the output to our LED.

2.3 Subsystem Requirements

The requirements for each of our subsystems are listed below.

2.3.1 Power Subsystem

1. The system must provide overcurrent, overvoltage, undervoltage, and short-circuit protection.
2. It must generate stable regulated **5 V** and **3.3 V** DC rails for all electronics.
3. It must provide sufficient current capacity to simultaneously power two servo motors (peak draw ~1 A each), the PIR sensor, the mmWave sensor, and the microcontroller.
4. It must isolate low-voltage logic electronics from the AC mains supply used by the LED driver.
5. It must include filtering and decoupling to minimize electrical noise affecting the sensors and microcontroller.

2.3.2 Motor Subsystem

1. The subsystem must drive two servo motors: one for panning (180°) and one for tilting (90°).
2. It must accept PWM control signals from the microcontroller and convert them into mechanical motion.
3. It must provide stable and repeatable motion to sweep the mmWave sensor across the room.
4. It must operate from the regulated 5 V rail without introducing noise into the logic rails.

5. It should include optional homing/limit switch feedback to ensure safe startup positioning.

2.3.3 Sensing Subsystem

1. The subsystem must include a PIR sensor powered from 5 V to detect coarse motion and human entry.
2. It must include a C4001 mmWave radar sensor powered from 3.3 V to detect fine micromotions such as breathing and typing.
3. The PIR sensor must provide a digital logic output compatible with the microcontroller’s GPIO.
4. The mmWave sensor must communicate with the microcontroller over a UART interface at 3.3 V logic levels.
5. The subsystem must reliably detect a human presence within 10–15 meters.

2.3.4 Microcontroller Subsystem

1. The microcontroller must process sensor inputs from the PIR and mmWave subsystems to determine occupancy state.
2. It must generate PWM control signals to drive the motor subsystem for pan/tilt sweeping.
3. It must generate a high-frequency PWM signal to the lighting subsystem for dimming control.
4. It must implement a state machine for occupancy detection, with entry, occupied, verification, dimming, and shutoff states.

2.3.5 Lighting Subsystem

1. After detecting a person in a room, the lights should gradually illuminate within 3 seconds.
2. The lights should dim to an intermediate state after not detecting a human for 1 minute, and turn off after verification of an empty room (through two more passes of the sensor).
3. The lighting system should have consistent gradual illumination and dimming, along with a steady “on” stage (no flickers).

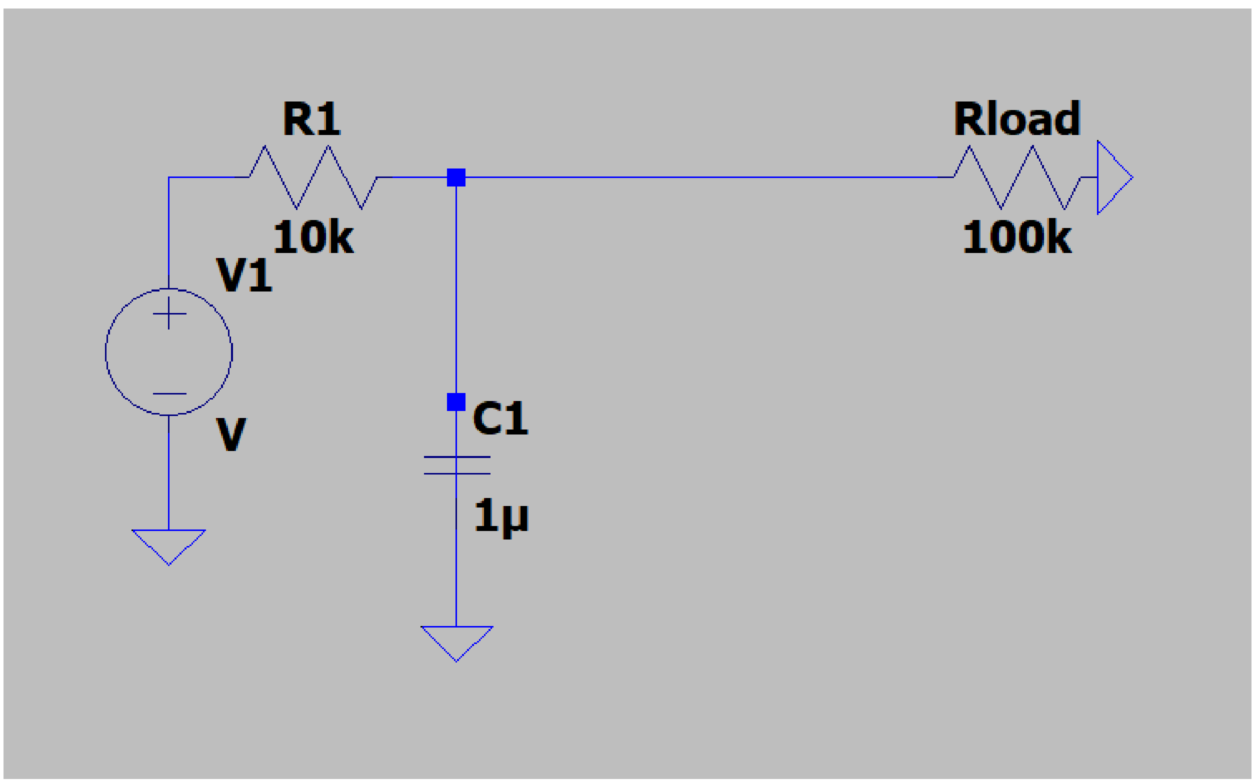
2.4 Tolerance Analysis

A vital function of our lighting component is the gradual brightening and dimming of our LED. This is done through a multi-stage circuit, converting a PWM to DC voltage, amplifying it, and then feeding it into an LED driver. The most important, and potentially risky, stage of this is the initial conversion of the PWM to DC voltage. If the RC Filter is designed incorrectly, we will not reach the voltage needed to achieve full brightness.

The time constant τ is calculated to be:

$$\tau = RC$$

If we use a resistance of 10 kΩ and a capacitance of 1 µF, we get a time constant value of 0.01s. This means that it takes 0.01s for the capacitor to charge to 63% of its final value of 3.3V. We are planning on ramping up the duty cycle in 2 seconds, so if we ramp up the duty cycle in 5% intervals over the 2 seconds, the amount of time each duty cycle has is 100 ms. Based on our time constant of 0.01s, and the time each duty cycle will have, the capacitor will have no problem charging up. Worst case, the tolerance of the capacitor is 10%, and the tolerance of the resistor is 5%. Then, the new time constant will be 11.5ms. This is still more than enough time for the capacitor to charge up.



3 Ethics and Safety

Ethical and Safety Issues

Our project must be developed in accordance with the professional responsibilities outlined in both the ACM and IEEE Codes of Ethics. The ACM Code stresses avoiding harm, respecting privacy, and being honest and trustworthy, while the IEEE Code emphasizes prioritizing public welfare, ensuring safety, and maintaining integrity. Since our system uses a PIR sensor and a mmWave radar to detect occupancy, a key ethical concern is privacy. Even though our design does not capture video or personally identifiable data, it can still reveal sensitive patterns of room use. To mitigate this, we will process all data locally, store nothing by default, and clearly disclose to users the system's intended scope so it cannot be misinterpreted as a surveillance device. Another ethical responsibility is honesty about performance and limitations. We will not exaggerate the detection range or accuracy of our design, and we will explicitly state that it is not intended for life-safety or emergency lighting applications. To further align with the ACM and IEEE principles of competence and fairness, we will seek expert consultation for areas outside our expertise, document all assumptions, and ensure accessibility so that users with limited mobility or sensitivity to light changes are not disadvantaged.

From a safety and regulatory perspective, our project must also comply with established standards and policies. Electrical safety for our LED driver and control electronics is defined by UL 8750 (LED equipment safety) and IEC 61347-2-13 (LED controlgear requirements). Our 0–10 V dimming interface will follow ANSI C137.1-2022, which specifies voltage levels and compatibility between controllers and drivers. Because our system includes digital electronics, it falls under FCC Part 15 Subpart B (Class B) for unintentional radiators, and the mmWave radar module must operate under the grant conditions of FCC Part 15.255. We will use pre-certified modules and avoid any RF hardware modifications. In the laboratory, we will comply with the University of Illinois ECE 445 safety policies, which include completing mandatory training, never working alone with high-voltage circuits, and obtaining TA approval before connecting to mains power. To protect against accidental harm, our system will incorporate galvanic isolation through an isolated AC-DC converter, include fuses and MOVs for surge protection, and default to a failsafe "lights on" mode in the event of a fault. By explicitly addressing these ethical and safety concerns, we reduce the risks of accidental misuse, privacy harm, and electrical hazards, and we demonstrate adherence to both professional codes of conduct and regulatory expectations.

4 References

ACM Code of Ethics and Professional Conduct - Association for Computing Machinery. https://www.acm.org/code-of-ethics

IEEE Code of Ethics - Institute of Electrical and Electronics Engineers. https://www.ieee.org/about/corporate/governance/p7-8.html

UL 8750: Light Emitting Diode (LED) Equipment for Use in Lighting Products. UL Standards & Engagement. https://ulstandards.ul.com/standard/?id=8750

ANSI C137.1-2022: Lighting Systems – 0 to 10 V Analog Control Protocol. American National Standards Institute. https://www.ansi.org/standards-activities/standards-coordinating-committees/c137-lighting-systems

FCC Part 15: Radio Frequency Devices. Electronic Code of Federal Regulations. https://www.ecfr.gov/current/title-47/part-15