Design and Implementation of an ESP32 Based Dual – Channel Intelligent Bracket – Lighting Controller

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Abstract- ***This paper presents the design and implementation of a compact embedded controller for two independently operated bracket-lighting loads. The prototype combines an ESP32 microcontroller, an isolated relay-output stage, ambient-light and passive-infrared sensing, temperature and humidity monitoring, local push-button control, a liquid-crystal display, audible feedback, and an IEEE 802.11 wireless local area network interface. A modular hardware architecture separates mains conversion and load switching from the extra-low-voltage sensing and logic domain. The implemented unit supports independent or simultaneous switching, local override, sensor-assisted automation, and browser-based control on the local network. Functional integration tests confirmed stable low-voltage operation, correct sensor response, dependable relay actuation, and restoration of network communication after interruption. The principal contribution is a low-cost, explainable, and locally operable architecture that preserves essential lighting functions when Internet access is unavailable. The study also identifies the need for quantified energy, latency, electromagnetic-compatibility, and endurance testing before product deployment.***

Keywords: Dual-channel lighting; ESP32; Embedded controller; Intelligent lighting; Relay driver; Wireless local area network

I. INTRODUCTION

Lighting controls have been shown to have an impact on energy consumption, occupant comfort, safety, and lamp longevity. Although they lack remote status, scheduling, and context-aware response, conventional wall-switch installations are nonetheless appealing due to their affordability and ease of use (Taylor et al., 2021). The ease of manual control becomes a barrier to energy management when users keep luminaires powered in unoccupied or well-lit areas. As a result, sensor-based tactics and networked lighting are now crucial components of building automation. (Pandharipande & Newsham, 2018; Wagiman et al., 2019).

Internet-of-things systems, which are widely used nowadays, combine identifiable physical items, sensing, actuation, connectivity, and software applications. (Atzori et al., 2010; Gubbi et al., 2013). Connecting a bulb to Wi-Fi is not the only practical engineering challenge for an indoor lighting controller. In order to be comprehensible and maintainable, the controller must coordinate physical switches, environmental measurements, remote commands, load separation, user feedback, and fault recovery (Perera et al., 2025).

In this work, a prototype for dual-channel bracket lighting is developed around the ESP32. In contrast to cloud-dependent demos, the controller runs automatic rules locally and hosts its interface on the local WLAN. The paper focuses on the hardware architecture, circuit implementation, safety boundaries, and functional integration. Its contributions are: (i) a modular two-load control architecture; (ii) coordinated interfaces for light, occupancy, environmental, and manual inputs; (iii) protected relay actuation for mains-connected luminaires; and (iv) a compact PCB prototype with local display and audible status.

II. RELATED WORK AND DESIGN GAP

Prior smart-lighting studies report substantial benefits from occupancy and daylight control, including improved illumination management and reduced unnecessary operation. Caicedo & Pandharipande, (2012) examined distributed illumination control with local sensing and actuation, while Lee et al., (2018) combined dimming and location awareness. Burmaka et al., (2020) demonstrated that the attainable savings depend strongly on control strategy and installation conditions. These works establish the value of sensing, but many prototypes emphasize algorithms or building-scale optimization rather than a reproducible, two-load embedded implementation with conventional local control.

The ESP32 provides integrated 2.4-GHz Wi-Fi, general-purpose input/output, analogue conversion, timers, and sufficient processing for a small web server (Maier et al., 2017). It is therefore suited to a controller that must arbitrate between manual, sensor, and network inputs.

The remaining engineering gap is the integration of this logic with protected relay drivers, a regulated supply, clear channel state, and a usable enclosure.

III. MATERIALS AND METHODS

A. System Architecture

Power conversion, embedded processing, sensing and local input, isolated load actuation, and human-machine/network interfaces are the five functional levels that make up the system. The lighting loads and a step-down supply are powered by a 230-V alternating current source. The development board provides the 3.3-V logic domain, and rectification, filtering, and linear regulation supply the nominal 5-V rail. An LDR module provides analog light data, a PIR sensor provides digital occupancy data, a DHT22 provides environmental data, and four push buttons and the WLAN interface provide commands to the ESP32. The block diagram of the prototype is shown in the figure 1.0 below:

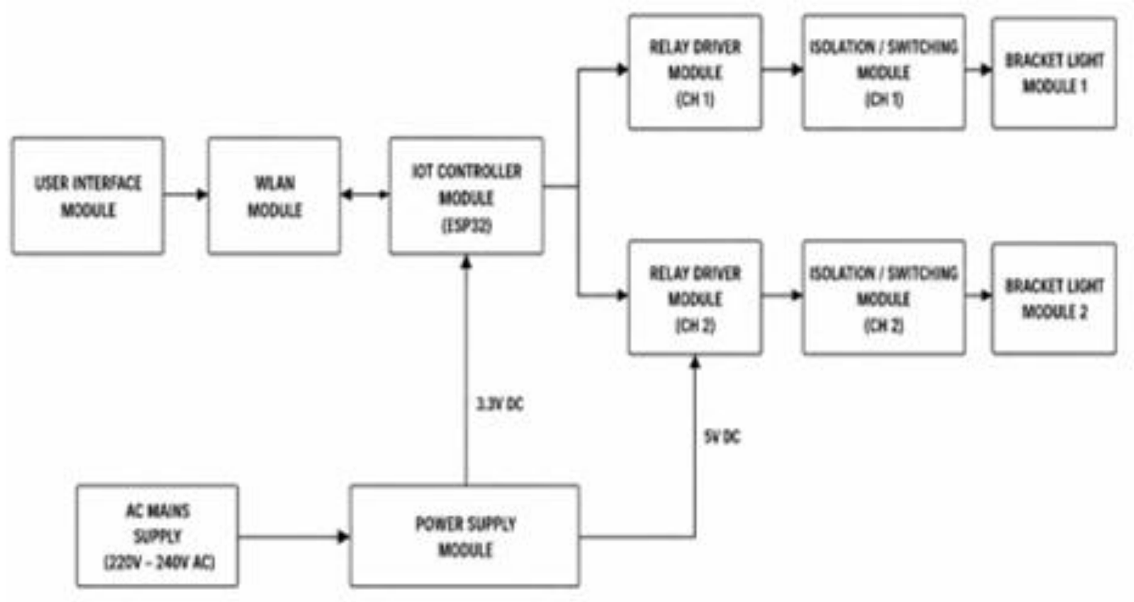

Figure 1. Block Diagram/Architecture of the Implemented Dual – Channel Lighting Controller.

B. Hardware Selection and Interfaces

The prototype was developed using carefully selected hardware components, each performing a specific role to ensure reliable and intelligent operation of the smart lighting system. At the core of the design is the ESP32 development board, which operates with 3.3 V logic and incorporates IEEE 802.11 b/g/n Wi-Fi for wireless connectivity. The ESP32 coordinates sensor data acquisition, system control, display management, and online communication. Ambient illumination is monitored using a Light Dependent Resistor (LDR) connected through an analogue input. The measured light intensity enables the controller to determine whether the bracket lights should be activated or inhibited under automatic operation. Human presence is detected by a Passive Infrared (PIR) sensor connected via a digital input, allowing the system to switch the lighting automatically whenever motion is detected in low-light conditions, thereby enhancing energy efficiency and user convenience. Environmental monitoring is provided by the DHT22 sensor, which communicates through a single-wire digital interface to continuously measure ambient temperature and relative humidity for display and intelligent system control. Lighting loads are controlled through two independently operated relay channels equipped with 5 V coils and electrically isolated contacts, enabling separate control of Bracket Lights A and B. Relay driving is achieved using a BC547 NPN transistor and a 1N4007 flyback diode, where the transistor amplifies the ESP32 GPIO current while the diode suppresses inductive voltage transients generated during relay switching. A 16 × 2 I²C LCD, connected through a two-wire serial bus, provides real-time information on sensor readings, network status, and channel operation. Push buttons and a buzzer provide manual override, audible confirmation, and operational feedback. To ensure reliable switching, the relay contacts are selected according to supply voltage, LED driver inrush current, enclosure temperature, expected switching frequency, and electrical load characteristics rather than steady-state lamp power alone.

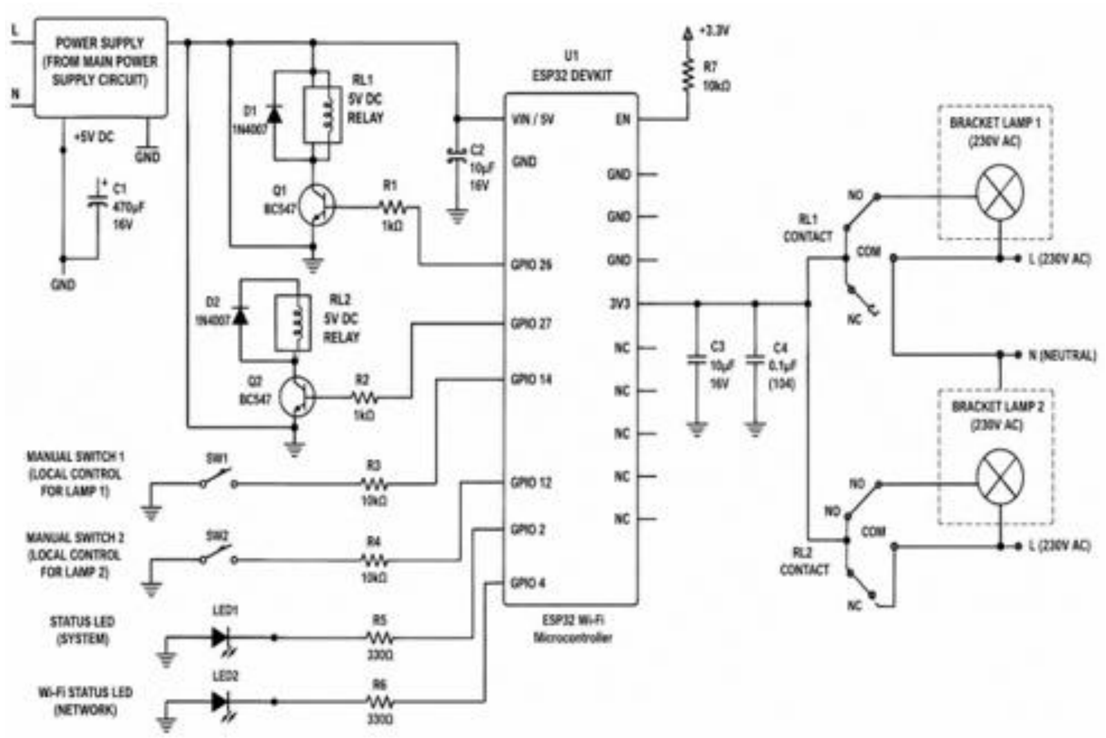

Figure 2. Integrated ESP32 Controller Schematic Showing Sensor, Display, Relay-driver, and Load Interfaces.

C. PCB and Prototype Construction

The circuit was assembled on a printed circuit board to reduce loose wiring and provide repeatable component placement. Low-voltage sensing and logic were arranged separately from the mains and relay-contact paths. Terminal blocks provide external connections, while indicators and the LCD expose operational state. The board layout supports inspection and replacement of the controller and switching components.

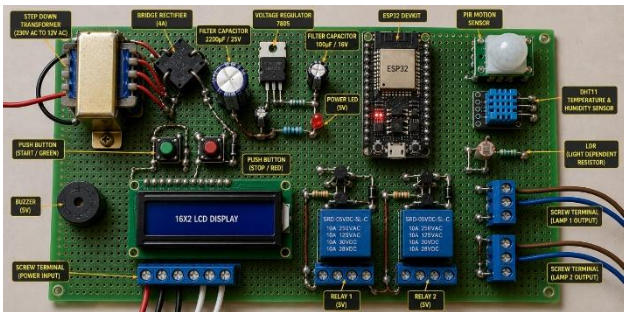

Figure 3. Completed PCB with ESP32, Power stage, Sensing Interfaces, Display, Buzzer, and Dual relays.

D. Firmware

Using the Arduino programming environment and libraries for Wi-Fi, web serving, the DHT sensor, I2C, and the LCD, firmware was created in Embedded C/C++. Input and output pins are configured, the display is turned on, WLAN association is established, and both lighting channels are set to a specific state during initialization. The cyclic task delivers HTTP requests, refreshes the display, samples inputs, applies control rules, updates outputs, and tries to reconnect following a WLAN outage. While automated mode considers motion and ambient light, manual and remote instructions are handled as explicit user requests. A motion hold timer prevents an instantaneous switch-off when occupancy is momentarily missed, and debouncing prevents repeated button actions. Because the controller maintains relay state and reports it to all interfaces, this state-oriented architecture keeps the interface from being the only source of truth.

IV. PROTOTYPE TESTING

A. Test Procedure

Subsystem and integrated tests followed inspection in the testing process. Prior to energization, component location, polarity, terminal connections, and the distance between the mains and low-voltage sections were examined. The regulated supply was seen when the relay switched and the controller started up. Sensors were activated in both bright and dark environments, as well as in motion and no motion. After testing each local and web command for both channels, a combined automatic-control sequence and a WLAN interruption/reconnection test were performed.

B. Test Analysis

To assess the produced prototype's performance, dependability, and operational integrity under a range of

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operating situations, extensive functional testing was conducted. The outcomes verified that every subsystem fulfilled the expected functional criteria and functioned in accordance with the design specifications. The power supply's stability was evaluated during the power-up test by confirming that the ESP32 controller, sensors, LCD, and relay modules were successfully initialized as soon as they were energized. The prototype showed that the power supply circuit offered steady and dependable performance by finishing the startup sequence without any unforeseen resets or faults. The Light Dependent Resistor's (LDR) ability to discriminate between bright and low light conditions was evaluated in the ambient-light input test. Under enough illumination, the system prevented automatic lighting activation as intended, demonstrating the efficiency of the threshold-based management algorithm and light-sensing hardware in cutting down on needless energy use. The Passive Infrared (PIR) sensor's capacity to identify human movement in low light was assessed by the occupancy detection test. Relay activation was effectively initiated by motion detection, exhibiting precise occupancy sensing and dependable automatic lighting management. Bracket Lights A and B underwent an independent switching test to verify the dual-channel architecture. The efficiency of the independent relay control concept was confirmed by the findings, which demonstrated that both channels could be operated separately or simultaneously without interfering with one another. The push-button switches were also used to confirm the local control interface. Every lighting channel's current operating state was effectively overridden by manual orders, which also provided instant operational feedback. This ensured dependable local management in situations where automatic or wireless operation was either unnecessary or unavailable.

By sending control orders from authorized web browser clients, the embedded wireless local area network (WLAN) interface's responsiveness was evaluated. The system confirmed that the ESP32-based wireless architecture is appropriate for real-time smart lighting applications by carrying out all commands with little connection latency. Additionally, a network recovery test was used to assess the communication subsystem. In this test, the controller immediately re-connected to the WLAN following a brief disruption without the need for user intervention. This behavior illustrated the communication system's resilience and fault tolerance.

The intelligent dual-way bracket lighting system demonstrated stable power-up operation, accurate ambient-light classification, reliable occupancy detection, independent dual-channel switching, efficient manual override capability, responsive WLAN-based control, and dependable automatic network recovery, all of which demonstrated that the system met its design objectives. These outcomes validate the prototype's efficacy, stability, and practical appropriateness for intelligent lighting applications.

C. Discussion

By coordinating two lighting loads, responding to environmental inputs, maintaining manual control, and exposing status and control via a local WLAN, the prototype achieved the specified functional requirements. Elegant functional separation is the most significant architectural outcome. Because sensing and arbitration operate on the ESP32, losing Internet access does not eliminate local automatic control; losing the router impacts browser access but does not need disabling the physical buttons.

V. SAFETY, SECURITY, AND DEPLOYMENT CONSIDERATIONS

Protective fusing, strain relief, flame-retardant enclosure materials, touch-safe terminals, competent inspection, and creepage and clearance suitable to the relevant voltage and pollution level are all necessary for mains-powered lighting hardware. Although the prototype's transformer and relay contacts offer functional isolation, a product version should be evaluated in light of the intended jurisdiction's electrical safety and electromagnetic compatibility regulations.

The web service only accepted approved control routes, and the local network's WPA2 or WPA3 authentication protected the WLAN. Although these steps lessen casual access, they do not offer complete transport security. Per-user authentication, TLS, secure update signing, session restrictions, secured credential storage, and rate limitation should all be included in production deployment.

VI. LIMITATIONS AND FUTURE WORK

The prototype was tested in a controlled setting and manages two channels within WLAN coverage. Direct energy metering, cloud access, long-term field data, calibrated illumination measurement, and a formal threat model are not included. Channel energy, command delay, wireless range, reconnection time, sensor false-positive/false-negative rates, relay endurance, and thermal performance should all be measured in future research. Then, without compromising local fail-safe operation, dimming, overthe-air updates, additional channels, and a backup supply can be evaluated.

VII. CONCLUSION

For two independently switched bracket lights, a small ESP32-based controller was created and put into use. Protected relay drivers, occupancy and ambient light sensors, environmental monitoring, push-button override, local display and audio feedback, and a browser interface on a WLAN are all integrated into the system. The architecture's viability and capacity to maintain local control in conjunction with connected operation are validated by functional testing. Instrumented field evaluation is pending for quantified energy and reliability claims.

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