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Rule-Based Occupancy and Daylight Control for a WLAN-Connected Dual-Way Lighting Prototype

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Abstract- This study develops and evaluates a deterministic control strategy for a wireless LAN-connected two-channel indoor lighting prototype. An ESP32 uses online commands, passive-infrared motion events, manual push-button inputs, and ambient light measurements to execute the control loop locally. Automatic operation is only triggered when the ambient light level drops below a predetermined threshold; occupancy then initiates the selected channel, and a hold time prevents it from shutting off prematurely. The controller synchronizes the states of the relay, display, and web interface; manual and network inputs permit express override. Scenario-based testing was used to demonstrate automated Wi-Fi reconnection, independent and simultaneous channel control, motion-triggered activation in the dark, correct bright-condition inhibition, and local network access. The contribution is an explainable edge-control architecture that reduces dependence on the cloud while preserving user agency. Since the source experiment did not record illuminance, energy, delay, or occupancy ground truth, the results show functional validity rather than quantifiable energy savings. A measuring process is recommended for additional comparison analysis.

Keywords: Occupancy Sensing; Daylight-responsive Control; Rule-based Automation; WLAN; ESP32; Smart Buildings; Human Override

I. INTRODUCTION

Indoor lighting is sometimes seen as a binary service, despite the fact that the need for illumination fluctuates according to daylight, occupancy, task, and user desire. Manual switching provides direct agency but necessitates continuous user involvement. Network control makes things more accessible, but connectivity is not enough to get rid of waste. For smart lighting to be effective, a control policy that incorporates environmental context with unique override behaviour is required. (Karapetyan et al., 2018; Soheilian et al., 2021).

Sensing-based control often uses occupancy events and illuminance to avoid daylight-period operation and limit lights to active areas. Reviews show that tenant behaviour, building type, time-delay settings, and sensor position all impact performance. (Wagiman et al., 2019). Without baseline energy measurements, reported reductions from previous installations cannot be applied straight to a new prototype. As a result, this research separates energy-performance evaluation from functional control validation.

An ESP32 linked to two bracket lights is used in the study to build an explainable rule set. In order to read sensors and switch loads, the controller functions at the network edge without the need for a distant cloud. Whether a small embedded platform can (i) maintain independent channel and manual operation, (ii) coordinate bright/dark and motion inputs without unstable switching, (iii) maintain consistent state across local and browser interfaces, and (iv) recover local-network service after interruption are the research questions.

II. CONTROL FRAMEWORK

A. INPUT AND OUTPUT MODEL

The controller receives an analogue LDR value, a digital PIR event, four push-button inputs, and HTTP requests from authorized devices on the same WLAN. The DHT22 supplies environmental information for display and monitoring but does not directly determine lighting state in the implemented rule set. Outputs are two relay commands, LCD information, buzzer acknowledgements, and the state values returned by the web interface.

A number of control factors, including occupancy detection, daylight sensing, manual override, timing, relay switching, and wireless communication, regulate how this system prototype operates. Together, these

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factors carry out the rule-based control algorithm that guarantees the system prototype's intelligent, dependable, and energy-efficient lighting operation.

The surrounding lighting level that the Light Dependent Resistor (LDR) detects is represented by the ambient light variable, represented by the letter L. Its main job is to decide whether to allow or prohibit automatic lighting activation. The controller suppresses automatic switching when there is enough daylight, while occupancy-based lighting management is made possible by low ambient light.

Every time human motion is detected, the Passive Infrared (PIR) sensor generates the Occupancy Event (O) variable. This setting ensures that the lighting system only reacts when occupancy is present by requesting illumination under dark working conditions by starting the automatic lighting sequence.

The prototype's operating mode is set by the Mode/Override (M) variable. It allows the controller to choose between explicit user commands received via the WLAN internet interface or local push buttons, or automatic rule-based operation. When manual control is needed, this enables users to override automatic judgements.

After the most recent motion detection event, the Hold Timer (T-hold) keeps the lights on for a predefined amount of time. By guaranteeing continuous illumination while the occupied space is in use, this timing technique improves user comfort and avoids needless relay switching brought on by brief disruptions in occupancy detection.

Relay A and Relay B's respective operational states are represented by the relay state variables, RA and RB. The two separate bracket-light channels are switched by these variables, enabling each lighting output to be turned on or off in accordance with the embedded control algorithm's judgements. Lastly, the status of the wireless network connection is represented by the WLAN State (W) variable. Its main purpose is to offer browser-based local access for lighting system monitoring and control. Nevertheless, even in situations when WLAN connectivity is momentarily unavailable, the embedded controller may maintain both automated and manual lighting operation because this variable is not necessary for the execution of the basic sensor-based control logic.

B. DECISION LOGIC

When recent motion is detected and the measured ambient light situation is categorized as dark, a channel in automatic mode is allowed to energize. After the final motion event, a configurable hold interval keeps the active state. The controller de-energizes the appropriate channel when the interval passes without a new event. When natural or existing light is sufficient, bright-condition inhibition takes precedence in automated mode, limiting needless activation.

Explicit overrides include browser commands and manual push-buttons. Depending on the mode that is chosen, they enable a user to operate either channel separately or both channels at once. Multiple transitions cannot be created with a single press thanks to button debouncing. When the LDR measurement varies close to the decision point, relay chatter can be minimized by using a threshold band or hysteresis around the light boundary. Figure 1 below illustrates the program flowchart and program logic for the rule-based WLAN smart lightning system.

C. STATE PRIORITY AND FAILURE BEHAVIOR

An explicit priority policy is necessary for a functional controller. Software for emergency electrical protection is still external. When the override expires or the user switches the system back to automatic mode, the automated rule restarts, but valid local or authenticated remote commands take precedence within firmware as configured. The controller writes changes to the state once, and the relays, display, and web response all receive them. Contradictory interface indications are avoided in this way. Sensing, timing, local buttons, and relay control are unaffected by WLAN loss, but browser access is eliminated. Using credentials that have been stored, the firmware regularly tries to reconnect and displays the network status on the LCD. Because local function is independent of cloud or Internet availability, this edge-first approach is better for fundamental building functions.

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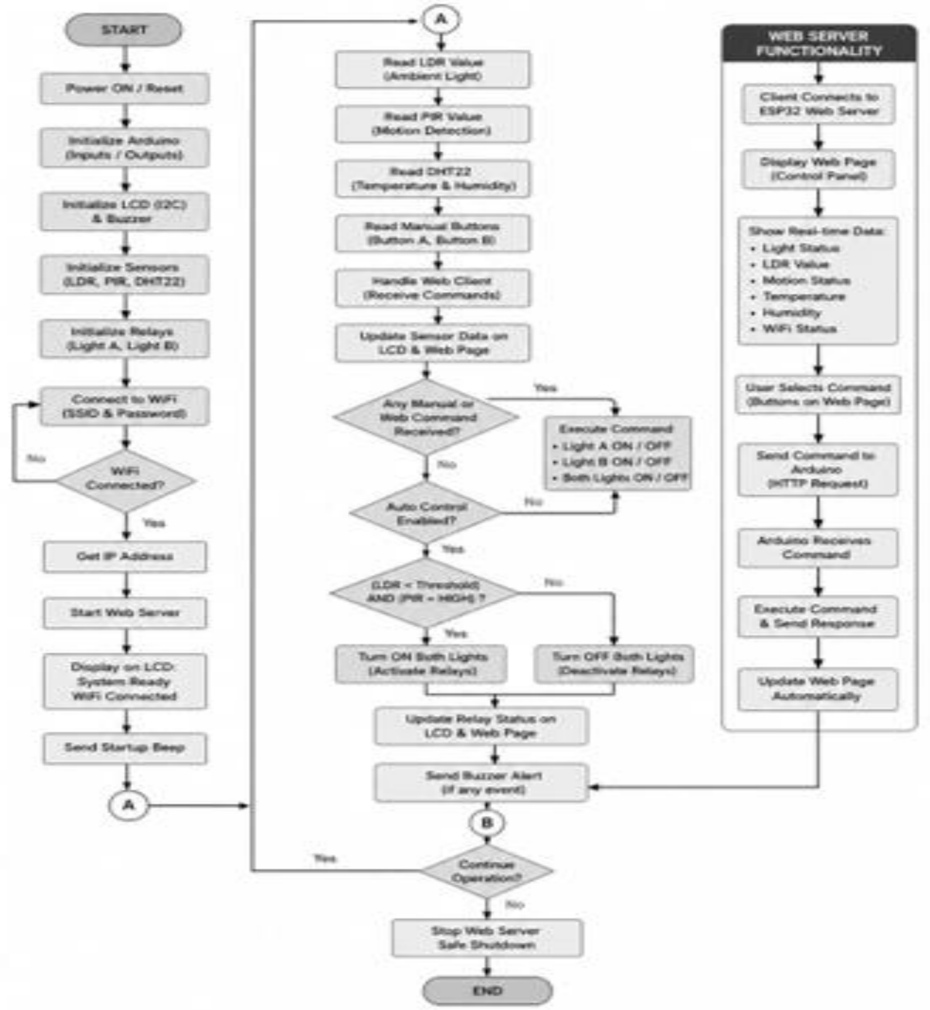

Figure 1. Program flow for Initialization, Sensing, Automatic Decisions, Manual Inputs, and WLAN Service

III. PROTOTYPE AND EXPERIMENTAL METHOD

D. PHYSICAL IMPLEMENTATION

The experimental unit contains an ESP32, LDR, PIR sensor, DHT22, two transistor-driven relays, four local buttons, a 16 x 2 I2C LCD, buzzer, regulated supply, and two bracket lights. The components were first integrated on a PCB and then housed in a protective prototype enclosure. The front panel provides channel controls and status, while sensors are positioned to observe ambient conditions and nearby movement.

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Figure 2. Enclosed prototype with two bracket lights, sensing modules, display, status indicators, and local controls.

E. FUNCTIONAL EVALUATION

A scenario matrix was used in the functional evaluation of the WLAN-connected dual-way lighting prototype to confirm that the rule-based occupancy and daylight control algorithm operated under a variety of communication and environmental conditions. Effective daylight-based energy conservation was demonstrated by the successful inhibition of automated lighting activation during bright ambient circumstances, regardless of occupancy. When there was no motion and it was dark, both lighting channels stayed off after the predetermined hold time, but when motion was detected, the chosen lighting channel was correctly triggered. The successful execution of separate Channel A and Channel B orders sent through local push buttons served as validation for manual control. Similarly, while erroneous requests did not result in any unintentional relay switching, legal control commands sent over the WLAN browser interface were correctly handled. By preserving embedded automated and local control after a WLAN outage, the prototype also showed fault tolerance. The ESP32 controller automatically restored browser access and communication upon the restoration of network connectivity, demonstrating dependable wireless operation and strong system functionality.

F. PROTOCOL FOR A PERFORMANCE STUDY

To move from functional validation to publishable comparative performance evidence, a follow – up experiment should log time – stamped illuminance, PIR state, relay state, HTTP command time, received-command time, power, energy, WLAN signal strength, and connection state. A manual – only baseline and the automatic strategy should be tested over matched occupancy schedules and daylight conditions. The observation period should cover multiple days and room – use patterns.

A number of quantitative performance metrics were used in the performance evaluation of the rule-based occupancy and daylight control system for the WLAN-connected dual-way lighting prototype. These metrics were chosen to evaluate the efficacy, responsiveness, dependability, and communication performance of the developed smart lighting system. Energy reduction was used to evaluate the energy-saving capability of the automatic lighting control algorithm; the percentage energy reduction was calculated using the following expression:

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$$\text{Energy Reduction (\%)} = \frac{E_{baseline} - E_{control}}{E_{baseline}} \times 100$$

Where,
Ebaseline represents the electrical energy consumed under conventional manual lighting operation, while Econtrol denotes the energy consumed when the rule-based automatic control system was active. This statistic quantifies the degree of energy conservation attained by the prototype by offering a direct comparison between the suggested intelligent control technique and manual lighting operation.

Command latency was used to assess the WLAN – based control system's communication efficiency. The time interval between the arrival of a legitimate control request at the controller and the completion of the associated relay switching operation was referred to as command latency. In order to offer a thorough evaluation of the responsiveness of the wireless control interface, the recorded latency values were statistically evaluated by providing the median reaction time, the 95th percentile latency, and the maximum observed latency.

Occupancy recall was used to evaluate the performance of occupancy detection. The ratio of accurately identified occupied intervals to the total number of real occupied intervals derived from ground-truth data was used to calculate this statistic. The capacity of the passive infrared (PIR) sensing subsystem to reliably detect human presence while reducing missed occupancy events that can result in insufficient lighting control is known as occupancy recall.

Using the false activation rate, the occupancy sensing algorithm's resilience was further assessed. By dividing the total observation time by the number of needless lighting activation events, this statistic was calculated. The false activation rate shows how well the PIR sensor and the chosen daylight threshold avoid undesired lighting operations brought on by false motion detection or improper environmental circumstances.
Availability, which was defined as the ratio of the total time that a valid local lighting control remained operational to the complete observation duration, was used to quantify system reliability. Availability shows the smart lighting prototype's capacity to continue operating without interruption during regular use and displays the continuity of service it offers.

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IV. RESULTS

The required decision logic was adhered to by the functional scenarios. While motion-based activation was made possible by darkness, bright exposure inhibited automatic illumination. Both relays had independent responses and could be used in tandem. The LCD and web interface displayed system and sensor data, and local buttons offered a control path without a browser. The controller automatically restored communication following a purposeful disruption of the WLAN.

The test results provide a feasibility-level response to the four study topics. Coordinating ambient and occupancy inputs, maintaining separate channel control, integrating local and web interactions around controller-held state, and recovering network service without altering the local logic of the controller were all accomplished by the ESP32. During the functional sequence, there were no reports of unexpected resets or unreliable relay operations.

V. DISCUSSION

Deterministic edge processing is the primary design decision. Without the uncertainty or connectivity reliance of a remote inference service, the rule can be examined, adjusted, and tested. An LDR gate and occupancy hold timer offer a commensurate level of intelligence for a two-channel space since they directly address premature switch-off and functioning in adequate light. This is consistent with the body of research on networked lighting and local sensing.(Caicedo & Pandharipande, 2012; Karapetyan et al., 2019).

The importance of user agency persists. One light sensor might not accurately reflect task-plane illumination across a room, and occupancy sensors might overlook people who are stationary. Thus, fault tolerance and usability are enhanced by independent local override. On the other hand, a production controller should reveal an override period or a clear return-to-auto action because an infinite override could undermine energy objectives.

A numerical energy savings is purposefully not claimed in the study. The reported savings for daylighting, dimming, or stairwell controls, for example, are based on baseline schedules and installation conditions.(Burmaka et al., 2020; Lee et al., 2018). It would be methodologically flawed to apply those percentages to this prototype. The proof needed for a future comparison of energy and responsiveness is provided by the suggested logging technique.

VI. LIMITATIONS

A controlled prototype setting was used for evaluation, and categorized results were documented. Calibrated lux levels, power or energy traces, command timestamps, signal strength logs, sensor confusion matrices, and repeated trials are not included in the source data. Network congestion, stationary occupancy, lighting variability, room shape, and sensor placement were not systematically changed. Cloud-scale coordination and dimming are not implemented, and the system is restricted to two relay-switched channels.

VII. CONCLUSION

An explicable combination of ambient-light gating, PIR occupancy events, a hold timer, and explicit manual or web commands controlled a two-channel lighting prototype connected to a WLAN. The desired functional behaviour and automatic network recovery were validated by scenario tests, and local embedded operation continued to be accessible without the need for public Internet connectivity. The architecture provides a reliable foundation for smart building experiments, but before energy-saving, latency, or reliability performance can be measured, an instrumented baseline comparison is needed.

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