

Occupant-aware Lighting Control Algorithm with Dynamic Retention Time

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Abstract—Energy-efficient lighting control is an essential element in modern intelligent indoor spaces, aiming to minimize energy consumption while maintaining occupant comfort. Conventional occupancy-based lighting systems often rely on fixed retention times and zone-based actuation, leading to unnecessary lighting of unoccupied areas or premature deactivation that degrades user comfort. This paper proposes a lighting control algorithm that optimizes both dimming levels and retention times based on real-time occupant positioning. An influence-based illuminance model is introduced, incorporating luminous intensity, incidence angle, and the inverse-square law to determine each luminaire's contribution to an occupant's illuminance. Optimal dimming levels are obtained via linear programming to minimize total energy consumption under task lighting constraints. Furthermore, retention times are dynamically adjusted according to the occupant-luminaire distance and its rate of change, with predefined minimum and maximum bounds to ensure stability. Monte-Carlo simulation results in various ceiling luminaire configurations demonstrate that the proposed algorithm achieves notable energy savings in typical and moderately dense lighting layouts compared to a static-retention baseline, confirming its effectiveness for practical smart lighting deployments.

Index Terms—Smart lighting, occupancy sensing, dynamic retention time, dimming control, energy efficiency.

I. INTRODUCTION

Energy-efficient lighting control has emerged as a critical research area within the domain of intelligent indoor spaces, driven by the dual imperatives of energy conservation and occupant comfort. In commercial environments such as offices, educational facilities, and commercial spaces, lighting accounts for a significant portion of total electricity usage, underscoring the substantial potential for optimization and energy cost reduction in lighting usage. To address this challenge, recent advancements in lighting technologies have enabled more sophisticated control schemes that go beyond traditional binary ON/OFF operation. These developments support continuous dimming, adaptive brightness modulation, and integration with occupant-aware sensing systems, thereby facilitating lighting strategies that reduce energy consumption while enhancing visual comfort and user satisfaction.

A wide range of intelligent lighting control methodologies have been proposed to improve energy efficiency and occupant satisfaction. Among the most established simple techniques are occupancy-based controls using Passive Infrared (PIR)

sensors, which switch lights ON upon motion detection and OFF after a fixed timeout period [1], [2], [9], [14]. While simple and cost-effective, such binary control schemes are limited in their responsiveness and flexibility. More advanced systems integrate ambient light sensors to support daylight harvesting, whereby artificial lighting is continuously dimmed in response to available daylight to maintain desired illuminance levels [3], [4], [10], [11], [15]. These strategies have proven effective in reducing energy consumption by adapting lighting to environmental and occupancy conditions. In practice, zonal control architectures where multiple luminaires are governed by a shared set of sensors remain widely used due to their simplicity and low installation cost [1], [5], [12], [13], [19]. However, such systems suffer from limited spatial resolution, often illuminating large areas based on the presence of a single occupant. To overcome this limitation, recent studies have explored sensor fusion approaches, combining PIR with ultrasonic, vision-based, or Wi-Fi signal-based occupancy detection to enhance robustness and spatial accuracy [2], [6], [18], [20]. In parallel, user-centric paradigms have emerged, leveraging real-time occupant localization and activity recognition to personalize lighting conditions at the individual level [7], [8], [16], [22], [23]. These prior works collectively highlight the growing demand for fine-grained, adaptive lighting control systems that can dynamically respond to both user behavior and environmental context.

In response to these trends and limitations of fixed timeouts or purely rule-based strategies, this paper proposes a lighting control algorithm that adapts *retention time* (i.e., the duration a dimming level is held before reconsideration) dynamically based on the geometric relationship between luminaires and occupants. The key idea is to couple control decisions with simple, physically grounded quantities that reflect how much a luminaire actually contributes to the illuminance experienced at occupied locations. By exploiting occupant-luminaire distance and incidence direction, the controller prioritizes updates where they matter most, while naturally de-prioritizing distant or weakly contributing luminaires. This occupant-aware, geometry-informed adaptation results in more frequent and localized updates in regions of interest and fewer updates elsewhere, aiming to reduce unnecessary lighting while preserving target illuminance on the working plane.

The remainder of the paper is organized as follows. Section II presents the system model and details the proposed lighting-control algorithm, including the definition of dynamic retention time and its design bounds. Section III describes the simulation setup and evaluation methodology, and reports comparative results against a static-retention baseline across multiple grid densities. Section IV concludes the paper and discusses practical implications and future research directions.

II. PROPOSED METHOD

A. System Model

This section defines the mathematical model used to compute optimal dimming levels in response to occupant positioning. Let there be a set of occupants indexed by $i \in \{1, 2, \dots, n\}$, and a set of luminaires indexed by $j \in \{1, 2, \dots, m\}$. The position of occupant i is denoted by $\mathbf{p}_i \in \mathbb{R}^3$, and the fixed position of luminaire j is denoted by $\mathbf{l}_j \in \mathbb{R}^3$. Each luminaire j has a dimming level $d_j \in [0, 1]$, where 0 represents the OFF state and 1 represents full brightness. To represent the spatial contribution of luminaires to the illumination of occupant i , we adopt the luminous intensity-based illuminance equation, which accounts for the inverse square law and incidence angle:

$$f_{ij} = \frac{I_j(\theta_{ij}) \cdot \cos \theta_{ij}}{\|\mathbf{p}_i - \mathbf{l}_j\|^2} \quad (1)$$

where $I_j(\theta_{ij})$ is the luminous intensity [cd] of luminaire j in the direction of occupant i , θ_{ij} is the angle between the luminaire's optical axis and the line connecting the luminaire to occupant i , and $\|\mathbf{p}_i - \mathbf{l}_j\|$ is the Euclidean distance [m]. Since luminaires are nadir-aimed, the emission polar angle equals the incidence angle on the working plane.

The illuminance at occupant i 's position is expressed as:

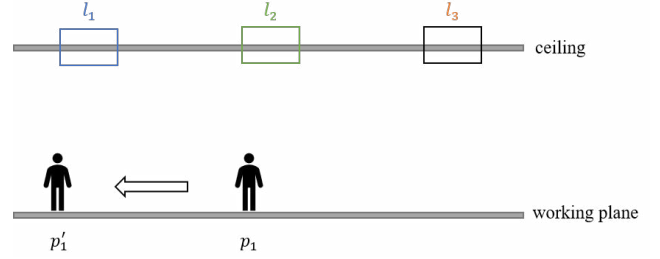
$$E_i = \sum_{j=1}^m f_{ij} \cdot d_j \quad (2)$$

Here, d_j scales the luminous intensity proportionally to the dimming level, assuming a linear relationship between dimming and luminous flux.

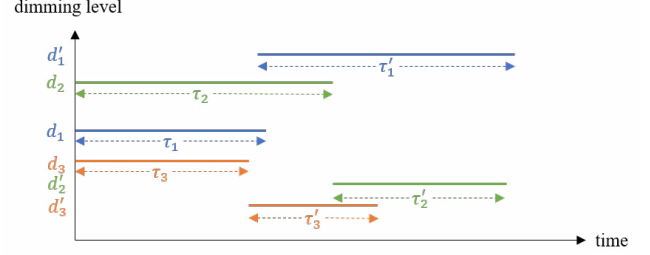
The dimming control is cast as a linear programming (LP) problem:

$$\begin{aligned} \min \quad & \sum_{j=1}^m d_j \\ \text{s.t.} \quad & E_i \geq S, \quad \forall i \\ & 0 \leq d_j \leq 1, \quad \forall j \end{aligned} \quad (3)$$

where S is the target illuminance on the working plane according to the space's task lighting requirements. The first constraint ensures that the illuminance at each occupant's location satisfies the target value, while the second constraint enforces the physical operating range of the dimming levels.



(a) Geometry with three luminaires and one occupant position.



(b) Dimming level and retention timeline

Fig. 1: Example of the proposed occupant-aware dynamic-retention lighting control with three luminaires and one occupant.

B. Lighting Control Algorithm

The proposed control algorithm operates iteratively at each time step, dynamically updating both the dimming levels and retention times of all luminaires. The algorithm first collects real-time occupant positions $\mathbf{p}_i$. Based on these, it solves the linear program to obtain optimal dimming levels d_j . Once the optimal dimming level for each luminaire is determined, it is necessary to decide how long that level should be maintained.

At the initial stage of the algorithm, the retention time τ_j is determined based on the distance between the luminaire and the occupant. We define a distance-based weighting term g_{ij} as:

$$g_{ij} = \frac{1}{\|\mathbf{p}_i - \mathbf{l}_j\|} \quad (4)$$

where $\|\mathbf{p}_i - \mathbf{l}_j\|$ is the Euclidean distance [m] between occupant i and luminaire j . The initial retention time is then given by:

$$\tau_j = \tau_{\text{base}} \cdot g_{ij} \quad (5)$$

where τ_{base} denotes the maximum retention time when the occupant is at the closest point to the luminaire. We normalize g_{ij} so that $g_{ij} \in (0, 1]$ with $g_{ij} = 1$ at the closest approach. Then we set τ_j described in (5) and finally clip it within the admissible bounds $\tau_{\min} \leq \tau_j \leq \tau_{\max}$, where $\tau_{\min}$ and $\tau_{\max}$ denote the minimum and maximum allowable retention times, respectively. This implies that the proposed algorithm assigns longer retention times to luminaires that are closer to the occupant, while those located farther away are given shorter retention periods.

As the lighting system operates based on the initially configured retention times, certain luminaires will eventually

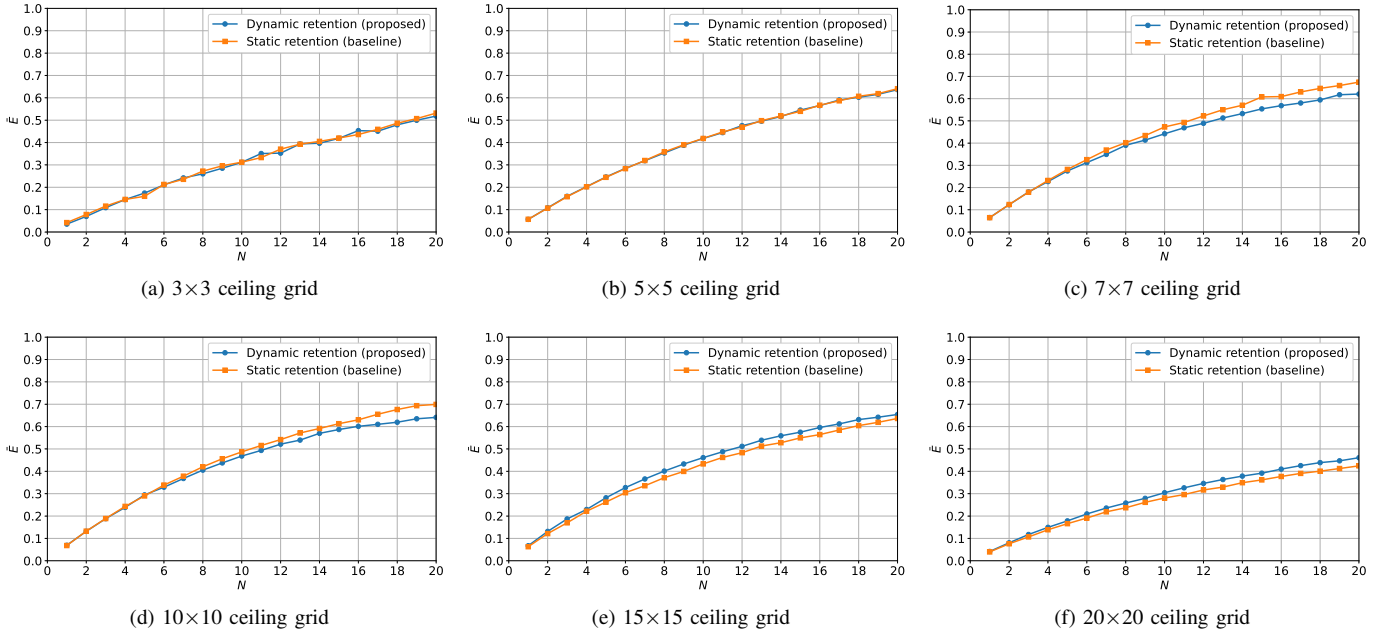


Fig. 2: Normalized energy consumption vs. number of occupants for different ceiling luminaire arrangements.

reach the expiration of their retention periods. Upon expiration, the luminaires update their dimming level and retention time based on the updated occupant's position p'_i . The updated dimming levels d'_j are obtained by minimizing the sum of those associated with luminaires whose retention times have expired, while considering the fixed dimming levels of active luminaires and satisfying the constraints defined in (3).

Meanwhile, the retention time is updated based on the rate of change in the distance-based weighting term g_{ij} . The rate of change is defined as:

$$r_{ij} = \frac{g'_{ij} - g_{ij}}{g_{ij}} \quad (6)$$

where g'_{ij} is the value of g_{ij} when the retention time of luminaire j expires. If $r_{ij} < 0$, it indicates that the occupant is moving away from the luminaire; otherwise, it implies that the occupant remains in the same location or is approaching the luminaire. The updated retention time is computed as:

$$\tau'_j = \tau_j \cdot (1 + r_{ij}) \quad (7)$$

Finally, τ'_j is clipped to $[\tau_{\min}, \tau_{\max}]$, to prevent excessively short or long retention times.

Figure 1 illustrates this mechanism for a simple case with three luminaires and one occupant. For a given occupant position, the controller determines the dimming levels $\{d_j\}$ via (3) and assigns the corresponding retention times $\{\tau_j\}$. When a retention time expires (e.g., τ_3), the occupant's updated position p'_1 is sampled and the expiring luminaire is re-computed, yielding (d'_3, τ'_3) , while the remaining luminaires keep their previously assigned (d_1, τ_1) and (d_2, τ_2) until their own expirations.

This sequence of operations is repeated whenever a luminaire's retention time expires. In the absence of any occupants, the luminaires are either turned off or maintained at a user-defined minimum dimming level. In such cases, all distance-related parameters and retention time states are reset to their initial configurations, ensuring a clean restart when new occupancy data becomes available.

III. PERFORMANCE EVALUATION

We evaluate the proposed lighting control algorithm against a static-retention baseline using Monte-Carlo simulations. The metric of interest is the normalized energy consumption $\bar{E}$, which represents the ratio of the total energy consumed during the simulation to the energy that would be consumed if all luminaires operated at full dimming level ($d_j = 1$) for the entire simulation period. Formally, it is defined as:

$$\bar{E} = \frac{1}{T} \sum_{t=1}^T \frac{1}{m} \sum_{j=1}^m d_j(t) \quad (8)$$

where T is the total number of time steps, m is the number of luminaires, and $d_j(t) \in [0, 1]$ is the dimming level of luminaire j at time t .

The simulation assumes a $20 \text{ m} \times 20 \text{ m}$ indoor space with a ceiling height of $h = 3 \text{ m}$. Luminaires are placed on the ceiling according to uniform grids of size 3×3 , 5×5 , 7×7 , 10×10 , 15×15 , and 20×20 , and occupant height is neglected in the model ($z = 0$). Occupants move according to a random-walk process with reflecting boundaries. The luminous intensity of each luminaire is set to $I_j = 800 \text{ cd}$, and we set $S = 500 \text{ lx}$ across all settings. We simulate $T = 60$ time steps and average results over 100 Monte-Carlo runs for each occupant count

$N \in \{1, \dots, 20\}$. The baseline method uses a fixed retention time $\tau = 10$ s for all luminaires. The proposed method applies the dynamic retention mechanism, with parameters set to $\tau_{\text{base}} = 6$ s, $\tau_{\text{min}} = 2$ s, and $\tau_{\text{max}} = 10$ s. These bounds prevent excessively short or long retention periods, ensuring both responsiveness and stability.

The simulation results are illustrated in Fig. 2, where subplots (a)–(f) correspond to the six grid configurations listed above. Across all cases, $\bar{E}$ generally increases as the number of occupants grows, since more luminaires are activated at higher dimming levels to meet the target illuminance. In sparse grids such as 3×3 and 5×5 , both algorithms exhibit similar performance at low occupancy, with slight divergence at higher occupancy levels. As the luminaire density increases (7×7 and 10×10), the proposed method shows a more noticeable reduction in energy consumption compared to the static baseline, thanks to its ability to shorten retention times for luminaires far from occupants while maintaining sufficient illumination locally. In the highest-density cases (15×15 and 20×20), the baseline shows slightly lower energy consumption, which is attributed to the dense layout reducing the need for frequent updates. Nevertheless, for typical and moderately dense lighting layouts, the proposed method demonstrates clear advantages in energy savings by adapting more responsively to occupant movement, confirming its effectiveness for practical smart lighting deployments.

IV. CONCLUSION

This paper presented a lighting control algorithm that integrates occupant-position awareness with dynamic retention time adjustment to improve energy efficiency in indoor environments. By employing an influence-based illuminance model and formulating the dimming control problem as a linear program, the proposed method ensures that each occupant's target illuminance is satisfied while minimizing overall energy usage. Retention times are adaptively modulated based on occupant proximity and movement trends, constrained within predefined bounds to avoid excessively short or long retention durations.

Performance evaluations through Monte-Carlo simulations across multiple luminaire density configurations showed that the proposed method consistently reduces normalized energy consumption in typical and moderately dense layouts compared to a static-retention baseline. While in very high-density lighting configurations the baseline exhibited slightly lower consumption, this scenario is less representative of practical deployments. Overall, the results validate that the proposed approach is particularly effective in environments where lighting density and occupant movement patterns demand localized, responsive control, making it a promising solution for next-generation intelligent building lighting systems.

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