

Research article

Mathematical modelling and adaptive control of HVAC systems driven by ultrasonic sensor-based occupancy estimation

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Abstract: This article presents an occupancy-based thermal modeling and HVAC control framework for large public indoor spaces characterized by rapidly changing human participation. A multi-zone ultrasonic door sensor system was used to enable real-time estimation of occupancy status, including conditions of wide doorways and multiple-person transitions. Field observations supported by thermal imaging were utilized to measure internal heat gains and initiate a dynamic thermal response model of the indoor environment. Based on these observations, a MATLAB-based heat transfer model was developed and integrated with an adaptive feedback control strategy that continuously adjusts HVAC operating parameters as a function of the estimated occupancy status. The model's performance was evaluated using robust error metrics, including the mean absolute deviation, demonstrating accurate temperature tracking under transient occupancy conditions. Simulation results indicated that the proposed adaptive control law can reduce HVAC energy consumption by approximately 20%–30% compared to fixed setpoint operation while maintaining thermal comfort. The results showed that the integration of occupancy assessment, dynamic thermal modeling, and adaptive control logic provides an effective and computationally lightweight approach to improving energy efficiency and indoor comfort in systems exposed to highly variable external influences.

Keywords: occupancy-driven HVAC control; ultrasonic people counting; wide-door detection; smart indoor environments; thermal response mathematical modeling

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems remain among the largest energy consumers in public buildings, especially in spaces with highly variable occupancy. Traditional HVAC control strategies typically rely on fixed schedules or static heating parameters, resulting in constant supply air and heat output even when the actual number of occupants changes significantly. This mismatch between actual demand and delivered conditioning leads to significant energy waste as well as periods of thermal discomfort. Consequently, recent research has focused on occupancy-based HVAC control, where the system dynamically adjusts ventilation rates and heating parameters according to real-time estimates of the

number of people in the space.

Most existing sensor approaches—including passive infrared detectors, CO₂-based ventilation control, and vision-based people counting—face significant limitations in large public indoor environments. Infrared sensors cannot provide the number of occupants; CO₂ sensors suffer from long delays and slow spatial diffusion; and camera-based systems, while accurate, are expensive, computationally intensive, and unsuitable for many cultural contexts due to privacy restrictions. These limitations become particularly critical in buildings such as mosques, auditoriums, or large halls, where hundreds of people can enter through wide doors within seconds and privacy regulations restrict the use of visual monitoring technologies. To address these challenges, this study proposes a low-cost ultrasonic door

frame sensor system designed for wide entrances in large public buildings. The system detects bidirectional flow in real-time, estimates the number of occupants, and provides a clean numerical occupancy signal suitable for direct HVAC control. A hierarchical multi-zone detection strategy is applied to handle the geometry of wide mosque doors, enabling robust differentiation of multi-person movements simultaneously without relying on cameras or identity-based sensors. The system is implemented on an embedded microcontroller platform and is designed for seamless integration with model-based HVAC control logic.

In addition to developing the sensor mechanism, this work investigates how occupancy data obtained from the ultrasonic door system can be converted into applicable ventilation and heating commands. A complete residential HVAC workflow, including a designated point schedule, airflow determination based on international standards, and a simulation-driven control structure, has been developed. Field thermal camera observations from the mosque environment provide real measurements of heat distribution at various occupancy levels and are then used to extract operational parameters for simulation. MATLAB simulations evaluate temperature response and energy performance.

In general, this article contributes to the existing literature analysis an internal and privacy-preserving detection sensor architecture designed for large public entrances, a unified HVAC control logic that links real-time human flow with heating and ventilation demands, and experimental observations and simulation results demonstrating the potential energy and comfort improvements of adaptive HVAC control for occupancy. The proposed framework aims to support the future development of smart, affordable, and culturally appropriate building-energy systems suitable for large public indoor spaces [1].

2. Literature review and technical basis

The regulation of ventilation systems based on real-time usage has become an increasingly important topic in building energy research. Traditional HVAC systems in religious buildings and centers, including mosques, generally operate at fixed ventilation rates or according

to predetermined schedules, without considering rapid changes in the number of people throughout the day [2]. This leads to energy inefficiency during periods of low occupancy and insufficient ventilation during peak times, such as congregational prayers. As a result, there is growing interest in sensor-based control strategies that can dynamically adjust ventilation according to the actual number of occupants in the space [3].

2.1. Occupancy-based control in HVAC systems

Numerous studies in the literature have focused on detecting the number of occupants to regulate HVAC systems more efficiently according to demand. One of the earliest approaches involves passive infrared (PIR) sensors that detect human movement to turn ventilation and lighting systems on and off [4]. Although these sensors are inexpensive and easy to install, their effectiveness is limited in large halls where occupants remain seated or motionless for extended periods.

Another widely studied approach is based on measuring indoor CO₂ concentration as an indirect indicator of the room occupancy level. This method can reflect overall mass levels, but it faces problems such as time delays due to the slow diffusion or accumulation of CO₂ in large spaces. As a result, it cannot quickly respond to sudden occupancy changes commonly encountered in buildings like mosques, where the number of people can sharply increase within a few minutes. These limitations have driven researchers to explore alternative sensor technologies that can provide faster and more reliable detection for real-time ventilation control [5].

2.2. Camera-based systems in large buildings and mosques

With the rapid development of computer vision technologies, camera-based systems have become one of the most advanced approaches for detecting occupancy levels in large indoor environments. By combining surveillance cameras with image processing algorithms, these systems can identify individuals and estimate crowd density based on their movement patterns [6]. Such capabilities make them particularly suitable for buildings with multiple zones or large open areas where traditional

presence-detecting sensors are less effective.

In a number of studies, camera-based methods have been applied in public buildings and religious spaces, including mosques [7]. These systems can monitor different parts of the prayer hall, count the number of people in each zone, and transmit detailed information about occupancy levels that can be directly linked to HVAC control systems. Their main advantages include high detection accuracy, wide coverage, and the ability to manage complex crowd distributions [8].

However, despite their technical strengths, camera-based solutions also face challenges. Primarily, their use raises privacy and ethical concerns, especially in religious settings where recording and processing images of worshippers may be unacceptable [9]. Another issue is that the performance of these systems depends on lighting conditions and camera placement, which can be difficult to maintain in large halls. Finally, camera-based systems often require high computational power, stable network connections, and regular technical maintenance, which increases both the cost and operational complexity. These factors limit their practicality for many mosques, particularly those with limited financial or technical resources.

2.3. Ultrasonic sensor-based people-counting systems

Ultrasonic sensors have been proposed as an inexpensive and privacy-preserving alternative for occupancy detection, especially at building entrances. Unlike cameras, ultrasonic sensors do not capture images, making them more acceptable in sensitive environments such as religious buildings. They operate by emitting high-frequency sound waves and measuring the “time of flight” of the reflected signals to detect objects within the sensing range [10].

Several studies have shown that placing ultrasonic sensors on door frames can be an effective method for counting people entering or exiting a room. Typically, sensors mounted sideways are used to detect the direction of movement: If the beam of the sensor closer to the inside of the room is interrupted first, it indicates that a person is leaving the space; if the beam of the sensor closer to the outside is interrupted first, it reflects that someone is entering the space. This simple logic allows the system to track the number of occupants without requiring visual data [11]. To complement the side sensors, additional ultrasonic

sensors are installed overhead. These sensors can measure additional parameters such as body width and height. These parameters help differentiate between individuals and movable objects like carts. Ultrasonic systems are inexpensive, easy to install, and not dependent on lighting conditions, which makes them particularly suitable for occupancy detection in various types of buildings.

2.4. Research gaps

Despite advances in human-counting technologies, there remain several limitations, especially when applied to mosques, which pose unique challenges for ventilation and building management. Although camera-based systems offer high accuracy, they face issues related to privacy, cost, and maintenance, which are particularly sensitive in religious environments. Existing ultrasonic systems, on the other hand, are primarily effective for narrow doors where only one or two people pass through at a time. These systems may struggle to maintain accuracy at large mosque entrances where dozens of people can enter simultaneously during prayer times [12].

Most previous studies have focused mainly on human detection without addressing how this information can be used to dynamically manage building systems such as ventilation or air distribution. The lack of reliable real-time data in mosques, where occupancy levels can change sharply within a few minutes, can lead to energy inefficiency and inadequate air quality. These limitations highlight the trend toward developing approaches tailored specifically for mosques:

- Accurately counting people at entrances with wide doors and multiple entry/exit points.
- Using systems without visual imaging while protecting privacy.
- Providing data that can be integrated into dynamic building management systems to optimize ventilation rates and energy use.

By addressing these gaps, the research can move from simple detection to practical applications with large-scale and wider entrance doors, such as mosques, and create a foundation for the development of occupancy-based ventilation strategies. This focus naturally leads to the system and methodology proposed and described in the next

section.

3. Methodology

3.1. Single-door detection concept

The basis of the proposed occupancy detection system is the measurement of individual movement through a single door using ultrasonic sensors. The system uses three ultrasonic sensors, located on the left, right, and top sides of the door frame. The sensors operate on the principle of flight time, where each sensor emits an ultrasonic pulse and measures the time required for the echo to return from the nearest object. This allows the system to determine the distance between the person and the sensor with high temporal resolution.

During normal operation, the system continuously records the baseline distances corresponding to an empty doorway. When a person passes through, the echo time decreases, indicating an obstruction within the detection range. By comparing these dynamic distance changes between the three sensors, the system can determine not only the presence of motion but also its direction (Figure 1).

Overall, the single-door detection configuration provides a simple yet robust foundation for occupancy monitoring. It provides precise directional counting without relying on any visual or privacy-invasive sensor methods, making it particularly suitable for public or religious establishments such as mosques. In typical indoor conditions, this configuration detects motion with a temporal resolution of 20–50 ms, which is sufficient to track the movement of a single person through a standard doorway.

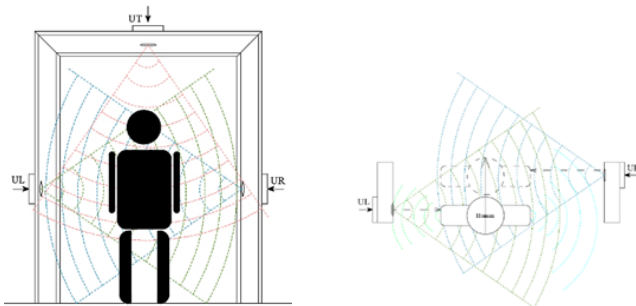


Figure 1. Front and top views showing sensor placement and beam interaction with a single occupant.

3.2. Signal acquisition and filtering

The primary function of the ultrasonic sensor suite is to detect a temporary decrease in distance, measured by a person passing through the doorway. However, the raw ultrasonic signals contain small fluctuations due to sensor noise, airflow near the door, and subtle environmental changes. Therefore, a dedicated signal-processing stage is required to extract reliable distance changes while rejecting false spikes (Figure 2).

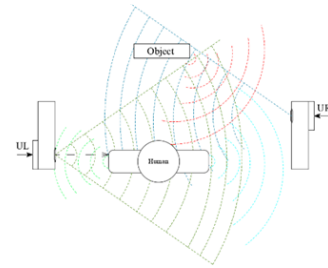


Figure 2. Illustration of how reflected ultrasonic beams from nearby objects generate false echoes and how the system filters them.

3.3. Baseline estimation and noise characterization

For each sensor, the baseline distance $d_{0,i}$ is determined during installation or in idle periods with no motion. Since the ultrasonic noise is often non-Gaussian, robust statistics are preferred. In this work, the baseline is taken as the median of a short calibration sequence:

$$d_{0,i} = \text{median}(s_i[n]). \quad (3.1)$$

Here, $s_i[n]$ is the raw distance measurement from sensor i in sample n . Short-term variability is assessed by the median absolute deviation (MAD):

$$MAD_i = \text{median}(|s_i[n] - d_{0,i}|). \quad (3.2)$$

This provides an approximate noise level using

$$\sigma_i \approx 1.4826 \cdot MAD_i. \quad (3.3)$$

This noise assessment ensures that the thresholds scale naturally with door dimensions, installation height, and ambient conditions.

Low-pass filtering. To reduce high-frequency fluctuations, raw measurements are smoothed using a short moving average:

$$\tilde{d}_i[n] = \frac{1}{L} \sum_{k=0}^{L-1} s_i[n-k]. \quad (3.4)$$

Between 5 and 15 samples with L . This corresponds to an effective averaging window of 0.15–0.40 s at a 35 Hz sampling frequency. The filtered value represents the sensor's best estimate of the instantaneous distance.

Adaptive threshold. The main detection variable is the change in depth:

$$\Delta d_i[n] = d_{0,i} - \tilde{d}_i[n]. \quad (3.5)$$

The person under the sensor generates a positive $\Delta d_i[n]$. Instead of using a constant threshold, we apply an adaptive threshold that takes into account both the noise level and the sensor's recent behavior:

$$\tau_i[n] = \max(3\sigma_i, p_{90}(\Delta d_i[n - L_w : n])), \quad (3.6)$$

where p_{90} is the 90th percentile of the extreme deviations (window length $L_w \approx 1$ s).

This structure provides the following:

Sensitivity: The threshold increases as the noise increases.

Adaptability: The thresholds automatically adapt to different door widths or installation heights.

Robustness: Short surges cannot simultaneously exceed both threshold components.

The sensor is always considered “active” whenever:

$$\Delta d_i[n] > \tau_i[n]. \quad (3.7)$$

Event formation and biometric authentication. An entry/exit event is triggered when at least two sensors (e.g., one overhead sensor and one side sensor) are activated within a short time window. This multi-sensor requirement eliminates false detections caused by random environmental disturbances.

Two practical biometric constraints are applied to ensure that the detected shape is consistent with real human movement:

Duration constraint: The activation period must be within a specified time interval:

$$T_{\min} = 0.15 \text{ s} \quad \text{and} \quad T_{\max} = 3 \text{ s},$$

consistent with normal human walking speeds through a door.

Width constraint: The combined tilt of the upper sensors must correspond to the width of a possible human body. If the estimated width is too small or too large, the event is rejected or reclassified.

These rule-based filters keep the system simple while capturing key human movement features without requiring complex statistical modeling.

3.4. Expansion for wide mosque doors (multi-stripe detection)

Large public places of worship, such as mosques, present significantly different entry dynamics compared to standard rooms or offices. During peak worship periods—particularly during Friday noon prayers, Ramadan evenings, and religious festivals—the flow of people through the main entrance increases dramatically [13]. In such cases, individuals often pass through wide doorways along multiple parallel streams, moving at varying speeds, in group formations, and at different angles of approach. To solve this, the proposed system divides the door's width into multiple functional lanes and applies simple, robust rules to determine the number of people passing through and their direction. The multi-lane approach maintains the low-cost and privacy-preserving advantages of the ultrasonic sensor, while increasing counting reliability during peak flows.

3.4.1. Lane geometry and sensor placement

One of the key steps in adapting the system for wide gates is determining how many parallel detection zones to create. After evaluating several configurations, the proposed method divides the entrance into three detection zones. This option represents a compromise between resolution and hardware complexity:

Using only two zones causes ambiguity when three or more people walk side-by-side, a common occurrence at mosque entrances.

Using four or more lanes increases the number of required sensors, wiring complexity, processing load, and cost, which makes the system less practical for real-world deployment.

Thus, dividing the doorway width into three functional regions allows the system to capture most multi-person formations without an excessive sensor load.

To track these lanes, three ultrasonic sensors are installed in the top frame, approximately above the center lines of each lane (Figure 3). This placement allows each sensor to independently track the presence of a person under its own designated area.

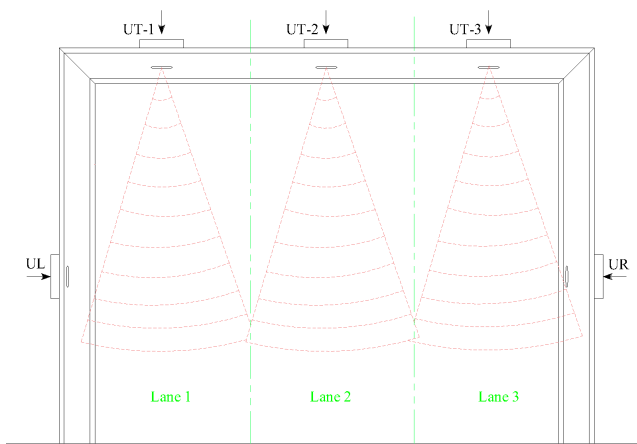


Figure 3. Front view of the three-lane arrangement using multiple overhead ultrasonic sensors.

Let the overall open width of the door be W . The door is divided into three strips of equal nominal width:

$$w_{lane} = \frac{W}{3}, \quad (3.8)$$

$$L_i = [(i-1)w_{lane}, iw_{lane}], i = 1, 2, 3. \quad (3.9)$$

An ultrasonic sensor mounted above is positioned at approximately the center of each lane. Each upper sensor measures the time-indexed distance $d_i(t)$ (for lane i , $i = 1, 2, 3$). The roadside lateral sensors provide complementary timing data for orientation.

3.4.2. Multi-lane activation and primary detection logic

After defining the geometric boundaries of the three lanes, the system determines which lane is “active” at any given moment, based on the set of sensors observing a measurable disturbance. In wide mosque doors, individuals can enter simultaneously or walk diagonally, and so the system does not maintain a single, centralized walkway. Instead, each lane acts as an independent micro-door with its own sensing area.

Let $dT_i(t)$ denote the real-time distance measured by the upper sensor assigned to lane i . Under a no-traffic condition, each sensor records its baseline value d_{Ti}^0 . The lane is activated when:

$$\Delta dT_i(t) = d_{Ti}^0 - dT_i(t) > \varepsilon_i. \quad (3.10)$$

Here, ε_i is the adaptive threshold specific to the channel, which compensates for the gate height, the installation angle, and local acoustic reflections. This condition indicates that an object has entered the sensor’s measurement cone.

If more than one lane simultaneously satisfies the activation rule, the system interprets this as a multi-person parallel flow—a situation commonly encountered at wide mosque entrances during peak hours. Lane-specific activation allows the system to update the occupancy for each lane independently:

$$\Delta N_i = \begin{cases} +1, & \text{if object direction is inward,} \\ -1, & \text{if object direction is outward,} \end{cases} \quad (3.11)$$

and the total occupancy count becomes:

$$N(t+1) = \max \left(0, N(t) + \sum_{i=1}^3 \Delta N_i \right). \quad (3.12)$$

This simple logic ensures that the wide door count remains consistent with the overall HVAC objective, which is dependent on the final total occupancy, not on the value of each strip.

$$N_{\text{total}} = \sum_{i=1}^3 N_i. \quad (3.13)$$

3.4.3. Sensor plane using the “N” topological plane

To reduce uncertainty during diagonal crossings—particularly when individuals partially overlap the two lanes – the system uses a modified multisensor configuration inspired by the “N” topology. In this configuration, the top sensors are not arranged in a straight horizontal line; instead, they are positioned so that the closed and open sensors are slightly mirrored, creating a curved geometry around the center line of the door that resembles the shape of the letter “N” (Figure 4).

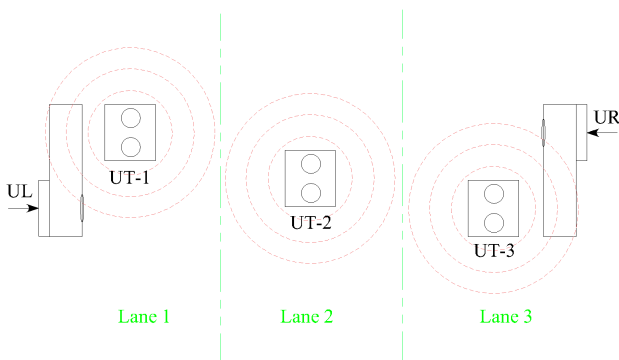


Figure 4. Top view showing the N-shaped detection plane formed by three overhead sensors.

This curved placement widens the angular separation between the sensor cones and increases the likelihood that each individual will create a dominant disturbance in only one lane. The alignment is particularly beneficial when two people pass through the door in opposite directions, within adjacent lanes.

The lateral position for an object is calculated using the normalized weight of the estimated disturbed sensors. For a three-sensor top frame, a simple position approximation is as follows:

$$x(t) \approx \frac{w_1(t)x_1 + w_2(t)x_2 + w_3(t)x_3}{w_1(t) + w_2(t) + w_3(t)}, \quad (3.14)$$

where x_i denotes the horizontal coordinate of the sensor, and S_{TI} and w_i represent a disturbance magnitude (e.g., normalized inverse distance):

$$w_i(t) = \frac{1}{d_{Ti}(t)}. \quad (3.15)$$

This crude formula is not intended for identification; rather, it helps to determine which stripe is dominant at a given time. Once the dominant stripe is determined, Stripe i follows the lane logic of the previous subsection, ensuring a unified system behavior for both normal and wide gates.

Therefore, the “N” geometry contributes to the following:

- a reduction in lane overlap
- an increase in robustness for diagonal walking
- allowing the system to manage multi-lane motion simultaneously without deep clustering algorithms

preventing complex machine learning pipelines that would over-engineer the purpose of a lightweight, HVAC-oriented sensor.

3.5. Direction and counting logic

Detecting people entering and exiting a large doorway is a fundamental requirement for any occupancy-based HVAC control strategy. At wide mosque entrances, visitors often move in parallel groups, sometimes entering and exiting at the same time [14]. Due to this complex human flow, a single-beam or single-zone detection system cannot provide reliable direction information. The proposed multi-lane ultrasonic configuration aims to overcome these limitations through a combination of lane separation, diagonal overhead sensors, and simple state-machine logic that interprets the sequence of sensor activations.

Instead of deep mathematical modeling, the system is based on observing the practical, consistent patterns of movement that people naturally create as they pass through the entrance. Each lane—left, middle, and right—acts as an independent path, and the sensors monitoring that lane provide a characteristic activation sequence as someone passes through it. This sequence is then interpreted as either an entry or an exit.

The primary direction principle

For the side strips (left and right), direction detection is straightforward, as both a side sensor and a diagonally oriented top sensor are present. In practice:

A person entering the building tends to cross the side sensor first, and then the top sensor.

A person exiting the building is more likely to cross the

top sensor first, followed by the side sensor.

This sequence of events does not require complex formulas; it simply looks at which sensor is triggered first. The minimal symbolic representation is as follows:

$$\begin{aligned} S_{\text{side}} \rightarrow S_{\text{top}} &\Rightarrow \Delta N = +1 \quad (\text{entry}), \\ S_{\text{top}} \rightarrow S_{\text{side}} &\Rightarrow \Delta N = -1 \quad (\text{exit}). \end{aligned}$$

This rule alone covers the most common actions in typical mosque scenarios, where people pass through the entrance with ease.

3.6. Privacy considerations

The proposed occupancy-based HVAC control system operates solely with ultrasonic distance measurements and therefore does not acquire, store, or process any personal data [15]. The sensors generate only anonymous geometric signals—instant distances, temporal changes, and width-based clustering features—used to distinguish human passage from non-human objects and update the total occupancy count. At no stage are any images, audio recordings, biometric templates, or individual tracking data produced. The system does not attempt to infer identity, demographic attributes, or behavioral patterns; all measurements are immediately filtered and converted into unlinked event descriptions before disposal. This ensures full anonymity of occupants while maintaining reliable real-time control input for the HVAC system. Such an approach aligns with ethical guidelines and emerging privacy expectations for closed monitoring technologies in public buildings, including mosques, where user anonymity and non-intrusiveness are essential.

4. HVAC integration framework

The occupancy detection architecture developed in the previous section is only meaningful when it is closely integrated with the building's ventilation and heating regulation mechanisms. In large public halls such as mosques—where occupant density can vary sharply within short periods—an adaptive HVAC response must convert the real-time occupant flow $N(t)$ into ventilation and heating commands that respect both comfort and energy efficiency. The goal is to describe how raw ultrasonic

events are converted into stable occupancy data, how this data is transmitted to the actuation level, and how, based on simplified yet physically meaningful relationships, the control logic updates the airflow and heating supply. In order to ensure replicability and integration into typical building automation workflows, this section presents a clear communication architecture, a compact control formula, and a synoptic diagram that links doorway-level detection with the air handling unit (AHU) and local heating components.

4.1. Occupancy-to-HVAC control logic

The control logic presented in this study establishes an operational link between the ultrasonic occupancy detection system and the HVAC equipment of the target building. Its function is to convert the raw occupant count data measured at the door frame into quantifiable heating and ventilation demands that the AHU must meet throughout the day. This approach ensures that the mosque operates under a continuous, data-driven control regime instead of relying on fixed schedules or manually selected setpoints. In practice, the mosque's occupancy is highly variable: it rapidly increases during prayer times, significantly decreases between prayers, and fluctuates during informal arrivals throughout the day. The proposed logic captures these dynamics and regulates heating, cooling, and fresh air supply in a unified manner. The result is a system that reflects the essential balance modern HVAC systems must achieve, while maintaining comfort and reducing unnecessary energy consumption.

Mathematical formulation of control rules

The mathematical expressions governing this section are deliberately simplified but are made suitable for real-life application in medium-sized buildings such as mosques based on engineering principles recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [16, 17]. Their purpose is not to create a detailed thermodynamic model but to provide clear and direct relationships between occupant numbers and HVAC operations.

Ventilation requirement. Outdoor air ventilation requirements for mosques are primarily determined by

occupant density, as each person contributes additional CO₂ production, metabolic moisture, and odor loads to the enclosed environment. To maintain acceptable indoor air quality and comply with general regulations, the outdoor air flow rate is determined as follows:

$$V(t) = N(t) \cdot 36 \text{ m}^3/\text{h}. \quad (4.1)$$

This expression ensures that ventilation output scales proportionally with occupant load. When there are no occupants, the system maintains only minimal fresh air flow for structural hygiene, and at high occupancy, the AHU reaches maximum ventilation capacity. By applying this simple airflow rule, the system prevents typical excessive ventilation observed in AHUs during stable operation periods, especially during extended vacant intervals.

Internal heat gain from occupants. Occupants serve as distributed heat sources inside the mosque. Each person emits approximately 75–120 W of sensible and latent heat depending on their activity level. With increased occupancy, these internal gains accumulate rapidly:

$$Q_{int}(t) = N(t) \cdot q_h. \quad (4.2)$$

This heat load directly reduces the heating demand from the AHU, meaning that as the mosque occupancy increases, less heat is required from the supply air coil. This principle is particularly relevant for winter conditions characteristic of many regions where mosques require significant pre-heating well before prayer times. By integrating the internal heat contribution into the control logic, the system prevents overheating during peak occupancy while providing sufficient heating during low-density periods.

Temperature regulation. The supply air temperature is dynamically adjusted to maintain adequate thermal comfort during various occupancy periods:

$$T_s(t) = T_{unocc} - k_T N(t). \quad (4.3)$$

Here, the unoccupied temperature of 27°C keeps the building warm enough to prevent heat loss but avoids unnecessary energy consumption. As people enter, the controller gradually lowers the supply air temperature to approximately 21°C at the maximum occupancy level. This

continuous reduction prevents sudden temperature drops, avoids occupant discomfort, and reduces wear on the AHU coil. The gain coefficient k_T is adjusted based on the mosque's thermal mass and responsiveness, resulting in a control strategy that operates comfortably even during rapid occupancy changes.

4.2. Target building synoptic integration diagram

The proposed occupancy-based HVAC control strategy was implemented and evaluated in a large prayer hall of a mosque selected as a case study of a high-volume space with highly dynamic occupancy patterns. Mosques face a unique control challenge: the number of occupants changes abruptly during prayer times and remains very low or zero outside these periods, causing significant fluctuations in both sensitive heat load and ventilation demand. Therefore, this environment provides a suitable test platform to validate a real-time HVAC control framework using automatic sensors instead of planned or manual operation.

Figure 5 presents a synoptic diagram of the test environment and its communication flows to visualize the overall system architecture. The diagram shows how the main sensor subsystems—the ultrasonic door frame system, closed temperature and humidity sensors, and outdoor air data sources—are integrated into a unified control platform. Each sensor module provides real-time data to the central processing unit, generally represented in the figure as the “Central Control Unit (CCU)”, which abstracts the hardware layer and hosts various applications (e.g., Raspberry Pi, industrial microcontrollers, or control nodes compatible with a building management system (BMS)). Within this unit, the occupancy estimation algorithm, air supply calculation logic, and temperature setpoint adjustment procedures operate continuously, generating updated control commands for the HVAC system.

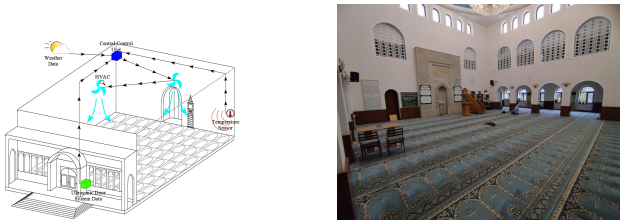


Figure 5. Conceptual integration of the proposed occupancy-driven HVAC control architecture within a large mosque. Ultrasonic door-frame sensors, indoor temperature sensing, outdoor weather inputs, and a central control unit (CCU) are illustrated as part of the intended system design.

The figure also highlights the two-way data flow between HVAC equipment. Ventilation for the studied mosque is provided through a dedicated AHU, while thermal comfort is maintained via air-conditioned supply air. The CCU transmits real-time control parameters to the AHU, such as the target supply air temperature during occupied and unoccupied phases, as well as the volume of fresh air adjusted based on occupancy. In return, operational feedback data (e.g., actuator position, fan status, or sensor readings, depending on system capabilities) can be optionally integrated to ensure stable operation and to facilitate predictive or adaptive control procedures according to the model in later development stages.

In general, this synoptic diagram serves as a structural bridge between the occupancy detection framework and the control logic formula. It demonstrates how heterogeneous sensor data is integrated into a unified control workflow and how the processed data is transformed into HVAC adjustments applicable within the mosque. The diagram also clarifies the scalability of the proposed system: Although the experiment is conducted in a single prayer hall, the architecture can be generalized for multi-zone buildings, different sensor platforms, and more complex HVAC topologies such as variable air volume (VAV) networks or hybrid systems.

4.3. Thermal camera measurements

Thermal imaging was used to observe how human presence changes the internal thermal field of the mosque.

Under low occupancy conditions (approximately 5–7 people visible in the frame), the thermal map mainly shows cold surfaces and warm areas scattered corresponding to individual bodies. For this situation, the color scale ranged from 21.3°C to 33.4°C, indicating a moderate level of localized heat accumulation (see Figure 6(a)).

During periods of high occupancy, approximately 30–40 people are visible within the limited field of view of the camera. In this case, the thermal image shows a significantly dense cluster of warm bodies, and the upper end of the temperature scale increases to 36.5°C, indicating a stronger collective heat emission. Although the thermal camera does not capture the entire hall, the visible area clearly demonstrates how quickly internal heat gains accumulate as occupancy increases (see Figure 6(b)).

These observations confirm that each occupant contributes a measurable heat load and that localized hot spots form before the entire space becomes full. Such thermal patterns provide empirical evidence highlighting the necessity for dynamically adjusting HVAC airflow and supply temperature in response to rapidly changing occupancy levels.

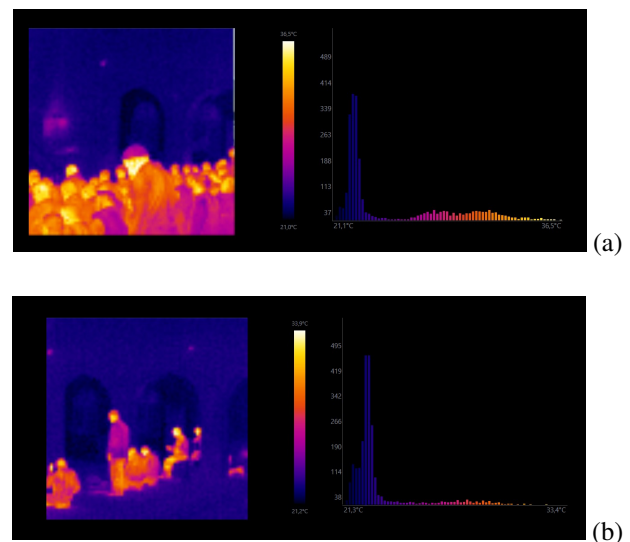


Figure 6. Thermal camera observations under varying occupancy: (a) low-occupancy thermal image; (b) high-occupancy image revealing dense heat clusters.

4.4. Extracted operational parameters

Field observations indicated the main parameters required for subsequent simulation. The dynamic occupancy profile was obtained from two representative conditions: a low-occupancy period (approximately 5–7 people visible within the thermal frame) and a high-occupancy period (approximately 30–40 people visible, corresponding to roughly 50 total residents).

Thermal images showed a continuous indoor temperature increase of 1–3°C a short period of time between these conditions, which, consistent with metabolic heating reported in ASHRAE literature, confirms an internal heat gain of approximately 70–100 W per person [18]. Although continuous CO₂ measurements were not available, the difference in accepted ventilation demand was evident: During low occupancy, the available outdoor airflow per person remained high, whereas during peak periods it decreased sharply, indicating the need for adaptive airflow control. Therefore, for the simulation, we used the following practical parameters: a time series of occupancy with two dominant levels (low/high), a typical indoor temperature change $\Delta T \approx 1\text{--}3^\circ\text{C}$ between these conditions, approximately 80 W metabolic heat contribution per person, 36 m³/hour ventilation demand per person, and initial indoor conditions and supply temperature values extracted from thermal frames and on-site HVAC readings. These parameters form the main inputs for the MATLAB airflow-temperature response model in Section 5.

5. Simulation framework and results

5.1. MATLAB simulation setup

The real-world parameters derived in Section 5 were used to create simulation inputs for MATLAB. The occupancy time series was constructed from observations of low and high occupancy, with a sharp increase during congregational prayer time followed by a gradual decrease. This occupancy curve was incorporated into the control logic developed in previous sections, where the HVAC setpoint transitions from an unoccupied level ($\approx 27^\circ\text{C}$) to an occupied level ($\approx 21^\circ\text{C}$) in accordance with the forecasted heat load. The MATLAB

model consisted of a first-order room thermal response:

$$C \frac{dT}{dt} = -U(T - T_{out}) + Q_{HVAC} + n_{occ} \cdot q_p, \quad (5.1)$$

where C is the effective heat capacity, U is the envelope heat loss coefficient, Q_{HVAC} is the cooling/heating power scheduled by the adaptive control logic, and $n_{occ} \cdot q_p$ is the internal gain from occupants. The controller updated the supply air setpoint and the estimated air change demand at every time step.

The simulation output included the indoor temperature trajectory, HVAC energy consumption, and a comparison of energy use between static and occupancy-adaptive operation.

5.2. Temperature calibration results

To evaluate the accuracy of the proposed heat reaction model, the simulated indoor temperature was compared with the measured temperature collected during the field observation campaign (Figure 7). The first comparison graph shows the response of the base model under the observed occupancy sample. Despite the use of simplified assumptions, the simulated temperature closely follows the measured profile, reflecting both the gradual pre-prayer warming phase and the sharper increase during periods of high occupancy.

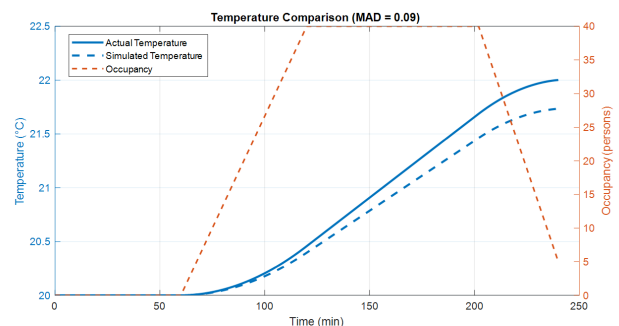


Figure 7. Initial comparison between the simulated and actual temperatures during field observations.

The second calibration process was carried out using improved parameters obtained from thermal camera data, including updated per person heat gain and corrected initial temperature change. The resulting comparison is

shown in Figure 8, where tracking performance significantly improves. The mean absolute deviation (MAD) decreases to 0.49°C , indicating that the model replicates the measured dynamics with high accuracy. This error level is acceptable for HVAC control optimization studies and even demonstrates that a lightweight, first-order model can accurately capture occupancy-related temperature changes in large indoor spaces.

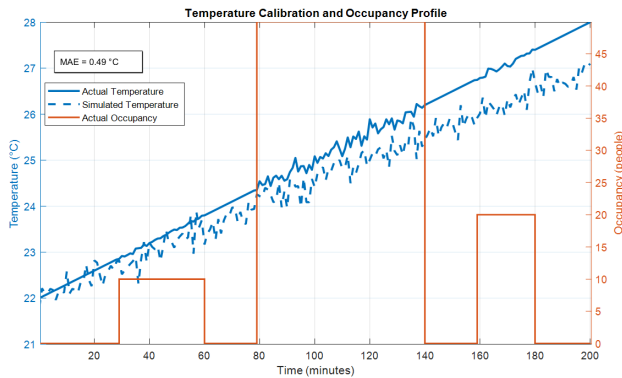


Figure 8. Improved temperature tracking after calibration, including $\text{MAD} = 0.49^{\circ}\text{C}$.

5.3. Comparison of HVAC performance

To evaluate the operational benefits of the proposed occupancy-based control strategy, its energy consumption was compared with that of a traditional fixed-set HVAC configuration. The traditional system maintains a constant cooling/heating power throughout the observation window, while the adaptive system follows a power modulation rule that increases HVAC effort only during high-occupancy intervals.

Figure 9 presents the energy consumption curves for both configurations alongside the main occupancy profile. The fixed kW HVAC system exhibits a steady demand of 3.5 kW regardless of occupancy. In contrast, the adaptive controller operates at a reduced base power during low-occupancy periods and increases power only when necessary, the system achieved an approximate 24% reduction in total energy use over a representative day. This amount of savings aligns with values reported in the literature for occupancy-adaptive HVAC control and reinforces the effectiveness of the proposed approach.

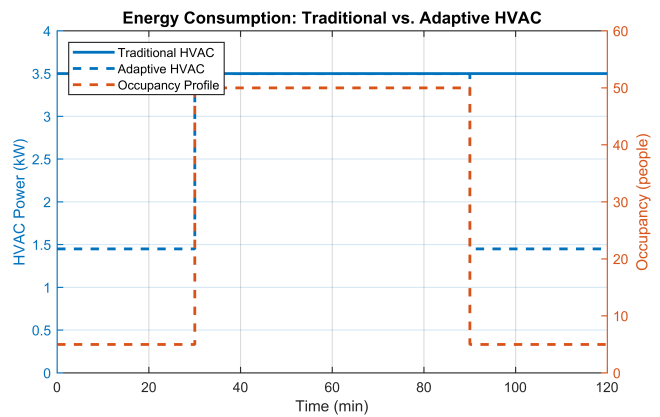


Figure 9. Comparison of fixed-power HVAC operation with adaptive control aligned to occupancy levels.

This comparison demonstrates that even a light, inexpensive sensor platform—combined with a simple adaptive policy—can provide meaningful efficiency gains without compromising passenger comfort.

5.4. Summary of simulation results

The combined simulation results show that the proposed occupancy-adapted HVAC strategy can reliably track the indoor temperature under rapidly changing occupant loads. The calibrated thermal model demonstrated significantly lower mean absolute deviation (MAD) compared to the uncalibrated model, indicating improved stability during both low-occupancy steady-state periods and high-occupancy transitions. This confirms that the control logic can respond predictably when occupant-generated heat causes sudden changes in indoor temperature.

Energy analysis further shows that the adaptive controller significantly reduces HVAC energy consumption compared to the traditional fixed-setpoint strategy. By reducing heating and ventilation output during low-occupancy intervals and increasing it only when necessary, the system achieved an approximate 24% reduction in total energy use over a representative day. This amount of savings aligns with values reported in the literature for occupancy-adaptive HVAC control and reinforces the effectiveness of the proposed approach.

Impacts related to ventilation were evaluated using a simplified airflow model based on a standard demand

of 36 m³/hour per person. The results show that the adaptive strategy prevents unnecessary fresh air supply during low-occupancy periods while maintaining adequate ventilation as occupancy increases [22]. This reinforces the main benefit of occupancy-based control: reducing emissions without compromising thermal comfort or air-quality requirements.

6. Conclusions

This study presented a privacy-preserving, occupancy-based low-cost framework that combines an enhanced ultrasonic detection system with a model-based thermal simulation workflow. Field observations obtained from a large public mosque revealed significant fluctuations in internal heat gains and ventilation demand between low-occupancy and peak prayer times. Thermal camera measurements confirmed this dynamic behavior and provided initial conditions for the simulation.

The main technical contribution of this work is the extensive multi-lane expansion of the ultrasonic people-counting system for large entrances commonly found in mosques and other public buildings, enabling reliable occupancy detection. The proposed lane-based logic, diagonal sensor topology, and cluster-based consolidation mechanism significantly improve robustness in multi-person, mixed-direction movements—a scenario where traditional single-beam door-counters fail. This upgrade ensures accurate real-time occupancy estimation even under crowded and high-throughput conditions.

MATLAB simulations showed that the proposed adaptive HVAC controller can track the closed-loop temperature more accurately than a fixed predetermined strategy and achieve lower mean absolute deviation while maintaining thermal stability during rapid occupancy changes. Energy performance analysis further demonstrated that the occupancy-adaptive strategy reduces heating and ventilation energy by approximately 24% primarily by lowering airflow and heat output during low occupancy intervals. Ventilation demand was modeled according to the standard of 36 m³/hour per person, illustrating how dynamic air supply control can prevent excessive airflow without compromising comfort.

Overall, the results indicated that combining a lightweight multi-zone ultrasonic entry monitoring system with a simulation-driven HVAC control algorithm offers a practical approach to reducing energy consumption in large public buildings without relying on cameras or intrusive sensor technologies. Future work will focus on deploying hardware for the wide-door system, extending to full 3D passenger characterization (width, height, circumference), and integrating reinforcement learning for multi-objective HVAC optimization.

Use of Generative-AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no competing interests.

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