Crowdsurf: Realtime Crowd-Monitoring for Indoor spaces

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Problem

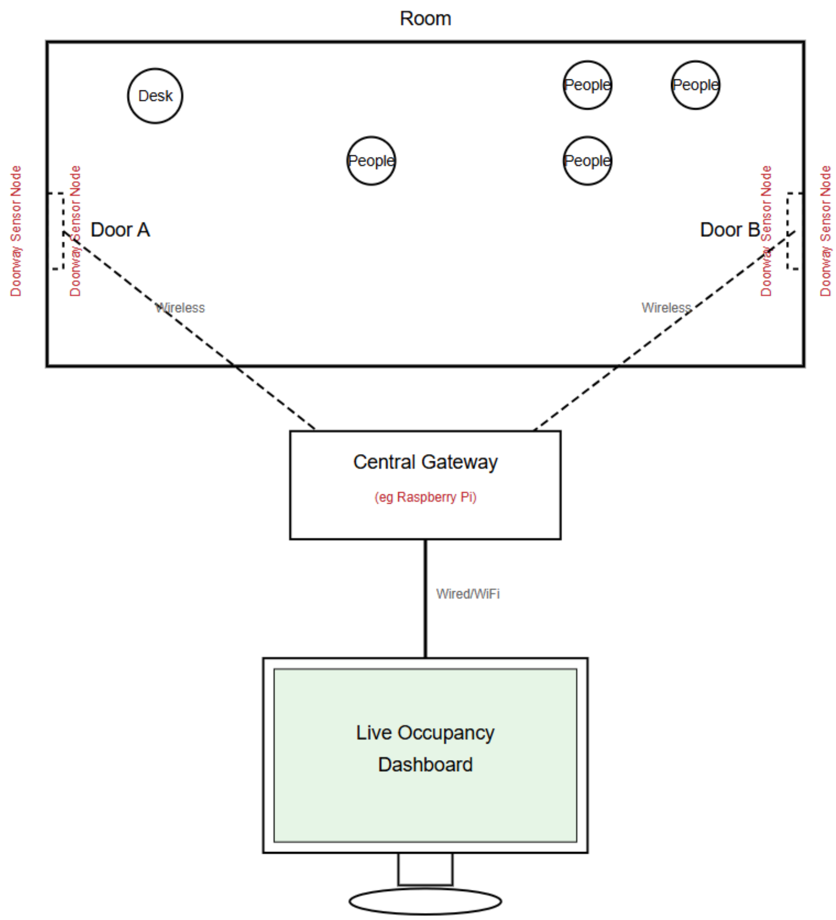
Indoor public spaces such as libraries, study lounges, gyms, and student centers frequently experience congestion during peak hours. Students often arrive at these spaces only to find them overcrowded, while facility staff lack real time, localized information about room level occupancy and traffic flow. This results in inefficient use of shared spaces, reduced user comfort, and unnecessary crowding in environments where safety, accessibility, and productivity are important concerns. Existing approaches to occupancy monitoring typically rely on camera based systems, which raise significant privacy concerns, require high computational resources, and may conflict with campus policies. Other approaches such as manual counting or badge based access control, are labor intensive, prone to error, or provide broad estimates on the total rather than actionable room specific information. As a result, there is a need for a low cost, privacy preserving system that can provide real time, localized occupancy and directional flow data without relying on imaging or personal identifiers. This problem intersects with societal concerns related to public safety, privacy, and efficient use of shared infrastructure. In crowded environments, real-time awareness of congestion can improve safety during emergencies, reduce stress and overcrowding, and support better planning and resource allocation. A privacy first design is particularly important in academic and public settings, where trust and ethical data collection are essential.

Solution

We propose a privacy preserving, real time crowd monitoring system that estimates room occupancy and directional flow using distributed, non-imaging sensor nodes installed at doorways. Each node performs local sensing and processing to detect entry and exit events, inferring direction based on the order in which sensors are triggered. Only processed, aggregate data is transmitted wirelessly to a central gateway, ensuring that no raw personal or identifying information is collected. For the minimum viable system, the project will monitor a single enclosed room with two physically separated doorways, each equipped with its own sensor node. A central gateway aggregates data from both doorways to maintain a live occupancy, directional flow rates, and node health status in real time. The system is designed to be robust to sensor noise and temporary wireless communication loss, while remaining simple to deploy and scale.

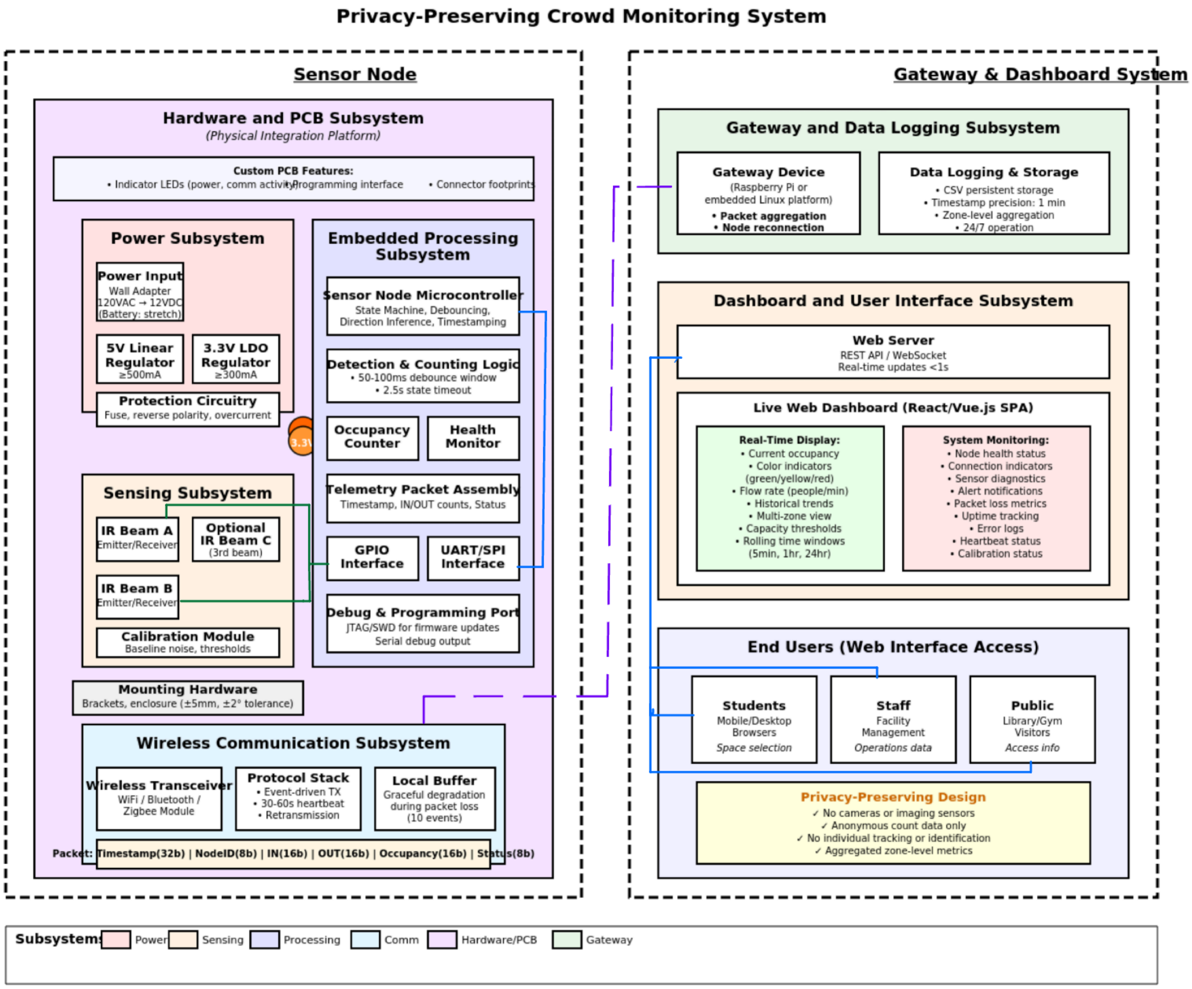
High Level Requirements

- The system will achieve at least 90% directional counting accuracy for sequential doorway traffic under moderate flow conditions.
- The system shall remain operational and recover automatically from temporary wireless packet loss without losing internal occupancy state.
- The user dashboard will display current occupancy estimates, directional flow rates in people per minute, visual indicators for congestion levels based on thresholds, and node health status for all deployed sensors with all data updates occurring in real time with latency not exceeding 3 seconds.



High level system overview of proposed occupancy monitoring solution

Block Diagram



Subsystem Overview

<u>Sensing Subsystem</u>

Each doorway has 2 non-imaging infrared (IR) break-beam sensors mounted across the doorway with a small spatial separation (around 10-20 cm). When a person passes through the doorway, the beams are interrupted in a specific order. The sequence of beam interruptions is used to infer directionality. The sensors produce clean digital signals and do not capture images or personal data, preserving privacy. Sensor placement is standardized using a mechanical mounting solution to ensure consistent height and alignment across doorways. A calibration procedure establishes baseline noise conditions during installation, measuring ambient IR interference and setting appropriate detection thresholds.

Embedded Processing Subsystem

Each sensor node includes a microcontroller that timestamps sensor events and runs a finite state machine to detect valid crossings. The firmware implements debouncing, timing windows, and gating logic to handle common edge cases such as individuals pausing in doorways, people that are close together, and brief direction reversals. The microcontroller maintains a local occupancy delta and monitors node health, including sensor timeouts and heartbeat status. By performing direction inference locally, the system minimizes wireless bandwidth and ensures graceful degradation if communication is interrupted.

Wireless Communication Subsystem

Sensor nodes communicate wirelessly with the central gateway using a low power wireless protocol. Each transmitted packet includes a timestamp, incremental IN/OUT counts, current node status, and a sequence number. Periodic heartbeats allow the gateway to detect node disconnections. If packets are lost, the node continues operating locally and transmits updated counts once communication resumes. This prevents loss of occupancy information and avoids system crashes during temporary interference.

Gateway and Data Logging Subsystem

A central gateway device (Raspberry Pi) receives telemetry from both doorway nodes and aggregates IN/OUT events to maintain a shared room occupancy estimate. The gateway logs data to persistent storage in CSV format and handles node reconnection after communication loss. The gateway acts as the single source of truth for occupancy and provides data to the user interface.

Dashboard and User Interface Subsystem

A live dashboard displays current room occupancy, directional flow rate (people per minute), and node health status. Visual indicators show whether the room is "crowded" or "not crowded" based on configurable thresholds. The interface updates in real time and allows basic monitoring and debugging.

Power Subsystem

For the initial implementation, each doorway node is powered via wall power to reduce system risk and complexity. An onboard voltage regulator provides stable operating voltages for the microcontroller and sensors. Basic power monitoring is included to detect brownouts or resets. A stretch goal is to explore battery-powered operation with low-power modes, but wall power is used for the core demonstration to ensure reliability.

Hardware and PCB Subsystem

At least one doorway sensor node will be implemented on a custom fabricated PCB integrating the microcontroller interface, sensor connectors, power regulation, and wireless module interface. The hardware is designed for consistent deployment, stable mounting, repeatable wiring, and clear debug access. A typical node includes:

- Two IR pairs (emitter/receiver) connected via headers
- Microcontroller for FSM and timestamps
- Wireless transceiver/module connection
- Power input and regulation

- Status Indicators (LEDs) + debug header (UART/SWD/JTAG)

Subsystem Requirements

Highlevel Requirements (HLR) to quantify success or failure of system

HLR1: Accuracy: System achieves 90% correct IN/OUT classification at each doorway under normal conditions.

HLR2: Latency: Live occupancy estimate shown on dashboard updates within 3 seconds of a doorway event.

HLR3: Reliability: System runs and logs continuously for more than 1 hour and remains stable during wireless loss.

Sensing Subsystem

Contribution to requirements

- Enables HLR1 by producing reliable, low noise digital events that the processor can sequence into direction
- Supports HLR2 because the beams create near instantaneous triggers
- Supports HLR3 by using non-imaging sensors that are stable and easy to calibrate and troubleshoot

Interfaces

- Interacts with Embedded Processing. There are 2 digital inputs, logic level 3.3 V, sampled at at least 100Hz or interrupt based.
- Interacts with physical objects when mounting the beam so that alignment tolerance is maintained within 5 mm lateral and within 5 degrees angular.

Requirements

1. Must provide 2 independent beams
2. Must generate stable digital transitions after calibration
3. Must support valid crossing recognition within 20ms to 500ms (corresponds to regular walking speed)
4. Includes a standardized mountain approach to keep alignment consistent

Embedded Processing Subsystem

<u>Contribution to requirements</u>

- Enables HLR1 by implementing deterministic direction logic
- Enables HLR2 by converting sensor events into a count update immediately and packaging telemetry quickly.
- Enables HLR3 by continuing to count locally during wireless outages and reporting health status.

<u>Interfaces</u>

- Interacts with Sensing. The 2 digital signals, and debounce threshold has to be at least 20 ms.
- Interacts with Wireless Communication by making sure the telemetry packet is emitted by at most 200 ms of validated crossing; heartbeat around every 2s.
- Interacts with Power by having the reset flag readable within 1s of reboot and the status bit in next heartbeat

<u>Requirements</u>

1. Must detect a valid crossing by recognizing Beam A then Beam B or the reverse within 500 ms (configurable).
2. Must implement debounce/filtering rejecting pulses < 20 ms to prevent false counts.
3. Must maintain monotonic sequence numbers and local counters for reconciliation after packet loss.
4. Must generate and transmit a heartbeat at least every 2 seconds including health/status flags.
5. Must treat invalid/ambiguous patterns as no count update and increment an “ambiguous event” counter for logging/diagnostics.

Wireless Communication Subsystem

Contribution to requirements

- Supports HLR2 by delivering event updates to the gateway fast enough for ≤1 s dashboard updates.
- Enables HLR3 by tolerating packet loss and enabling reconnection/recovery without crashes or permanent drift.
- Supports HLR1 by ensuring the gateway receives correct, ordered deltas (sequence numbers).

Interfaces

- Interacts with the Gateway and Sensors. Sensor nodes transmit event driven telemetry packets and periodic heartbeats to the gateway. Each packet includes a node ID, sequence number, timestamp, IN/OUT count deltas, and status flags.

Requirements

1. Must deliver event telemetry such that the gateway receives updates within 1s under normal conditions.
2. Must include sequence numbers (at least 16-bit) to detect duplicates/missing packets
3. Must include periodic heartbeats. Without heartbeats, node health cannot be monitored.
4. Must remain stable (no crashes) under ≥ 10% packet loss during a 1-hour run and recover automatically when link returns.
5. Must support a reliable indoor range of ≥ 10 m with at least one typical obstruction.

Gateway and Data Logging Subsystem

Contribution to requirements

- Supports HLR1 by correctly applying deltas and using sequence numbers to prevent double counting.
- Enables HLR2 by aggregating events quickly and providing updated occupancy to the dashboard within 1s.
- Enables HLR3 through continuous logging and graceful handling of node dropouts/reconnections.

Interfaces

- Interacts with Wireless Communications by making sure to parse through packets and process them within 200 ms of receipt.
- Interacts with the Dashboard by providing API/WebSocket updates at around 1Hz with occupancy and node status.

Requirements

1. Must compute occupancy as Occ(t+)=Occ(t)+Σ(in_delta−out_delta) across both doorways; without correct aggregation, room count is meaningless.
2. Must log telemetry and occupancy continuously for at least 1 hour to persistent storage
3. Must detect that the node is offline if no heartbeat has been recorded for at least 6 seconds and expose this status to the dashboard.
4. Must support reconnection without restart and reconcile counts using sequence numbers
5. Must provide a stable API/feed so the dashboard can refresh at around 1 Hz.

Dashboard and User Interface System

Contribution to requirements

- Reinforces HLR1 by exposing accuracy/ambiguity indicators
- Demonstrates HLR2 by surfacing occupancy updates within ≤1 s to end users.
- Supports HLR3 by clearly indicating node offline/fault states (no silent failures).

Interfaces

- Interacts with Gateway by sending updates via API/WebSocket at around 1 Hz; dashboard refresh latency is within 1s after gateway update.

Requirements

1. Must refresh and display occupancy + node status at 1 update/ 3 seconds.
2. Must show node health (online/offline + fault flags); otherwise staff cannot diagnose failures.

3. Must compute/display flow rate using a defined window to avoid noisy instantaneous rates.
4. Must implement a configurable “Crowded” threshold and update state within 2s of threshold crossing.
5. Must display only aggregate metrics (no identities/images), preserving privacy.

Power Subsystem

Contribution to requirements

- Supports HLR1 by preventing sensor/MCU reset flags that cause missed or phantom counts.
- Supports HLR2 by ensuring the node stays responsive and can transmit immediately
- Enables HLR3 by supporting ≥1 hour continuous operation without resets/crashes.

Interfaces

- Interacts with the Microcontroller Unit by supplying 3.3 V within 5%, peak current of at least 300 mA. Makes sure the MCU does not operate below 3.1V and must report rest in next heartbeat
- Interacts with Sensors by supplying 5 V within 5%, peak current of at least 250 mA.

Requirements

1. Must supply 3.3 V ± 5% continuously at at least 300 mA peak to MCU.
2. Must supply sensor/emitter rail (5 V ±5%) at least 250 mA peak if emitters are powered from the node.
3. Must include overcurrent protection to prevent permanent damage during a short.
4. Must enforce reset behavior so the node doesn’t run in undefined voltage states.

5. Must support ≥ 1 hour continuous operation on wall power without manual intervention.

Hardware and PCB Subsystem

Contribution to requirements

- Supports HLR1 by ensuring consistent sensor wiring/alignment and reducing intermittent faults that cause miscounts.
- Supports HLR2 indirectly by ensuring stable operation and communication without resets/disconnects.
- Enables HLR3 by improving reliability over breadboards (mechanical stability, strain relief, robust power).

Interfaces

- Interacts with Power. The Hardware subsystem accepts adapter output (5–12 VDC) and produces regulated rails (3.3 V ±5%, optional 5 V ±5%).
- Interacts with Sensor: The board provides connectors for two break-beam receiver signals and associated power.

Requirements

1. Must fabricate and use at least one custom PCB node in the final demo; otherwise you fail your stated success criterion.
2. Must include connectors for two break-beam pairs (power + receiver outputs) and route signals to MCU GPIO reliably.
3. Must include regulated 3.3 V ±5% rail sized for ≥ 300 mA peak and protection (fuse/polyfuse).

4. Must include at least one status LED (power/heartbeat) and a debug/programming interface (UART/SWD/JTAG).
5. Must include a mechanical enclosure/mounting solution that maintains alignment and provides strain relief so cables do not disconnect under light handling.

Tolerance Analysis

A key risk is miscounting when people come in through the door one after another and they are really close to each other. This is mitigated by selecting appropriate beam spacing and timing thresholds. For example, if two beams are spaced 15 cm apart and a person walks at 1 m/s, the expected delay between beam triggers is approximately 150 ms. Timing windows can be set conservatively around this value to distinguish valid crossings from noise or partial interruptions. Ambiguous patterns are flagged rather than miscounted.

Ethics, Safety, and Societal Impact

This project is designed to minimize ethical risk by avoiding imaging, facial recognition, or personal identifiers. Only aggregate occupancy counts are collected, aligning with principles from the IEEE and ACM Codes of Ethics regarding privacy, transparency, and minimizing harm. Safety considerations include secure mounting of hardware to avoid physical hazards and use of low-voltage electronics. The system does not interfere with building access or emergency egress. From a societal perspective, the solution improves space utilization, reduces overcrowding, and enhances safety while respecting individual privacy. The approach is scalable and adaptable to other public environments without introducing surveillance concerns.

Success

The project will be considered successful if it can accurately demonstrate real-time directional counting and occupancy estimation for one enclosed room with two separated doorways using non-imaging sensors. The system must update occupancy within one second of a doorway event, achieve at least 90% accuracy under moderate traffic conditions, and operate continuously for at least one hour while logging data and handling temporary wireless packet loss gracefully. A custom-designed PCB must be fabricated and used for at least one sensor node in the final demonstration.