

An Infrared–Microwave Dual-mode Human-presence Detection and Fail-safe Interlock Method for UV-LED Disinfection Lamps

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(Received June 12, 2026; accepted August 13, 2026)

Keywords: dual-mode human detection, passive infrared, 24 GHz microwave radar, fail-safe interlock, UV-LED disinfection, hierarchical state machine

UV-C disinfection equipment must prevent irradiation whenever a person is present, but low-cost interlocks based on a single sensor can miss stationary occupants or respond to targets outside the intended detection boundary. This study presents a low-cost infrared-microwave dual-mode human-presence detection and safety-prioritized interlock method for UV-LED disinfection lamps. A passive infrared (PIR) sensor provides rapid sensitivity to human motion, whereas a 24 GHz microwave radar provides complementary sensitivity to stationary occupants and micro-motion. The conditioned digital sensor outputs are fused using a conservative OR rule. Any presence indication, emergency-stop event, or diagnosed safety fault deasserts the UV-enable signal locally. Reactivation is permitted only after both sensors continuously report no presence for a 2 s confirmation interval and a valid operating request remains active. A hierarchical state machine separates the safety state from AUTO, MANUAL, and STOP operating modes, ensuring that no operating command can bypass the local presence interlock. Prototype experiments evaluated intrusion shutdown, stationary-person detection, short-range and breath-holding limitations, and out-of-zone radar triggering. In both AUTO and MANUAL modes, the UV-enable signal was deasserted within the prototype design target of 200 ms after intrusion. Repeated sampling within a finite observation window increased the measured probability of detecting stationary occupants under normal respiration. The tested modalities showed complementary behavior: radar mitigated the limited sensitivity of PIR to stationary occupants, whereas PIR retained useful sensitivity during entry, postural changes, and some close-range conditions. Radar triggering through thin partitions remained a major availability limitation when the electromagnetic sensing region extended beyond the intended UV hazard zone.

1. Introduction

Ultraviolet irradiation is widely used for disinfection in healthcare facilities, laboratories, public spaces, and water-treatment systems because it provides rapid microbial inactivation

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<https://doi.org/10.18494/SAM6481>

without chemical residues and can be integrated into compact equipment.^(1–3) Deep-ultraviolet LEDs have further enabled mercury-free, low-voltage, instant-start, and dimmable disinfection sources.^(4,5) However, UVC radiation can damage human skin and eyes;⁽⁶⁾ therefore, open and semi-open UV-LED equipment must operate only when the irradiated region is unoccupied. In this context, human-presence detection is not merely an automation function; it is a safety interlock that determines whether potentially hazardous optical output may be enabled.⁽⁷⁾

A passive infrared (PIR) sensor is attractive for low-cost safety interlocks because it has a simple digital interface and responds quickly to changes in human thermal radiation.^(8–12) Its response nevertheless depends on the temporal variation in received infrared field. A person who remains stationary, moves only slightly, or is thermally blended with the background can therefore be missed.^(13,14) Microwave radar provides complementary information by sensing Doppler and micro-Doppler components associated with body motion, breathing, and small postural sway.⁽¹⁵⁾ Radar is consequently more suitable than PIR for stationary-occupant detection, but it may suffer from a near-field blind region and can penetrate thin walls or plastic partitions, thereby detecting people outside the intended disinfection area. The near-field limitation is a radar-specific issue that can be partially compensated by PIR sensing.⁽¹⁶⁾

The contributions of this study are fourfold. First, a dual-mode sensing architecture combines PIR motion detection and microwave micro-motion detection while maintaining a low-cost digital interface. Second, a fail-safe fusion and delayed-recovery method immediately disables the UV output on any presence indication and requires continuous no-presence confirmation before restart. Third, a hierarchical state machine separates the operating mode from the safety state and ensures that manual commands, remote commands, and automatic timing cannot override the local interlock. Fourth, the experimental design evaluates not only moving-person shutdown and stationary-person detection but also near-field blind zones, breath-holding, out-of-zone radar triggering, and false shutdowns.

2. System and Safety Method

2.1 System architecture

The system contains two deliberately separated information paths. The local safety-control path comprises the PIR sensor, the 24 GHz microwave radar, the STM32F103C8T6 controller, the emergency-stop input, the output driver, and the UV-LED array. This path performs presence detection, safety-state evaluation, and output interruption without relying on a network connection. The supervisory path comprises the ESP8266 communication gateway, the message queuing telemetry transport (MQTT) link, the OneNET cloud platform, and the remote user interface. MQTT is a lightweight publish–subscribe messaging protocol commonly used in resource-constrained IoT systems. In this implementation, the ESP8266 forwards status and commands between the STM32 and OneNET, but it does not make safety-critical decisions.

The architecture in Fig. 1 distinguishes the solid local safety path from the dashed supervisory path. A remote start command can request operation, but the command is converted only into an operating request at the STM32. The final UV authorization is generated locally after evaluating

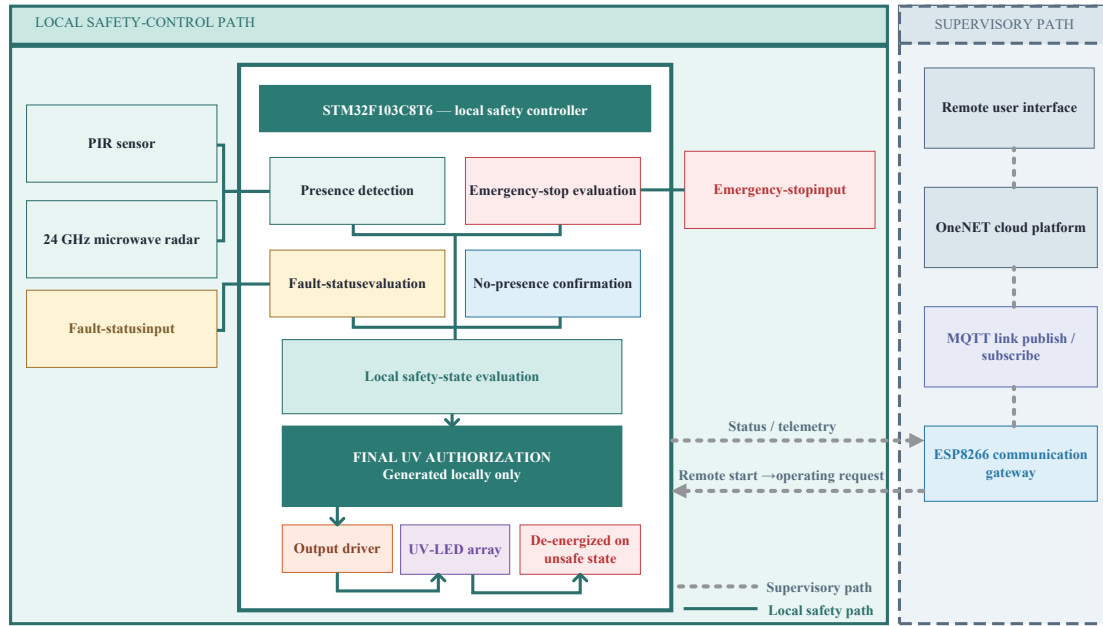


Fig. 1. (Color online) System architecture showing the local safety-control path and the supervisory communication.

human presence, emergency stop, fault status, and the no-presence confirmation state. Consequently, the loss of Wi-Fi, MQTT disconnection, cloud unavailability, or ESP8266 reset cannot prevent the local controller from shutting down the UV output.

2.2. Sensor characteristics and safety-prioritized fusion logic

The PIR sensor is sensitive to changes in infrared radiation produced when a warm human body enters or moves within the field of view. It is therefore assigned the role of rapid motion detection. The 24 GHz radar is sensitive to body displacement and micro-motion, including breathing-related chest movement and small postural sway, and is assigned the complementary role of stationary-occupant detection. Both modules provide internally conditioned digital outputs, so the controller processes logical states rather than raw analog amplitudes.

Let p_k and r_k denote the sampled digital outputs of the PIR and radar channels at discrete time k . A value of 1 means that the corresponding sensor reports a human-related event; a value of 0 means that it reports no event.

$$p_k \in \{0,1\}, r_k \in \{0,1\} \quad (1)$$

The conservative fusion variable h_k is defined by a logical OR operation. Thus, either sensing modality is sufficient to place the system in a presence-risk state.

$$h_k = p_k \cup r_k \quad (2)$$

The OR rule is intentionally asymmetric with respect to safety and availability. A single positive indication may cause a conservative shutdown, but a single negative indication can never authorize UV output. This choice reduces the risk of missed occupants at the cost of possible false shutdowns in radar penetration.

2.3 Digital input debouncing and delay-confirmed safety decision

For the unsafe direction, a validated high level from either sensor is accepted at the first sampling opportunity, or asynchronously if the input is connected to an interrupt-capable pin. The controller then disables the UV output and resets the no-presence timer. The shutdown rule is

$$h_k = 1 \Rightarrow u_k = 0. \quad (3)$$

For the safe direction, the output remains disabled until all of the most recent N_c samples indicate no presence. The no-presence confirmation variable s_k is defined as

$$s_k = 1 \text{ iff } h_{k-N_{C+1}} = h_{k-N_{C+2}} = \dots = h_k = 0. \quad (4)$$

Otherwise, $s_k = 0$.

If the sampling period is t_s , the clear-confirmation time is

$$T_{clear} = N_c \cdot t_s. \quad (5)$$

The original implementation sampled eight times per second, corresponding to $t_s = 125$ ms. A 2 s recovery delay therefore requires $N_c = 16$ consecutive no-presence samples. Any high level detected during this interval immediately resets the counter to zero. This approach prevents a transient low level or a short missed detection from causing premature UV restart. A high-level glitch may still cause a conservative shutdown, but this is consistent with the fail-safe objective. The dual-mode presence-fusion and fail-safe interlock rules are summarized in Table 1.

Table 1

Dual-mode presence fusion and fail-safe interlock rules. X denotes a don't-care condition that may be either 0 or 1.

PIR	Radar	Other safety condition	Safety decision	UV action
1	X	No fault required	Presence	Disable immediately
X	1	No fault required	Presence	Disable immediately
0	0	Clear timer < 2 s	Clearing	Remain disabled
0	0	Clear timer $\geq$ 2 s and valid command	Safe	Enable or resume
X	X	Emergency stop or fault	Fault	Disable and lock

2.4 Hierarchical safety state machine

The controller is represented by two interacting state machines. The operating-mode machine contains STOP, AUTO, and MANUAL. STOP contains no active operating request. AUTO generates an operating request according to the preset disinfection duration. MANUAL generates an operating request according to the local or remote manual switch. The MANUAL mode bypasses automatic timing control but never bypasses the human-presence interlock, emergency stop, or fault protection.

The safety machine has the following states: PRESENCE, CLEARING, SAFE, and FAULT. PRESENCE is entered whenever $p_k = 1$ or $r_k = 1$. CLEARING begins only after both sensors become zero and persists while the 2 s confirmation timer accumulates. SAFE is entered after the continuous no-presence criterion is satisfied. FAULT is entered after emergency-stop activation, failed self-test, a diagnosed sensor abnormality, or an internal controller fault. The UV output is authorized only when the operating request and the safety authorization are simultaneously true.

$$u_k = c_k \cap s_k \cap \bar{e}_k \cap \bar{f}_k \quad (6)$$

Here, c_k is the start request produced by the AUTO or MANUAL mode, s_k is the completed no-presence confirmation, e_k is the emergency-stop state, and f_k is the fault state. The logical expression makes the priority explicit: emergency stop, fault, or the loss of safety confirmation dominates every local or remote operating command. Emergency-stop activation latches the FAULT state. Releasing the emergency-stop input does not automatically restore UV authorization. A deliberate local reset is required after the fault condition has cleared, followed by a new continuous 2 s no-presence confirmation interval. Figure 2 shows the layered state transitions and the final authorization gate.

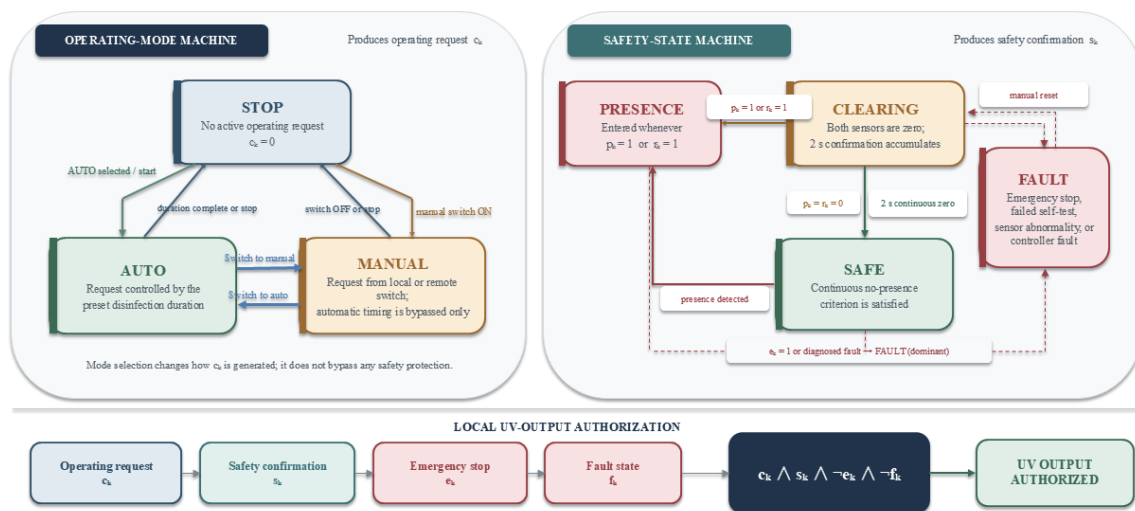


Fig. 2. (Color online) Hierarchical operating-mode and state machines with the local UV-output authorization logic.

2.5 Embedded software and communication architecture

At power-up, the STM32 initializes the GPIO, timer, UART, watchdog, and output driver while holding the UV output disabled. A startup self-test checks the emergency-stop input, sensor input plausibility, output-driver feedback where available, and communication-module status. A failed safety-related check places the system in FAULT; communication unavailability is reported but does not inhibit local shutdown capability.

A periodic timer service samples the digital sensor inputs every 125 ms and updates the consecutive-clear counter. Presence events, the emergency-stop input, and the manual switch may additionally use edge-triggered interrupts to reduce reaction latency. The UART receive interrupt stores framed data from the ESP8266 in a buffer, while the main loop validates the frame, checks the command type and checksum, and updates only the requested operating mode or command variable. MQTT messages are parsed in the ESP8266/STM32 communication task and are never written directly to the UV driver.

The watchdog is refreshed only after the completion of the safety task, state update, and output update. A watchdog reset, malformed serial frame, stale remote command, or communication timeout cannot force the output on. Remote commands are treated as requests with bounded validity; when a command expires, the controller returns to a locally defined safe operating condition. The status report contains the operating mode, safety state, sensor states, output state, remaining AUTO time, fault code, and communication status.

3. Experiments

3.1 Prototype

The prototype comprised an STM32F103C8T6 controller, an ESP8266 communication module, a digital PIR sensor, a 24 GHz microwave radar, a regulated power module, and a logic-level UV-output control interface. The prototype photograph is shown in Fig. 3. The study

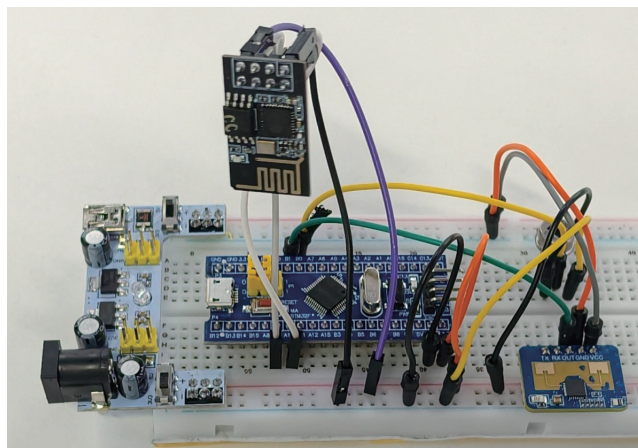


Fig. 3. (Color online) Prototype of the dual-mode sensing, control, and communication hardware.

evaluates the safety interlock and control signal rather than UVC irradiance or disinfection dose; the optical efficacy of the UV-LED array is outside the scope of this work.

The test region was divided by distance and posture. Moving-entry trials used a marked entrance line. Stationary trials included standing and sitting; normal breathing and short breath-holding; and positions inside and outside the radar near-field region. No-person control windows were included to estimate false alarms and false shutdowns. Boundary tests placed a person outside the intended region behind an open space, a thin wall, or a plastic partition.

A synchronized reference channel marked the instant at which the participant crossed the entrance line and the instant at which the participant left the region. Sensor outputs, the STM32 output command, and the reference channel were recorded on a common time base. For stationary windows, the ground label was assigned from the controlled test condition and verified by the experiment operator. Figure 4 shows the spatial layout and test-point definition.

3.2 Intrusion shutdown and delayed-recovery tests

Intrusion tests were performed with the UV control output initially active in the AUTO and MANUAL modes. For each repetition, the participant crossed the entrance line, entered the

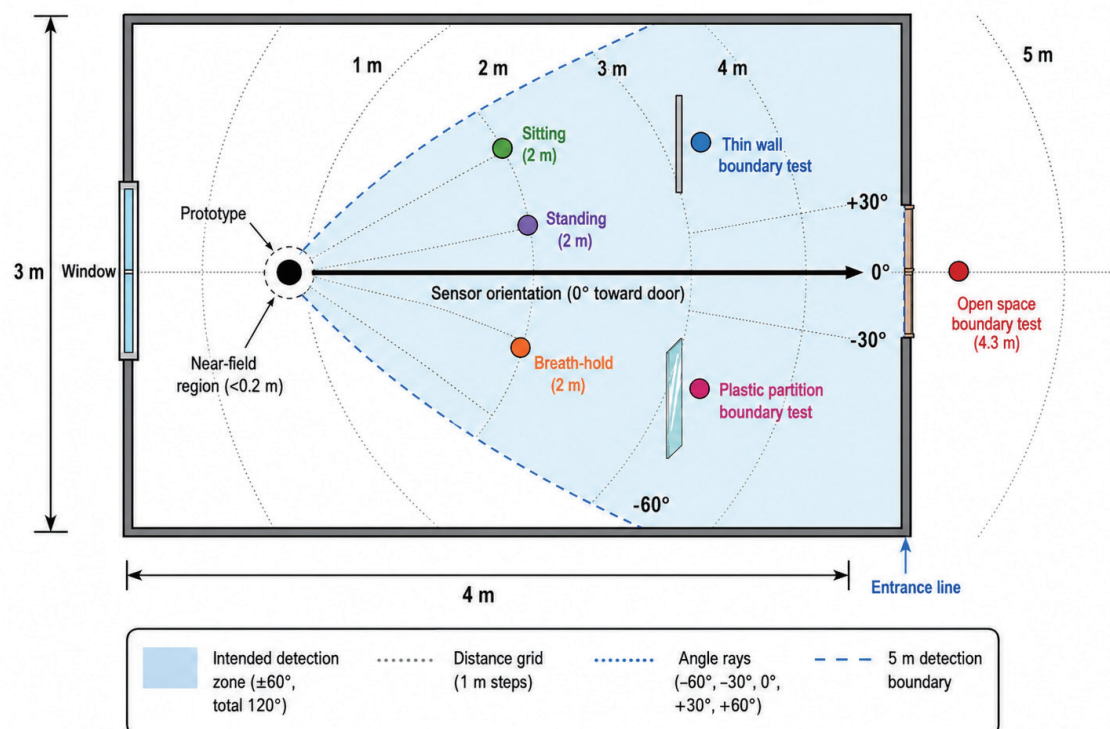


Fig. 4. (Color online) Experimental geometry, entrance line, sensor orientation, distance/angle grid, near-field region, and out-of-zone boundary-test positions.

sensing region, remained briefly, and then left. The event times were defined as t_{entry} (ground-truth entry), t_{detect} (first valid sensor presence indication), t_{off} (UV control output disabled), t_{leave} (ground-truth exit), and t_{resume} (output re-enabled after all safety conditions were satisfied).

$$t_{shutdown} = t_{off} - t_{entry} \quad (7)$$

$$t_{recover} = t_{resume} - t_{leave} \quad (8)$$

The shutdown distribution is summarized by the number of trials, mean, standard deviation, minimum, and maximum. Recovery time is analyzed separately because the 2 s confirmation delay is an intentional safety requirement rather than a response limitation. Figure 5 presents an event-aligned digital waveform and Table 2 reports the repeated-trial statistics.

3.3 Stationary-person detection and time-window analysis

Stationary-person performance was evaluated at the level of individual samples and complete observation windows. The single-sample detection probability for each sensor is the number of positive sensor samples divided by the total number of labeled presence samples. The dual-mode sample is positive when either sensor is positive. Results are stratified by distance, angle, posture, orientation, breathing condition, and near-field status.

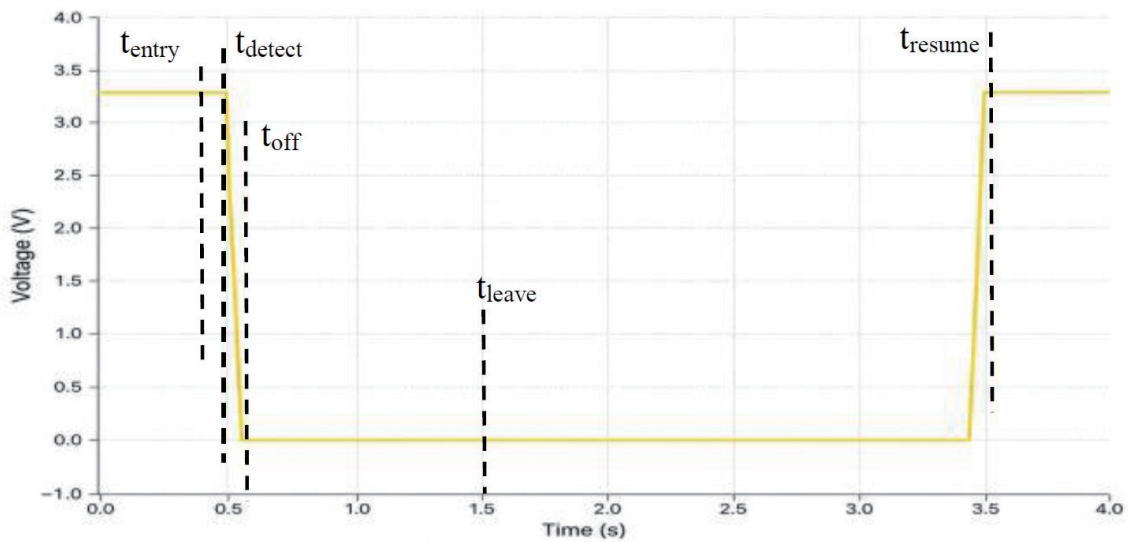


Fig. 5. (Color online) Digital waveform showing t_{entry} , t_{detect} , t_{off} , t_{leave} , the 2 s clear-confirmation interval, and t_{resume} .

Table 2
Repeated intrusion-shutdown and recovery-time statistics.

Mode	No. of trials	Mean shutdown	SD	Minimum	Maximum	Mean recovery
AUTO	20	116.9 ms	16.46 ms	85 ms	149 ms	2.0 s
MANUAL	20	122.5 ms	19.72 ms	80 ms	160 ms	2.1 s

A 1 s window contains eight samples at the 125 ms sampling period. A window is considered detected when at least one sample within that measured window is positive. The window-level detection probability is therefore calculated directly from experimental windows as

$$P_{\text{window}} = \frac{(\text{number of windows with } \geq 1 \text{ successful detection})}{(\text{total number of windows})}. \quad (9)$$

No independence assumption is applied to the eight samples, because the repeated samples obtained from the same person at the same location are temporally correlated. A person in a persistent near-field blind location may generate eight consecutive failures, whereas small breathing or postural changes may generate intermittent detections.

3.4 False-trigger and detection-boundary tests

Availability was evaluated using no-person controls and out-of-zone targets. In the no-person test, the sensing region remained empty for repeated observation windows. In the boundary test, a person moved or remained stationary outside the designated disinfection region at specified distances and behind different partitions. A false alarm is a sensor presence indication during an empty in-zone window. A false shutdown is an output interruption caused by an out-of-zone target or non-human living target while no human is present in the irradiated region. The near-field test examined very short sensor-to-person distances, where radar sensitivity can be reduced. The breath-holding test reduced periodic chest motion. The partition test examined radar penetration through thin walls and plastic panels.

4. Discussion

4.1 Intrusion shutdown and recovery

The event-aligned traces in Fig. 5 show that the first valid sensor transition was followed by the immediate removal of the UV control command. Across both AUTO and MANUAL trials, the measured shutdown time remained below the 200 ms design requirement. The repeated-trial distribution in Table 2 provides the mean, variability, minimum, and maximum.

AUTO and MANUAL exhibited the same safety behavior because the operating mode affects c_k but not the safety variables s_k , e_k , and f_k . In the MANUAL mode, an asserted manual ON request was retained while the person was present, but the output remained disabled. After the person left and the continuous 2 s no-presence requirement was completed, the output resumed only when the manual request was still valid. This result verifies that manual control bypasses timing but not the safety interlock.

The recovery traces also demonstrate the intended temporal asymmetry. Shutdown is event-driven and rapid, whereas restart is deliberately delayed. Separating the two time policies prevents a short negative sensor fluctuation from reactivating the UV source while an occupant remains in the region.

4.2 Stationary-person detection and temporal correlation

The stationary-person results confirm the complementary sensing mechanism. Radar provided a substantially greater sensitivity than PIR when the participant remained still under normal breathing conditions, whereas PIR retained useful coverage during entry, postural changes, and some close-range conditions. The OR fusion therefore reduced the missed-detection risk associated with a single PIR channel and partially compensated for radar-specific failures.

Repeated samples improved the probability of at least one detection in normal stationary conditions, but the gain depended on the temporal structure of the signal. Intermittent respiration or slight sway produced additional opportunities for radar detection, whereas a persistent geometric blind location or deliberate suppression of micro-motion produced correlated failures. Consequently, the measured window-level values in Table 3 are the valid performance indicators.

The comparison of Tables 3 and 4 also separates two different engineering questions. Single-sample probability characterizes instantaneous sensitivity and is relevant to rapid interruption. Window-level probability characterizes the chance of detecting a stationary occupant within a defined observation period.

Table 3
Measured 1 s window-level detection probabilities. Each window is counted once.

Condition	No. of total windows	PIR detected windows (%)	Radar detected windows (%)	Fusion detected windows (%)
All stationary conditions	52	71.2	76.9	86.5
Normal sitting	13	84.6	100	100
Standing	13	92.3	100	100
Deliberate breath-holding	13	23.1	30.8	46.2
Near-field region	13	84.6	76.9	100

Table 4
Single-sample stationary-person detection results for PIR, radar, and OR fusion.

Condition	No. of total samples	PIR successes (%)	Radar successes (%)	Fusion successes (%)
All stationary conditions	416	33.7	58.2	65.6
Normal sitting	104	38.5	92.3	94.2
Standing	104	44.2	94.2	95.2
Deliberate breath-holding	104	5.8	7.7	11.5
Near-field region	104	46.2	38.5	61.5

Table 5
False-trigger, missed-detection, and boundary-test results.

Scenario	Out-of-zone target	No. of trials	PIR false	Radar false	Fusion false	Rate (%)
Empty region	0	104	0	0	0	0
Person outside open boundary	1	104	8	12	13	12.5
Person behind thin wall	1	104	0	36	36	34.6
Person behind plastic partition	1	104	0	41	41	39.4

Table 6

Qualitative comparison of single-PIR, single-radar, and dual-mode fail-safe interlocks.

Condition	PIR only	Radar only	Dual-mode OR fusion	Engineering implication
Moving entry	Effective	Effective	Effective	All schemes can satisfy basic entry detection when correctly installed
Stationary occupant	May miss	Usually effective	Improved coverage	Radar complements PIR
Near-field stationary occupant	May detect thermal change	May fail	Risk reduced but not eliminated	Installation geometry remains important
Short breath-holding	May miss	Sensitivity reduced	Correlated misses remain possible	Use measured windows and conservative recovery
Person behind thin partition	Usually not triggered	May trigger	Conservative shutdown	Safety improves; availability may decrease

4.3 Detection boundaries, false shutdowns, and safety–availability trade-off

The boundary tests identify two distinct failure directions. In the radar near field, stationary detection may weaken, creating a missed-detection risk. Behind thin walls or plastic partitions, radar may detect an out-of-zone person, creating a false shutdown. The PIR sensor can partially mitigate the radar near-field blind-zone problem when a close human body produces a detectable thermal transition. However, PIR cannot suppress radar penetration through thin walls or plastic partitions because the OR fusion rule intentionally preserves any radar alarm. The false-trigger and boundary-test results are summarized in Table 5.

For a UV safety interlock, this conservative behavior is preferable to allowing UV output during an actual presence event. Nevertheless, repeated false shutdowns reduce disinfection availability and may make the system impractical in partitioned environments. Radar range, elevation, azimuth, shielding, and mounting location must therefore be selected so that the electromagnetic sensing volume does not extend substantially beyond the optical hazard region. The comparison of single-sensor approaches in terms of general design implications is shown in Table 6.

5. Conclusions

A fail-safe human-presence interlock combining passive infrared (PIR) and 24 GHz microwave sensing was implemented for UV-LED disinfection. PIR detects thermal transitions from moving occupants, while radar improves sensitivity to stationary persons and micro-motions. The safety-oriented OR fusion rule reduces the stationary-person missed-detection risk compared with a PIR-only scheme without slowing the response to entry events.

The prototype disabled the UV output within 200 ms after intrusion in both automatic and manual modes, and required a continuous 2 s dual-sensor absence before restart. Repeated observations within a 1 s window improved stationary-person detection under normal respiration; however, the gain must be evaluated from the measured window-level probabilities.

Several limitations remain. Reduced radar micro-motion sensitivity during breath-holding can cause correlated missed detections, and penetration through thin walls or plastic partitions

may trigger out-of-zone false shutdowns, lowering availability. The binary sensors provide neither identity, location, nor confidence; thus, the OR rule cannot distinguish a human from another living target.

The communication subsystem is outside the safety decision path—its failure cannot prevent local shutdown or authorize UV output. The proposed architecture provides a low-cost, redundant, and locally fail-safe foundation for UV-LED disinfection. Future work should extend testing to multi-participants, refine radar boundary control and shielding, and integrate UV irradiance and dose measurements for application-level validation.

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