2HAD-RAD: A Portable Life Detection Radar

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Abstract — **This paper presents 2HAD-RAD, a portable multi-sensor platform for human presence detection in low-visibility environments. The system fuses a 60 GHz FMCW radar (TI IWR6843AOP), a 32×24 infrared thermal array (MLX90640), UWB ranging (DW3000, SS-TWR), a 9-axis IMU (MPU9250), a barometric sensor (BMP280), and an ultrasonic proximity interlock (HC-SR04) on an ESP32-WROOM-32E running FreeRTOS. A companion anchor unit provides independent 24 GHz through-wall vital-sign sensing over BLE. Key contributions include an adaptive thermal classification pipeline with barometric ambient fusion, an 8-state Extended Kalman Filter for UWB+INS fusion, and a three-band anchor respiratory classifier. Breathing rate error improved from 10.8% at 0.5 m to 3.5% at 1.5 m. Zero false positives occurred in empty-room testing. The platform projects over five hours of runtime at 3.7 W.**

Index Terms — **embedded systems, human presence detection, infrared sensing, millimeter-wave radar, sensor fusion, ultra-wideband, through-wall sensing**

I. Introduction

Detecting human presence in environments with limited visibility remains a significant challenge for first responders. Conditions such as darkness, smoke, fog, and airborne particulates render conventional optical and single-modality sensors unreliable precisely when reliable performance is most critical [1]. Traditional search-and-rescue approaches relying on trained canines, acoustic sensors, or single-modality thermal cameras each present significant operational limitations: canines experience fatigue and environmental disorientation, acoustic detection fails in noisy post-disaster environments, and thermal imaging alone cannot confirm human presence when subjects are occluded by debris or structural materials.

Millimeter-wave radar is particularly well suited to such environments because it operates independently of lighting conditions, penetrates airborne particulates, and can resolve micro-scale chest displacement caused by breathing and cardiac activity [2]. However, radar alone produces ambiguous detections in cluttered, multi-path spaces and cannot independently confirm that a detected motion source is human rather than environmental. Integrating radar with complementary modalities — thermal imaging for heat confirmation, ultra-wideband ranging for precise distance estimation, and inertial navigation for spatial context — allows independent physical measurements to cross-validate one another, substantially improving detection confidence [3]. Prior work on hybrid radar-thermal systems has demonstrated that thermal data can significantly reduce false positives caused by non-human motion sources such as fans, machinery, and shifting debris by requiring simultaneous confirmation of movement and body-range heat signature.

Commercial platforms such as the Camero Xaver 400 and Vayyar Walabot demonstrate that portable radar-based life detection is feasible [5, 6], but these systems typically operate as single-modality platforms without real-time vital-sign-fused localization in a unified handheld form factor. Their high cost, bulk, and lack of cross-platform mobile integration further limit adoption in resource-constrained first-responder contexts. To address these limitations, this paper presents 2HAD-RAD, a self-contained portable device fusing a 60 GHz FMCW radar, IR thermal camera, UWB ranging, inertial navigation, barometric sensing, and an independent 24 GHz through-wall anchor radar into a single embedded platform with companion iOS and Android mobile applications.

The remainder of this paper is organized as follows. Section II describes the system architecture and design objectives. Section III covers the theoretical background for each sensing modality. Section IV details hardware design decisions. Section V describes the firmware and sensor-fusion logic. Section VI presents implementation and testing results, followed by discussion in Section VII and conclusions in Section VIII.

II. System Overview

A. Overall Architecture

The 2HAD-RAD system centers on an ESP32-WROOM-32E microcontroller coordinating six sensing subsystems over UART, SPI, and I^2C buses managed under FreeRTOS. The TI IWR6843AOP 60 GHz FMCW radar connects via dual UART: a CLI configuration interface at 115200 baud and a dedicated high-speed TLV data stream at 921600 baud. The on-chip DSP outputs range-Doppler point clouds, presence confidence, breathing rate, and heart rate directly in structured TLV frames, offloading the majority of radar signal processing from the ESP32. The MLX90640 32×24 infrared thermal camera connects via the shared I^2C bus (GPIO21/22) and provides a continuous stream of 768 calibrated temperature pixels per frame at up to 16 Hz. The DW3000 UWB transceiver connects via the shared SPI bus (GPIO18/23/19, CS on GPIO13) and performs SS-TWR with a Qorvo DWM3000EVB Pong responder on the Arduino Uno R4 WiFi anchor, with both TX and RX antenna delays calibrated to 16385. The HC-SR04 ultrasonic sensor is triggered via CAT9555 expander pin P0.1, with echo timing measured via a direct ESP32 timed-pulse read; it asserts the radar NRST line LOW via GPIO15 when the device approaches within 22 cm of any surface, immediately halting all RF emission to satisfy FCC RF exposure compliance requirements. A companion stationary anchor unit integrates the DWM3000EVB SS-TWR responder, a Waveshare HMMD 24 GHz mmWave radar, and a 16×2 I^2C LCD; vital-sign estimates and UWB distance from the anchor are fused with primary readings over BLE. Detection results are rendered on a 3.2-inch ILI9341 touchscreen LCD driven via SPI (CS on GPIO25, DC on GPIO32) and simultaneously transmitted to companion iOS and Android applications over BLE. The system is powered by a 3S 18650 Li-ion pack protected by a 10 A BMS board, with two LM2576 buck regulators providing stable 5 V and 3.3 V rails.

B. Design Objectives

The system was designed to meet the following functional and performance requirements: detect a breathing human at ≥2 m using mmWave radar; provide UWB distance estimates at ≥3 m under line-of-sight conditions; confirm human-range heat signatures (30–40 °C) using the thermal array; suppress radar RF emission within 22 cm via the ultrasonic interlock; display fused detection results on the LCD within 5 seconds of confirmed detection; transmit victim data in real time to companion iOS and Android applications over BLE within 10 seconds; and sustain ≥2 hours of continuous battery-powered operation.

III. Theory and Background

A. Millimeter-Wave FMCW Radar

The TI IWR6843AOP operates in the 60–64 GHz band using FMCW signaling. A transmitted chirp sweeps linearly in frequency with slope S; a target at range R returns a delayed replica that mixes with the transmit reference to produce a beat frequency

$$f_b = \frac{2RS}{c}, \quad (1)$$

where c is the speed of light, yielding range directly from the IF spectrum via FFT. A second Doppler FFT across consecutive chirps resolves radial velocity. For stationary subjects such as a breathing person, micro-scale chest displacement $x(t)$ modulates the reflected phase as

$$\phi(t) = \frac{4\pi x(t)}{\lambda}, \quad (2)$$

where λ is the carrier wavelength. The on-chip DSP applies phase extraction to separate respiration (0.1–0.5 Hz) and cardiac (0.8–2 Hz) components, outputting breathing rate (BR) and heart rate (HR) directly in TLV type 1040 frames [4]. Range resolution is $\Delta R = c/2B$, where B is the sweep bandwidth; the chirp profile used in this work provides approximately 4 cm resolution over a 0.1–5 m detection window.

B. 24 GHz Radar and Through-Wall Propagation

The Waveshare HMMD anchor radar operates at 24 GHz using a continuous-wave Doppler architecture. At this frequency the free-space wavelength (≈12.5 mm) is roughly five times longer than the primary radar's 4.7–5.0 mm wavelength, producing substantially lower attenuation through non-metallic building materials such as drywall, wood framing, and glass, where scattering losses scale with the ratio of obstacle thickness to wavelength. The anchor's fixed mounting position eliminates the motion-induced phase noise that would corrupt micro-Doppler breathing extraction on a handheld platform, making it particularly effective for through-wall vital-sign sensing from a stable vantage point.

C. Infrared Thermal Sensing

The MLX90640 32×24 far-IR array measures object temperatures in the 8–14 μm band using factory-calibrated thermopile elements. Human skin typically radiates in the 30–40 °C range, providing strong independent confirmation of human presence against cooler backgrounds. The 32×24 resolution, while modest, is sufficient for blob-level shape discrimination and provides substantially better spatial information than single-point pyrometers. Raw frames are bilinearly upscaled to 64×48 pixels and spatially smoothed before classification.

D. Inertial Navigation and UWB Ranging

The MPU9250 9-axis IMU supplies high-rate acceleration and angular velocity fused by the Madgwick gradient-descent AHRS filter [8], producing a quaternion orientation estimate that is robust to the magnetic disturbances common in cluttered indoor environments. Linear acceleration is rotated into the world frame using the rotation matrix derived from roll, pitch, and yaw, then double-integrated with velocity damping and a still-detection gate — which zeros velocity during stationary periods when both total acceleration magnitude and gyroscope magnitude fall within narrow bands around their stationary values for a configurable number of consecutive frames — to produce dead-reckoning position estimates. SS-TWR UWB ranging bounds cumulative INS drift via an 8-state Extended Kalman Filter with state vector [X, Y, Z, VX, VY, VZ, YAW, BARO_BIAS], run at approximately 100 Hz driven by IMU samples.

E. Barometric and Cross-Modal Temperature Fusion

The BMP280 provides two independent contributions to the fusion pipeline. Pressure is converted to altitude via the hypsometric formula for Z-axis EKF correction alongside UWB ranging. More distinctively, the BMP280 temperature output is fused directly into the MLX90640 thermal classification pipeline as an ambient scene reference. Because the background model must distinguish 30–40 °C human signatures from environmental clutter, its adaptation rates scale with ambient conditions: warm outdoor scenes use faster background updates (`bg_alpha_fast`=0.028) to suppress false positives from sun-heated surfaces, while cool indoor environments use slower, more stable models (`bg_alpha_fast`=0.020). This prevents the background model from being corrupted by the presence of a hot target and avoids the need for manual mode switching by the operator. This cross-modal fusion between a barometric sensor and a thermal classifier is a key architectural contribution of the 2HAD-RAD system.

IV. Hardware Design

A. Microcontroller and Peripheral Interfaces

The ESP32-WROOM-32E provides dual-core Xtensa LX6 processors at 240 MHz, 520 KB SRAM, and 4 MB flash. FreeRTOS manages concurrent tasks for sensor acquisition, data processing, fusion, and user interface rendering, with task priorities assigned to ensure radar data reception and proximity interlocking preempt display updates. A CAT9555 I^2C GPIO expander extends digital I/O across Port 0 and Port 1: P0.1 drives the HC-SR04 USS trigger; P0.2 drives the DW3000 UWB hardware reset (active-low); P0.3 drives the ILI9341 TFT hardware reset (active-low); P0.7 controls the XPT2046 touch chip-select; and P1.x provides the 5-way navigation button inputs with software debounce. Key native GPIO assignments include: UART0 (GPIO1/3) for debug console; UART2 (GPIO16/17) time-multiplexed between radar configuration and GNSS; UART1 RX-only (GPIO33) for high-speed radar TLV at 921600 baud; SPI clock/MOSI/MISO (GPIO18/23/19) shared between the ILI9341 LCD (CS GPIO25, DC GPIO32) and DW3000 UWB (CS GPIO13); I^2C SDA/SCL (GPIO21/22) shared among the MLX90640, MPU9250, BMP280, and CAT9555; I^2S data (GPIO14) for the MAX98357A audio amplifier; GPIO15 for the radar NRST interlock line; GPIO34 for the touch IRQ input; and GPIO4 for the detection status LED.

B. Radar Module

The IWR6843AOP integrates a 60–64 GHz RF front-end with three transmit and four receive antennas in an antenna-on-package configuration, a C674x DSP, and an ARM Cortex-R4F controller on a single chip. The evaluation module provides a UART data interface at 921600 baud and a separate UART configuration interface at 115200 baud accepting TI mmWave SDK commands. It was programmed using TI UniFlash with `vital_signs_tracking_6843AOP_demo.bin` from the mmWave Industrial Toolbox v4.12.1, and configured via a modified `vital_signs_AOP_6m.cfg` profile adapted for 0.1–5 m range at approximately 4 cm resolution. The radar operates from the 5 V system rail at approximately 2.5 W active. The NRST line serves as a hardware interlock: when the HC-SR04 detects an obstacle within 22 cm, the firmware asserts NRST LOW to immediately halt all RF emission, regardless of the radar's internal ARM core state. On subject clearance, NRST is released and after a 200 ms boot settling delay the full chirp configuration sequence is re-issued over the CLI UART before data collection resumes.

C. Anchor Unit

The stationary anchor unit on an Arduino Uno R4 WiFi integrates three peripherals operating concurrently on separate buses requiring no arbitration: the DWM3000EVB as SS-TWR Pong responder on SPI, the Waveshare HMMD 24 GHz mmWave radar on UART (Serial1, D0/D1), and a 16×2 I^2C LCD for local status display. The anchor's fixed deployment position provides a second independent physiological sensing vantage point. Breathing rate, heart rate, and UWB-measured distance are transmitted to the main ESP32 over BLE and averaged with the primary radar readings when the anchor BLE link is active, providing a second independent physiological measurement stream.

D. Power Subsystem

Two LM2576 step-down regulators convert the 3S pack voltage (9.0–12.6 V) to a 5 V rail for the radar module and LCD backlight, and a 3.3 V rail for the ESP32 and all sensors. A dedicated 3S 10 A BMS protection board enforces per-cell over-charge (4.2 V cutoff), over-discharge (2.5 V cutoff), over-current (10 A limit), and short-circuit protection. Table 1 summarizes the power budget. At the estimated 3.7 W system draw, three 2200 mAh 18650 cells (≈24 Wh usable) project approximately 5–6 hours of continuous runtime, satisfying the 2-hour design requirement with substantial margin.

Table 1
Power Budget Summary

Subsystem	Rail	Typ. Draw	Notes
Radar (IWR6843AOP)	5 V	2.50 W	Active scan mode
ESP32-WROOM-32E	3.3 V	0.55 W	BLE + dual-core processing
ILI9341 LCD	5 V	0.30 W	50% backlight
MLX90640 IR	3.3 V	0.05 W	4–16 Hz frame rate
DW3000 UWB	3.3 V	0.15 W	Active SS-TWR ranging
MPU9250 + BMP280	3.3 V	0.12 W	Continuous navigation
HC-SR04 + CAT9555	3.3 V	0.025 W	Periodic trigger duty cycle
Total (est.)	—	≈3.7 W	Full concurrent operation

V. Software Architecture

A. UART Resource Management and Radar Initialization

The radar subsystem requires two simultaneous UART interfaces — CLI configuration at 115200 baud and continuous TLV data at 921600 baud — while the INS/GNSS module requires a persistent UART connection. Since the ESP32-WROOM-32E provides only three hardware UART peripherals and the CLI interface is only needed during initialization, a time-multiplexed strategy was adopted. UART2 (GPIO16/17) carries radar configuration commands during startup with a 60 ms inter-command delay enforced between each command to allow the radar's internal ARM core to complete processing before the next arrives — omitting this delay caused consistent `sensorStart Error -1` faults during early bring-up. After `sensorStart` completes, UART2 is immediately reassigned to the INS/GNSS subsystem. High-speed TLV data continues uninterrupted on the dedicated receive-only UART1 (GPIO33, 921600 baud) throughout. This approach eliminated the need for external UART multiplexers while maintaining real-time performance across all sensor tasks. The DIP switch configuration required for correct 60-pin Samtec connector operation was determined empirically, as the configuration specified in the IWR6843AOP datasheet did not produce functional UART communication; the working configuration (S1: ON ON OFF OFF; S2: OFF ON OFF OFF; S3: OFF) was confirmed by observing the radar boot prompt on the serial monitor.

B. SPI Bus Arbitration and CAT9555 Shadow Register

The ILI9341 LCD and DW3000 UWB module share the SPI bus, requiring strict arbitration. A FreeRTOS binary semaphore (`spiBusMutex`) enforces exclusive ownership; all SPI transactions are wrapped in `xSemaphoreTake` / `xSemaphoreGive` pairs with both CS lines driven high before any transaction begins. Because the LCD chip-select is routed through the CAT9555 I^2C expander rather than a native ESP32 pin, acquiring the SPI mutex is always followed by an I^2C write to assert the correct chip-select, enforced in `lcdBeginAccess()` and `uwbBeginAccess()` helper functions. A shadow register (`cat9555Port0Shadow`) tracks expander output state locally; all writes to the CAT9555 are computed against the shadow value rather than a live bus read, eliminating the read-modify-write corruption that caused intermittent TFT white-screen flashes during early bring-up. This combination of mutex protection, explicit chip-select deselection, and shadow register maintenance eliminated all observed SPI corruption under sustained concurrent load.

C. Thermal Classification Pipeline

A multi-stage classification pipeline in `thermal_human_detector.h` overcomes the limitations of fixed-threshold detection, which proved unreliable due to environmental variability and non-human heat sources. Each 32×24 frame is first bilinearly upscaled to 64×48 and spatially smoothed. The pipeline then proceeds through five stages. *Adaptive background modeling* maintains a per-pixel background estimate using dual time-constant exponential averaging: a fast rate (`bg_alpha_fast`) applies when a pixel is cool, allowing the model to track slow environmental drift; a slow rate (`bg_alpha_slow`=0.003 indoors) applies when a pixel is hot, preventing the model from absorbing a stationary subject into the background over time. BMP280 ambient temperature scales these rates across deployment environments. *Dynamic thresholding* flags pixels as hot only if they exceed both the background estimate by `bg_delta_c` degrees and the scene 75th percentile by `percentile_delta_c` degrees, ensuring consistent performance across varying ambient temperatures. *Blob segmentation* groups hot pixels using 8-connected component labeling and rejects blobs outside valid size (8–340 pixels near-range) and fill-ratio (0.14–0.90) windows. *Shape classification* scores surviving blobs against seven human silhouette classes (HEAD_ONLY through LAYING_DOWN) using geometric features including bounding box aspect ratio, fill ratio, edge compactness, vertical energy distribution, and width taper ratio. Standing poses require aspect ratio below 1.35; LAYING_DOWN requires width-to-height ratio above 1.75. Temperature is used as a supporting rather than primary criterion, with a hard upper limit of 45 °C rejecting heater-like hotspots regardless of shape score. *Temporal smoothing* filters the per-frame classification result through an exponential moving average with asymmetric time constants (`rise_alpha`=0.12, `fall_alpha`=0.04) and hysteresis thresholds (`present_on`=0.66, `present_off`=0.50) to prevent state toggling from transient noise.

D. Inertial Navigation and Extended Kalman Filter

The 8-state EKF in `handheld_ekf.h` fuses IMU dead-reckoning with UWB scalar range updates and BMP280 barometric altitude at ~100 Hz. The state vector [X, Y, Z, VX, VY, VZ, YAW, BARO_BIAS] captures 3D position, 3D velocity, yaw heading, and a barometric bias term modeled as a random walk. Roll and pitch are handled separately by the Madgwick filter; yaw is maintained within the EKF with raw gyro-Z integration to avoid the Madgwick yaw drift common in magnetically disturbed indoor environments. UWB updates apply independent scalar corrections per axis with 3.5σ innovation gating to reject multipath outliers; barometric updates apply joint Z-axis and bias corrections with 3.0σ gating. UWB confidence degrades quadratically beyond 1.5 seconds with fusion weights of 0.70 for fresh readings, 0.50 for aging readings, and 0.25 for INS-only periods, ensuring that a stale UWB fix gracefully yields to INS dead-reckoning rather than producing large position jumps. Outlier rejection discounts UWB contributions by 70% when UWB and INS estimates disagree by more than 3 m within the first 30 seconds of operation. Pressing the START button executes quick calibration routines that collect 300 IMU samples for accelerometer and gyroscope bias estimation and 12 barometric samples for altitude zeroing, then resets the local coordinate origin, velocity, and position.

E. Anchor Radar DSP Pipeline

The anchor firmware in `Radar2.ino` performs fully independent vital-sign extraction on the 24 GHz HMMD radar data rather than relying on on-chip DSP output. Incoming 35-byte HMMD frames are parsed through a four-state machine (WAIT_HEADER → READ_LEN → READ_DATA → READ_TAIL), yielding a presence byte, raw distance, and 16 gate energy values at 70 cm spacing. Gate energies are log-compressed with `log1p` and pushed into a 128-sample ring buffer at 10 Hz, feeding a three-band respiratory classifier covering Adult (0.15–0.38 Hz, 9–23 BPM), Child (0.28–0.62 Hz, 17–38 BPM), and Infant (0.50–0.95 Hz, 28–60 BPM) ranges. A Hann-windowed FFT with parabolic peak interpolation, subharmonic preference weighting, and double-harmonic suppression extracts the dominant respiratory frequency per band. Band selection uses a hysteresis-gated classifier requiring five consecutive votes to switch bands, preventing oscillation. A Kalman filter with SNR-adaptive measurement noise smooths the final BPM output. Heart rate is extracted from a separate 256-sample ring buffer via breathing harmonic notching in the frequency domain followed by inverse FFT and autocorrelation over the physiologically valid lag range for the active age band. The FFT peak and autocorrelation result must agree within 12 BPM; disagreement triggers fallback to whichever estimate is closer to the prior valid reading. A bootstrap accumulator requires three consecutive consistent readings before the Kalman filter is seeded, preventing early false locks. All three operations — breathing analysis, fast breathing on 64 samples every 500 ms, and cardiac analysis — run sequentially in the anchor main loop with non-blocking budget-limited UART draining to maintain concurrent responsiveness across all three peripherals.

F. Scan Mode Engine and User Interface

A multi-phase scan engine in `scan_mode.h` orchestrates detection through RADAR → IR → POSITION → FUSION phases. The RADAR phase collects TLV presence flags, vital-sign readings, and target position data over a configurable window. Because HR estimation exhibits consistent subharmonic locking near 50.2 bpm regardless of true cardiac rate, the radar confidence contribution requires a presence flag and valid BR rather than accurate HR. The IR phase invokes the thermal classification pipeline and waits for a stable result. The POSITION phase queries the EKF for current fused position and UWB confidence weighting. The FUSION phase combines evidence using weighted summation with radar and thermal carrying the highest weights as independent physical confirmation modalities, and position evidence acting as a consistency multiplier that boosts confidence when spatial context supports the sensor readings.

Four display modes are implemented on the ILI9341 LCD with dirty-rectangle caching for smooth updates: Raw Data View (live numeric sensor outputs from all active subsystems at up to 10 Hz); INS Map View (top-down dead-reckoning track with victim markers, rotating with device YAW so the operator's heading always points upward); Radar Map View (360° polar sweep display driven by device YAW from MPU9250 magnetometer-gyro fusion and mmWave distance from the IWR6843AOP, with an aging blip ring buffer that fades detections proportionally over several seconds); and Thermal Heatmap View (upscaled 64×48 thermal image with dynamic color palette and classification overlay). Physical input is handled by a 5-way navigation button read through the CAT9555 expander. Audio feedback is provided by a MAX98357A I^2S amplifier applying a software filter chain: single-pole 120 Hz high-pass filter for DC removal, three-pole 3200 Hz low-pass filter for hiss rejection, noise gate at 0.005 normalized amplitude, and 0.3 output gain scalar with soft limiting. LCD updates are temporarily paused during active audio playback to prevent SPI bus contention. A native iOS application built in Swift with SwiftUI and CoreBluetooth mirrors the Android application, providing five dedicated views — radar and proximity, thermal heatmap, INS navigation, scan mode results, and BLE connection management — all updated in real time without manual refresh.

VI. Implementation and Testing

A. Prototype Integration and Key Bring-Up Challenges

The prototype was assembled on custom PCBs fabricated for four subsystems: main MCU/UWB/IR/INS, radar interface breakout, UI/display, and power management. Each board includes local decoupling (0.1 μF ceramic and 10 μF electrolytic) at every supply pin and 33 Ω series resistors on high-speed SPI and UART lines to reduce reflection and crosstalk. Bring-up proceeded subsystem by subsystem before full concurrent integration under FreeRTOS.

A significant DW3000 library issue was identified during UWB bring-up. The library's `spiSelect()` function, inherited from DW1000-era code, performed a full device reset and wrote DW1000-specific register values before initialization completed on every call, corrupting the DW3000 register map and producing garbage device ID reads. The fix reduced `spiSelect()` to a single `reselect()` call that asserts the chip-select pin without issuing any register writes, eliminating the corruption entirely [7]. This issue would affect any design reusing the same library without modification and is documented here as a caution for future implementations.

Intermittent UWB ranging dropouts during initial testing were traced to resistive voltage drop on the supply cables feeding the sensor subsystem PCB under the DW3000's transient TX current draw. Replacing the original wire with 16 AWG conductors reduced resistance sufficiently to maintain stable supply voltage through the transmission pulse, eliminating the dropouts entirely. Three bugs were also identified and corrected in the anchor unit's cardiac analysis function: a use-before-declaration on the heart rate candidate variable that caused undefined behavior on first entry, a scoping error that made the breathing frequency reference inaccessible to the harmonic rejection loop, and a structural early return that prevented parabolic peak interpolation from executing after harmonic rejection. All three were necessary to correct before stable cardiac estimates emerged.

B. Radar Testing

Radar testing was conducted indoors with a single subject positioned at measured distances of 0.5, 1.0, 1.5, and 2.0 m on boresight. At each distance, the Phase 1 chirp profile ran for a 30-second window while TLV type 1040 vital-sign frames were parsed and HR, BR, and presence output monitored. Phase 2 then ran its 30-second window and TLV 1010 target position distance estimates were recorded. An empty-room control condition was also recorded at each distance to evaluate false-positive behavior. Table 2 summarizes error across all distances.

Table 2
Radar Performance vs. Distance

Dist. (m)	HR Avg (bpm)	HR Err (%)	BR Avg (bpm)	BR Err (%)	Dist Avg (m)	Dist Err (%)
0.5	69.1	30.9	22.2	10.8	0.64	27.3
1.0	67.7	32.3	18.2	9.0	0.88	11.7
1.5	69.6	30.4	19.3	3.5	1.34	10.7
2.0	69.9	30.1	20.9	4.7	1.92	4.2

HR error is consistent due to FFT subharmonic locking. BR and distance accuracy both improve with range.

Breathing rate accuracy improved with range, from 10.8% error at 0.5 m to 3.5% at 1.5 m, reflecting the radar chirp profile's optimization for mid-range detection. Distance estimation error improved similarly, from 27.3% at 0.5 m to 4.2% at 2.0 m, consistent with the expected behavior of FMCW range estimation improving as range-resolution effects diminish relative to measured distance. Heart rate estimates averaged 67–70 bpm across all distances, a consistent underestimation of approximately 30% relative to the ground-truth resting heart rate of 100 bpm. This behavior is attributed to the FFT response locking onto a subharmonic of the true cardiac frequency rather than the dominant fundamental, a known limitation of phase-extraction-based HR estimation at 60 GHz. Heart rate is therefore treated as a presence-corroborating signal rather than a standalone measurement throughout the detection logic. The two-condition detection gate (`targetPresent` AND `vitalsReady`) produced zero false-positive `humanDetected` events during all empty-room control trials, confirming that the presence flag alone from background reflections was insufficient to assert a detection.

C. Thermal Classification Validation

The advanced thermal pipeline substantially outperformed the original fixed-threshold approach. Fixed-threshold detection frequently generated false positives from background heat sources including HVAC vents, computer equipment, and sunlight patches, and was highly sensitive to ambient temperature changes between test sessions. After implementing the full five-stage pipeline with BMP280 baro-temperature fusion, human subjects were consistently identified with high confidence in complete darkness, under indoor ambient lighting, and in outdoor daylight and nighttime conditions. The adaptive background model correctly suppressed false positives from warm outdoor surfaces that caused the fixed-threshold detector to fire. The 9-class shape classifier successfully rejected several non-human heat sources — including a table lamp, a laptop exhaust vent, and a heated floor register — that produced thermal blob areas and temperatures within the human range but failed the geometric feature scoring for aspect ratio and energy distribution.

D. INS and UWB Validation

The INS stack demonstrated acceptable short-term drift of less than 2 m over 10 m paths when the still-detection gate was active. Long-term drift accumulation confirmed the necessity of UWB fusion for extended operations. UWB SS-TWR ranging required iterative antenna delay calibration; both TX and RX delays were set to 16385 after measuring at a known 1 m reference distance and adjusting until ranging error was minimized. After calibration, UWB ranging achieved consistent line-of-sight performance with the fused EKF estimate tracking the subject's actual position qualitatively. The 8-state EKF substantially reduced position drift compared with pure dead-reckoning integration across all tested paths.

E. System Integration and Power Validation

Full concurrent operation of all subsystems under FreeRTOS was validated with no watchdog resets or observed scheduling conflicts across radar, thermal, INS, UWB, display, audio, and BLE tasks. The SPI mutex, I^2C bus scheduling, UART time-multiplexing, and CAT9555 shadow register together eliminated all bus conflicts observed during early bring-up. Both LM2576 rails held within specification under simultaneous radar scanning, UWB ranging, BLE advertisement, LCD updates, and audio playback — the highest concurrent load condition the system encounters. Fused victim location data was confirmed delivered in real time to both companion iOS and Android applications over BLE with latency consistently under the 10-second design requirement.

F. Subsystem Verification Summary

All major subsystems were verified against the final integrated firmware build. The IWR6843AOP radar passed TLV frame parsing, two-phase chirp sequencing, dual-UART bring-up, and real-time radar map rendering using device YAW. The MLX90640 thermal array was confirmed operational through the full classification pipeline including adaptive background modeling, 9-class shape scoring, and barometric temperature fusion. The DW3000 UWB transceiver completed SS-TWR exchanges reliably at all tested distances with antenna delays of 16385, and fused distance estimates were confirmed in the 8-state EKF output. The MPU9250 and BMP280 INS stack passed calibration, Madgwick orientation filtering, still-detection gating, and dead-reckoning track rendering in the INS Map View. The HC-SR04 proximity interlock correctly asserted NRST LOW at $\leq$22 cm and re-issued the full radar configuration sequence on clearance. The ILI9341 LCD, 5-way navigation button, and MAX98357A audio amplifier operated correctly across all four display modes under full concurrent sensor load, with the SPI mutex, CAT9555 shadow register, and UART time-multiplexing strategy producing no observed conflicts or watchdog resets. BLE connectivity was confirmed on both iOS and Android companion applications, with real-time victim data and thermal frames received correctly on each platform. The anchor unit passed SS-TWR Pong response, three-band respiratory classification, autocorrelation cardiac extraction, and BLE vital-sign transmission to the primary device. Power rail stability at 3.3 V and 5 V was confirmed under full concurrent load across all subsystems.

VII. Results and Discussion

The 2HAD-RAD platform achieved all primary design objectives. Radar-based human detection was confirmed at distances up to 2 m, with BR error improving from 10.8% at 0.5 m to 3.5% at 1.5 m as range-resolution effects diminish. The persistent HR subharmonic bias ($\approx$30%) is a known limitation of FFT-based cardiac extraction at 60 GHz and does not impair the detection decision, which requires valid BR and presence flags rather than accurate HR. The zero false-positive rate across all empty-room control trials confirms that the two-condition gate effectively suppresses background reflection events that would trigger single-condition detectors.

The BMP280 baro-temperature fusion into the thermal classification pipeline demonstrated measurable operational benefit: the system maintained consistent detection performance across indoor and outdoor conditions without requiring manual parameter adjustment, while the fixed-threshold baseline required recalibration between environments. The 9-class shape scoring further rejected non-human heat sources that the temperature criterion alone could not distinguish, including laptop exhaust vents and heated floor registers whose temperatures fell within the 30–40 °C human range.

The anchor's 24 GHz radar extended system coverage to scenarios where the primary 60 GHz device lacked line-of-sight to the subject. The longer wavelength's superior penetration through drywall and wood framing confirmed through-wall vital-sign detection from the fixed anchor vantage point. The three-band respiratory classifier achieved stable breathing rate lock within the first full 128-sample buffer window ($\sim$12.8 s at 10 Hz), with the fast-path 64-sample path providing earlier candidate estimates during the initial lock-on period. Cardiac extraction via autocorrelation with breathing harmonic notching produced consistent HR estimates after the three-reading bootstrap accumulator was satisfied, and the FFT-to-autocorrelation agreement gate (12 BPM tolerance) effectively rejected aliased lags that had caused early false locks prior to the bootstrap requirement being added. The three firmware bugs corrected in the cardiac analysis function — use-before-declaration on the HR candidate variable, a scoping error making the breathing frequency inaccessible to the harmonic rejection loop, and an early return blocking parabolic interpolation — each produced silent incorrect output rather than observable crashes, underscoring the importance of thorough code review in embedded DSP pipelines where control-flow errors are not self-announcing.

The UART time-multiplexing strategy exemplifies efficient embedded resource management under fixed hardware constraints. The CAT9555 shadow register fix and FreeRTOS SPI mutex together demonstrate that shared-bus architectures on resource-constrained microcontrollers require explicit tracking of peripheral state, and that standard I^2C read-modify-write sequences are insufficient when multiple tasks may interleave bus access. The projected 5–6 hour runtime at 3.7 W significantly exceeds the 2-hour requirement, providing operational margin for extended field deployment without recharging.

Several system limitations were identified during testing. Heart rate estimation from the IWR6843AOP exhibited a consistent subharmonic bias regardless of distance or subject, with estimates clustering near 50.2 bpm or averaging 67–70 bpm rather than tracking the true 100 bpm ground truth. This is a known behavior of the on-chip FFT-based cardiac extractor at 60 GHz and is not correctable through configuration; it limits HR to a presence-corroborating role rather than a clinical measurement. INS dead-reckoning drift, while acceptable over short paths (<2 m over 10 m), accumulates over extended traversals and requires periodic UWB corrections to remain useful; in environments where UWB line-of-sight to the anchor is obstructed, positional accuracy degrades toward pure inertial integration. The MLX90640 thermal range of 5–7 m and 32×24 native resolution limit detection to moderate distances and require the bilinear upscaling pipeline to produce a usable heatmap; at ranges beyond 5 m, human-sized blobs occupy only a few pixels and classification confidence drops. These limitations define the primary directions for future system improvement.

VIII. Conclusion

This paper presented **2HAD-RAD**, a portable embedded platform for multi-sensor human presence detection in visually constrained environments. The system integrates a 60 GHz FMCW radar, infrared thermal camera with advanced multi-stage classification, DW3000 UWB SS-TWR ranging, MPU9250+BMP280 inertial navigation with an 8-state EKF, HC-SR04 ultrasonic proximity interlock, and MAX98357A I^2S audio, coordinated by an ESP32-WROOM-32E under FreeRTOS. A companion anchor unit on the Arduino Uno R4 WiFi provides independent 24 GHz through-wall vital-sign sensing and SS-TWR UWB response, with results fused over BLE.

Experimental validation confirmed BR error improving from 10.8% at 0.5 m to 3.5% at 1.5 m, distance estimation error improving from 27.3% at 0.5 m to 4.2% at 2.0 m, and zero false-positive detections across all empty-room control trials. The thermal classification pipeline reliably identified human subjects in complete darkness and under varying ambient lighting and outdoor conditions. The 8-state EKF substantially reduced INS drift compared to pure dead-reckoning. All subsystems operated concurrently under FreeRTOS with no observed conflicts, and victim data was confirmed delivered in real time to both companion iOS and Android applications over BLE within the design latency requirement.

The 2HAD-RAD platform demonstrates that tightly coupled fusion of 60 GHz mmWave radar, infrared thermal imaging with barometric ambient fusion, UWB-corrected inertial navigation, ultrasonic safety interlocking, and independent 24 GHz through-wall anchor radar on a compact embedded system can provide a practical, robust, and field-ready tool to assist first responders in low-visibility search-and-rescue operations. Future work will evaluate through-wall radar detection at greater depths, integrate additional UWB anchor nodes for multi-point localization, and explore lightweight ML-based fusion classifiers trained on field-collected multi-sensor datasets.

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