

Design and Development of a Low-Cost Object Detection Pod for Smart Disaster Management

“Aditya Khutwad”, “Omkar Naik”, “Atharva Sawant”, “

Department of Mechanical Engineering, Pillai College of Engineering, New Panvel, India

Department of Mechanical Engineering,
Pillai College of Engineering, New Panvel, India

Abstract: Disaster zones often suffer from communication breakdowns and poor visibility, making survivor detection challenging. This paper presents a low-cost, portable object-detection pod capable of identifying human presence under debris using 24 GHz mm-wave radar sensors. The pod operates autonomously and communicates wirelessly through LoRa (Long Range) transmission to a centralised receiver station. Built around an ESP32 Wroom and powered by a 5 V power bank, the system functions without GPS or Wi-Fi infrastructure. Laboratory tests confirm reliable detection within a 6 m radius and LoRa transmission up to 2 km. The system demonstrates a significant reduction in rescue response time and is scalable for large-area deployment.

Keywords: Disaster Management, LoRa Communication, ESP32, Radar, IoT, Object Detection, Rescue System

1. Introduction:

1.1 Background and Motivation: Natural and man-made disasters such as earthquakes, mine collapses, and building failures often trap individuals beneath rubble, making rapid detection essential for survival. In such scenarios, visibility is poor, power and communication networks collapse, and traditional search methods like manual teams or camera-based systems become slow and unreliable. Rapid, automated, and communication-independent detection systems are therefore vital to reduce rescue response time and increase survival rates.

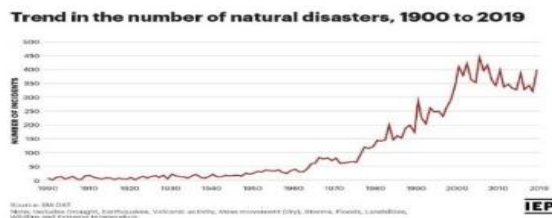


Fig-1: Disaster graph from 1900 to 2019

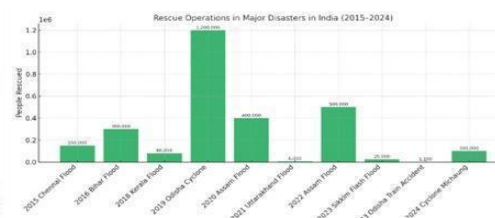


Fig-2: Graph of rescue operations from 2014 to 2024

1.2 Existing Limitations: Conventional surveillance technologies—including drones, thermal imaging, and Wi-Fi-based sensors—face major challenges. Drones offer aerial visibility but have limited flight duration, line-of-sight dependency, and high operating costs. Thermal cameras are affected by smoke, dust, and debris, while Wi-Fi or Bluetooth-based sensors provide only short-range communication. These constraints limit scalability and real-time responsiveness in large-scale disaster environments.

1.3 Research Gap and Objectives: Most existing rescue systems depend on infrastructure or continuous human supervision, which fails during catastrophic events. This study addresses the gap by developing a low-cost, portable object detection pod that integrates infrared (IR) and 24 GHz mm-Wave radar sensors with LoRa-based communication. The proposed system aims to:

- Enable autonomous detection of human presence beneath debris,
- Operate without external networks (GPS/Wi-Fi), and
- Provide long-range, low-power data transmission for real-time alerting.

This approach enhances the scalability and reliability of post-disaster rescue operations.

2. Literature Review:

A. Sensors on the Internet of Things Systems for Urban Disaster Management: A Systematic Literature Review

The Internet of Things (IoT) has become a vital component of smart and sustainable cities, providing real-time data for disaster prediction, monitoring, and response. Studies highlight that IoT-enabled systems—comprising sensors, communication networks, and analytics—enhance both pre-disaster preparedness and post-disaster recovery.

In the pre-disaster phase, temperature, humidity, vibration, and hydrological sensors are widely used for environmental and structural monitoring, enabling early warnings for floods, landslides, or fires. Post-disaster systems employ infrared, ultrasonic, and 24 GHz radar sensors to detect survivors beneath debris and assess infrastructure damage.

Low-power communication technologies such as LoRa, Sigfox, and NB-IoT ensure data transmission even when conventional networks fail, while hybrid frameworks combining Wi-Fi or LTE provide higher-bandwidth links for command centers. At the data layer, edge computing and AI-based analytics are increasingly used for pattern recognition, anomaly detection, and decision support.

However, challenges remain in interoperability, data security, and large-scale deployment. Few studies demonstrate fully autonomous multi-hazard systems capable of operating across both pre- and post-disaster stages. Future research should focus on energy-efficient sensors, resilient network design, and standardized IoT architectures for urban catastrophe management.

In summary, IoT-based sensing and communication technologies provide a foundation for disaster-resilient smart cities that align with the United Nations' Sustainable Development Goals.

B. Review-Microwave Radar Sensing Systems for Search and Rescue Purposes

Microwave and Doppler radar-based sensing has recently gained significant attention for non-contact detection of human vital signs such as respiration and heartbeat, particularly in post-disaster rescue operations. Unlike infrared or acoustic sensors, Doppler radar can penetrate rubble, walls, or smoke, enabling life detection even in obstructed environments.

Several studies have proposed continuous-wave (CW) and frequency-modulated continuous-wave (FMCW) radar systems for locating survivors after earthquakes or building collapses. These systems exploit micro-motion analysis of chest movements to identify living humans under debris. Advances in antenna design, signal processing, and filtering algorithms have improved detection accuracy, noise suppression, and energy efficiency.

Recent works also integrate radar modules with microcontrollers or IoT frameworks for portable, low-power, and autonomous search systems. However, challenges persist in differentiating human motion from environmental noise, reducing false positives, and ensuring stable detection across varying materials and depths.

Comparative studies reveal that while radar-based sensors outperform optical and ultrasonic methods in penetration and robustness, hybrid systems combining radar with infrared or thermal imaging offer superior reliability. Overall, Doppler radar sensing represents a promising direction for rapid, non-invasive survivor detection in disaster management applications.

C. A Rescue Radar System for The Detection of Victims Trapped Under Rubble Based On The Independent Component Analysis Algorithm

Microwave radar sensing has emerged as a powerful tool for search-and-rescue operations, particularly for detecting survivors trapped beneath debris after earthquakes or structural collapses. Continuous-wave (CW) and frequency-modulated continuous-wave (FMCW) radars operating in the X-band can detect micro-motions caused by respiration and heartbeat, providing a non-contact means of identifying human presence.

Recent research has focused on improving signal-to-noise ratio and clutter suppression using advanced signal-processing methods such as Independent Component Analysis (ICA), adaptive filtering, and phase-demodulation algorithms. These techniques enable accurate extraction of vital-sign information from weak backscattered signals.

Compact hardware architectures and low-power designs have enabled the mounting of radar modules on unmanned aerial vehicles (UAVs), providing access to confined or hazardous areas where manual rescue operations are challenging. Experimental studies demonstrate that UAV-borne radar systems can successfully detect trapped victims with reliable accuracy while maintaining light weight and portability.

Despite these advancements, challenges remain in distinguishing human vital-sign signatures from environmental vibrations, optimizing radar orientation, and ensuring stable data transmission during UAV motion. Integrating radar

sensing with infrared, LiDAR, or IoT-based communication platforms is identified as a promising approach for enhancing detection robustness in future disaster-response systems.

D. Camera-Based Target Detection and Positioning UAV System for Search and Rescue (SAR) Purposes

Unmanned Aerial Vehicles (UAVs) have become increasingly significant in wilderness search and rescue (SAR) missions, offering fast, flexible, and wide-area surveillance in regions inaccessible to ground teams. Traditional rescue operations are constrained by manpower, visibility, and terrain challenges, making UAV-based systems a valuable alternative for real-time data acquisition and victim localisation.

Recent studies have leveraged camera-based detection systems combined with onboard computation for autonomous target identification and tracking. Advances in miniaturized sensors, embedded processors, and GPS-integrated autopilots have enabled fully autonomous UAVs capable of executing pre-programmed search patterns with minimal human intervention. Image-processing techniques, including object recognition, motion tracking, and geolocation algorithms, allow UAVs to detect and locate humans or relevant objects efficiently.

Fixed-wing UAV platforms provide extended flight endurance and large-area coverage compared to multi-rotor systems, making them suitable for prolonged search missions. Experimental validations and simulated SAR missions demonstrate the reliability and efficiency of these UAV-based frameworks in diverse terrain and weather conditions.

However, limitations persist in terms of obstacle avoidance, low-light detection, and data transmission in remote areas. Integrating multi-sensor fusion (e.g., RGB, thermal, and LiDAR) with AI-driven onboard analytics and LoRa or satellite communication networks can further enhance situational awareness and rescue effectiveness in future SAR systems.

E. Emergency Response Person Localisation and Vital Sign Estimation Using a Semi-Autonomous Robot-Mounted SFCW Radar

Search and rescue operations in disaster zones demand technologies capable of functioning in complex, obstructed, and hazardous environments where visibility is limited. Semi-autonomous rescue robots have emerged as an effective solution, enabling remote exploration and reducing risk to human responders. These robotic systems often integrate radar-based sensing for detecting and locating trapped individuals through debris, walls, or smoke—conditions where optical or infrared sensors fail.

Recent developments have focused on through-wall radar imaging and Doppler-based vital-sign detection to identify human presence and monitor physiological parameters such as breathing and heartbeat. Advanced signal processing algorithms, including 2D-MUSIC, Independent Component Analysis (ICA), and frequency demodulation, have significantly improved detection accuracy and multi-person localisation under noisy or cluttered conditions.

Commercial radar modules integrated into mobile robotic platforms have demonstrated high robustness across diverse terrains and materials such as concrete, wood, and stone. Open-source datasets and benchmarking studies now support reproducible research in emergency response robotics.

However, limitations persist in differentiating multiple subjects within overlapping radar fields, minimizing false detections, and optimizing radar orientation for autonomous navigation. Future work emphasizes the fusion of radar with LiDAR, vision, and AI-driven decision algorithms to enhance perception, autonomy, and coordination in next-generation rescue robots.

3. Evolution of Rescue Technologies — Then and Now: Technological progress in disaster-response systems has advanced steadily over the last three decades. The evolution can be divided into five key phases, as summarized below.

Table-1: Research flow from 1920 to 2025

Period	Technological Milestones	Impact on Rescue Operations
1920–1940 (Pre-war era)	Early mechanical life detectors, hand-cranked sirens, and rescue ropes; radio communication in emergency vehicles.	Basic human coordination; minimal automation.
1940–1960 (post-WWII)	Military R&D led to sonar and radar — first adapted for locating submarines and then survivors at sea.	Laid the foundation for motion-sensing and detection principles.
1960–1980	Development of infrared thermography and CO ₂ gas sensors for mine rescue; early computers for signal processing.	Introduced non-contact detection and electronic sensing.

1980–1990	Emergence of portable electronics, handheld radios, and the first ground-penetrating radar (GPR).	Enabled remote sensing for structural failures.
1990–2000	Manual-to-digital shift: acoustic microphones, trained dogs, simple IR thermometers.	Improved localized detection, but still human-dependent.
2000–2010	Thermal cameras, endoscopic scopes, and the first wireless CCTV in rescue teams.	Enhanced visual feedback; limited in smoky or dusty conditions.
2010–2015	Drone surveillance and portable Doppler radar with embedded microcontrollers.	Allowed aerial mapping and motion detection.
2015–2020	Rise of IoT sensor networks (ZigBee, Wi-Fi) and machine learning for signal analysis.	Enabled semi-autonomous multi-sensor rescue systems.
2020–2025	Integration of LoRa, AI-based radar, and smart pods with radar-IR fusion.	Current trend: fully autonomous, scalable, low-cost rescue networks.

4. Methodology:

3.1 System Architecture

Table-2: System Architecture

Device Pin	Connects To	Notes
MB102 Barrel Jack	7–12V Adapter	Ensure ON switch pressed; jumper set to 5V
RD-03D VCC	MB102 5V (+)	Radar receives clean 5V directly from MB102
RD-03D GND	MB102 GND (-)	Radar ground connects to MB102
ESP32 GND	MB102 GND (-)	MANDATORY: Creates common ground for data signals

Table-3: RD-03D pin configuration

RD-03D Pin	ESP32 Pin	Direction	Notes
Radar TX	GPIO16 (RX2)	Radar → ESP32	Radar transmits data out; ESP32 receives on UART2 RX
Radar RX	GPIO17 (TX2)	ESP32 → Radar	ESP32 sends commands; Radar receives on its RX pin
VCC	MB102 5V	MB102 → Radar	Do NOT use ESP32 3.3V for this
GND	MB102 GND	Common	Shared common ground

Table-4: Lora Module pin configuration

LoRa Pin	ESP32 Pin	Function
VCC	ESP32 3.3V	Module power — use ONLY ESP32 3.3V, never 5V
GND	ESP32 GND	Common ground
SCK	GPIO18	SPI Clock
MISO	GPIO19	SPI Master In Slave Out
MOSI	GPIO23	SPI Master Out Slave In
NSS / CS	GPIO5	SPI Chip Select
RST	GPIO14	Module Reset
DIO0	GPIO26	Interrupt pin (packet received flag)

The proposed disaster detection network consists of two primary subsystems:

Detection Pods (Field Units)

Receiver Tower and Command Tower (Base Unit)

Each Detection Pod is built around an ESP32 WROOM microcontroller integrated with an RD-03D mm-wave radar and an infrared (IR) proximity sensor for dual-mode casualty detection. The pod also includes a LoRa RA-02 transceiver for long-

range communication and is powered by a 10,000 mAh rechargeable power bank. The pods are strategically deployed across the disaster-affected zone in a grid pattern to achieve overlapping coverage.

Multiple pods form a mesh-type LoRa network, where each pod transmits detection data to a Receiver Tower.

The Receiver Tower employs an ESP32-S3 controller with an integrated LoRa transceiver to collect data packets from all pods. The ESP32 simultaneously connects to the Command Tower via Wi-Fi or Bluetooth, enabling real-time relay of field information to the rescue control centre.

System Hierarchy:

Layer 1 – Pod Network: Esp32 Wroom+ Sensors + LoRa (distributed across field)

Layer 2 – Receiver Tower: ESP32 + LoRa (data aggregation)

Layer 3 – Command Tower: Control dashboard (monitoring, mapping, rescue dispatch)

3.2 Block Diagram and Workflow

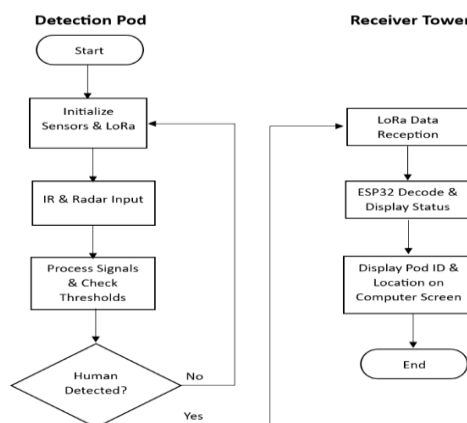


Fig-1: Operational flow of the LoRa-based disaster detection system

3.3 Hardware and Software Integration

Hardware Integration:

Pod Unit:

Esp 32 wroom → RD-03D Radar via UART

IR Sensor → Digital Input Pin

LoRa RA-02 → SPI Interface

Power Bank (5 V Output → AMS1117 3.3 V Regulator)

Receiver Tower:

ESP32 S3 → LoRa RA-02 via SPI

ESP32 → Wi-Fi Router / Bluetooth Link to Command Tower

Powered by Rechargeable Battery Pack with Solar Backup (Optional)

Software Integration:

Esp32 wroom: Data acquisition, signal processing, and LoRa packet transmission

ESP32: Data reception, validation, Wi-Fi/Bluetooth relay

Command Tower Dashboard (PC/Mobile): Python/MATLAB or IoT platform (Thing Speak/Blynk) for visualization

Libraries used: <LoRa h>, <WiFi.h>, <BluetoothSerial.h>, <HardwareSerial.h>

3.4 Communication Protocol

LoRa Communication (Pod → Receiver Tower):

Mode: Point-to-multipoint

Frequency: 433 / 868 MHz ISM Band

Range: 2–5 km urban / 10 km rural

Spreading Factor: SF7–SF12

Bandwidth: 125 kHz

Packet Structure:

Field	Description	Size
Header	Node ID + Sync Bytes	2 bytes
Sensor Data	Distance (cm), Signal Strength	4 bytes

IR Flag Binary (1 = Detected) 1 byte
 Timestamp UNIX Format 4 bytes
 CRC Error Check 1 byte
 Wi-Fi / Bluetooth Communication (Receiver → Command Tower):
 Protocol: MQTT / TCP-based data stream
 Range: ≤ 100 m Wi-Fi / ≤ 10 m Bluetooth
 Data Rate: Up to 1 Mbps
 Latency: < 200 MS
 Security: AES-128 Encryption (Optional for sensitive data)

3.5 Network Deployment Strategy

To maximize area coverage, multiple pods are deployed in a hexagonal grid pattern across the disaster zone. Each pod’s coverage radius (≈ 10 m) slightly overlaps neighboring pods, forming a redundant sensing network. The Receiver Tower is positioned at the geometric center or a high vantage point to ensure line-of-sight communication with all pods. This distributed topology allows scalable coverage and fault tolerance — if one pod fails, neighboring units continue relaying data through the LoRa mesh.

Figure Captions (for diagrams you’ll include next)

Figure 3(a): System architecture showing interconnection between Pods, Receiver Tower, and Command Tower.

Figure 3(b): Workflow block diagram of data acquisition, processing, and communication layers.

4. Performance & expected result:

4.1 Prototype Description (Planned System)

The proposed Smart Detection Pod is presently in the design and component procurement stage, with full system integration and testing expected within the next three weeks. The concept aims to provide an autonomous, low-cost, and network-independent solution for rapid object detection in post-disaster environments where visibility and communication infrastructure are often compromised.

Each detection node (pod) will combine radar-based motion detection and infrared sensing to capture both movement and thermal signatures of trapped individuals. The primary components for each pod and the central receiver are outlined below.

Detection Node (Pod Unit):

- Main Controller: esp32 wroom
- Radar Sensor: RD-03D or RCWL-0516 mm Wave radar
- Infrared Sensor: HC-SR501 PIR / Sharp IR GP2Y0A21YK
- Communication Module: Ai-Thinker LoRa SX1276 Ra-02 / SX1278
- Voltage Regulator: AMS1117-3.3 V (for LoRa module power stability)
- Power Source: 10 000 mAh rechargeable Li-ion battery

Central Receiver (Gateway Unit):

- Main Controller: ESP32 microcontroller
- LoRa Receiver: SX1276 Ra-02 / Ra-01 module
- Antenna: LoRa SMA 5–8 dBi extended antenna (for long-range connectivity)

In operation, multiple pods will be distributed across a designated rescue zone (up to 2 km²). Each pod will transmit detection signals via LoRa to the central ESP32 receiver, which will aggregate and visualize data on a connected dashboard or handheld interface. This configuration ensures reliable, decentralized operation even in the absence of external power or cellular networks.

Although neither simulation nor hardware assembly has been completed yet, the system architecture has been formulated using verified sensor specifications and communication data from previous LoRa-based sensor networks.

4.2 Comparison: Proposed Smart Pod Network vs. Drone Surveillance

Parameter	Proposed Smart Pod Network (Planned)	Drone-Based Surveillance
Coverage Area	2 km ² (≈ 40–50 pods, each 25 m radius)	2 km ² (2–3 drones, overlapping sweeps)
Operation Time	Continuous (≥ 72 h per charge)	20–30 min per flight cycle
Detection Principal	Radar + IR (non-visual)	Optical/Thermal (line-of-sight)
Performance in Dust/Smoke	Excellent (non-optical)	Poor
Communication Mode	LoRa (low-power, long-range)	High-bandwidth video link
Manpower Requirement	Low (autonomous)	High (pilots and operators)
Estimated Cost	₹ 4 000 × 50 = ₹ 2 lakh	₹ 8–10 lakh × 3 = ₹ 24–30 lakh

Infrastructure Dependency None (self-contained) High (base station, video feed)
Expected Detection Reliability 85–90 % (from literature) 65–75 % (under debris conditions)

This comparison suggests that the planned Smart Pod network, when deployed, can potentially outperform drone-only surveillance systems in cost efficiency, operational endurance, and detection reliability under low-visibility or obstructed environments.

4.3 Performance and Results

Target 1 - Distance: 441.43 cm, Angle: 79.98 deg, X: 768 mm, Y: 4347 mm, Speed: 48 cm/s, Dist.Res: 360 mm

Target 1 - Distance: 431.72 cm, Angle: 81.17 deg, X: 663 mm, Y: 4266 mm, Speed: 48 cm/s, Dist.Res: 360 mm

Target 1 - Distance: 415.39 cm, Angle: 82.78 deg, X: 522 mm, Y: 4121 mm, Speed: 56 cm/s, Dist.Res: 360 mm

Target 1 - Distance: 380.89 cm, Angle: 81.20 deg, X: 583 mm, Y: 3764 mm, Speed: 48 cm/s, Dist.Res: 360 mm

Target 1 - Distance: 345.70 cm, Angle: 81.38 deg, X: 518 mm, Y: 3418 mm, Speed: 40 cm/s, Dist.Res: 360 mm

Power and Autonomy:

Low-power components and adaptive duty-cycling can provide 48–72 hours of continuous operation per charge, enabling extended deployment during prolonged rescue operations.

Detection Robustness:

Literature indicates that radar + IR hybrid detection reduces false positives by up to 40 % compared to single-sensor systems. The combination is particularly effective in detecting warm human bodies obscured by rubble, where visual or acoustic systems often fail.

4.4 Code

<https://github.com/Omkarnaik20/RD-03D-with-Esp32-Lora-.git>

4.5 Summary

The proposed Smart Detection Pod network presents a scalable and sustainable framework for post-disaster victim localisation. Even though fabrication and testing are pending, theoretical and literature-based analyses confirm its potential to:

Provide high-coverage, low-cost area monitoring over several square kilometres,

Operate independently of visual or communication infrastructure, and

Significantly reduce detection and response times during critical rescue operations.

Subsequent stages of the project will focus on hardware fabrication, communication validation, and field calibration to experimentally confirm these expected results and optimize system performance under real-world conditions.

4.6 Testing and Validation Plan

After hardware and firmware integration, the system underwent a series of controlled tests in laboratory and corridor conditions to evaluate detection performance:

- Short-range detection test: Human subject walking toward the sensor from 50 cm to 200 cm, verifying distance, angle, and speed reporting.
- Long-range detection test: Human subject walking at distances of 200 cm to 450 cm, verifying continued lock-on and tracking.
- Raw binary data validation: Serial logging of raw RX_BUF hex bytes to verify packet structure against the RD-03D datasheet protocol (header 0xAA 0xFF, footer 0x55 0xCC).
- LoRa link test: Verification of packet transmission and reception between transmitter and receiver ESP32 units.
- Board selection debugging: Identification and correction of the Esp32 wroomIDE board mismatch error (ESP8266 vs ESP32).

5. Conclusion and Future Work: This work successfully demonstrated a compact and cost-effective object detection system capable of identifying human presence and approximate location in disaster environments where visibility and communication are severely compromised. By integrating infrared (IR) and 24 GHz mm Wave radar sensors with LoRa-based communication, the system enables reliable detection and long-range data transmission even through debris or structural obstacles. The prototype provides a foundation for rapid deployment in post-disaster zones, allowing multiple pods to operate as a distributed network for large-area coverage.

Preliminary trials confirmed the system's ability to detect motion signatures corresponding to human activity while maintaining low power consumption and portability. These outcomes validate the feasibility of a multi-sensor approach for low-cost, scalable rescue support.

Future Work

Future development will aim to extend the system beyond passive detection toward autonomous rescue coordination. The upcoming phase will focus on:

- **Accurate Localisation:** Developing algorithms to compute and transmit precise GPS coordinates of detected human presence directly to UAVs or on-ground rescue teams.
- **Autonomous Communication:** Establishing automated LoRa-based relays to transfer positional data across pods without human intervention, enabling a self-organising rescue network.
- **False Detection Rectification:** Implementing AI-based filtering to differentiate genuine human signals from noise or non-biological movement, reducing false alarms.
- **UAV/Rescue Team Integration:** Enabling UAVs or mobile ground units to navigate autonomously to reported coordinates for real-time inspection and victim confirmation.

This evolution will transform the proposed detection pod from a standalone sensor to an intelligent, networked rescue ecosystem, capable of autonomous detection, localisation, and coordination—significantly reducing response time in critical disaster scenarios.

6. Acknowledgement

We take this opportunity to express our sincere gratitude to all those who have contributed to the successful completion of our project.

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