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An Extended Reality (XR)-Based Tactical Support System Integrating Edge-AI Threat Detection and a Distributed Sensor Network for High-Risk Operations

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Abstract:

This paper presents the design and implementation of an Extended Reality (XR)–based tactical support system intended for use in high-risk defence operations. High-risk operational environments, such as defense battlefields, counter-terrorism missions, and disaster response zones, require instantaneous decision-making and seamless situational awareness. Until now, most defense-oriented immersive systems relied primarily on Virtual Reality (VR) and Augmented Reality (AR) interfaces simply to visualize preloaded mission data, lacking the capability to perform real-time threat identification. Building on earlier technologies, this paper proposes a next-generation Extended Reality (XR)-based tactical platform that performs intelligent on-ground analysis using Edge-Artificial Intelligence (Edge-AI) and a Distributed Sensor Network (DSN). The XR headset is equipped with a compact camera module capturing real-time visual feeds processed through an AI-driven facial recognition model to instantly match high-risk suspects against an encrypted database. Upon detection, the operator receives an immediate XR alert, while the base station receives captured imagery via a two-way wireless transceiver link. By offloading processing to the edge, the system dramatically reduces latency and cloud dependency, overcoming the limitations of traditional centralized surveillance. The integration of advanced hardware—including ESP32 microcontrollers, PIR sensors, vibration modules, and OLED displays—creates a resilient, lowpower, and highly scalable cooperative defense network.

Keywords—Extended Reality (XR), Edge-AI, Distributed Sensor Network, Threat Detection, Situational Awareness, Internet of Things (IoT), Tactical Support.

I. INTRODUCTION

A. Project Overview

High-risk operational environments such as military battle fields, disaster response zones, and hazardous industrial sites require rapid decision-making, accurate situational awareness, and seamless communication. In such scenarios, the ability to gather, process, and interpret large volumes of data in real-time can significantly influence the success and safety of an operation. Traditional tactical support systems rely heavily on manual observation, radio communication, and centralized monitoring systems. While these approaches have served operational needs for decades, they suffer from critical limitations such as delayed information flow, restricted field visibility, and increased cognitive load on personnel. As operations become more dynamic, there is a growing need for advanced technological solutions. Recent advancements in Extended Reality (XR), Edge Artificial Intelligence (Edge-AI), and Distributed Sensor Networks (DSN) offer powerful tools to transform tactical operations. XR encompasses VR, AR, and Mixed Reality (MR), enabling the seamless integration of digital information with the physical environment. Through wearable XR devices, operators can visualize real-time data overlays, navigation guidance, and threat alerts directly within their field of view, improving operational safety without diverting attention from their surroundings.

B. Role of Edge-AI and DSN

Edge-AI further enhances system capabilities by enabling real-time data processing at the source of data generation, rather than relying solely on centralized cloud servers. In high risk operations where communication networks may be unreliable, delayed, or compromised, Edge-AI performs intelligent data analysis directly on local microcontrollers and smart sensors. These algorithms detect threats, recognize objects, and identify anomalies in real time, minimizing latency and ensuring faster response times. Coupled with a Distributed Sensor Network consisting of motion detectors, vibration sensors, cameras, and emergency overrides, the system provides comprehensive environmental monitoring from multiple perspectives. The integration of XR technology with Edge-AI and DSN forms a powerful, resilient framework for intelligent tactical support, granting unprecedented situational awareness to field operators.

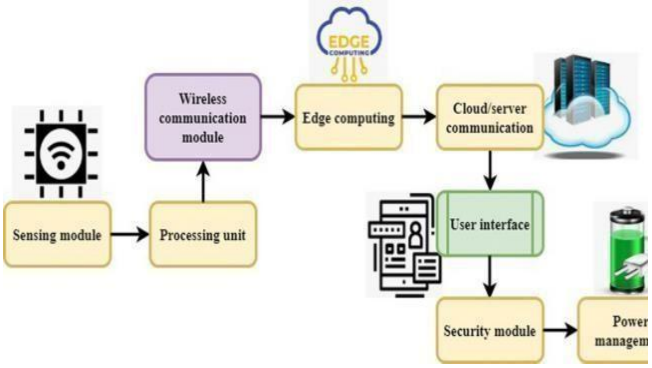
II. LITERATURE SURVEY

The evolution of tactical support systems and immersive technologies has been extensively researched. This section reviews ten foundational studies that informed the design of the proposed architecture.

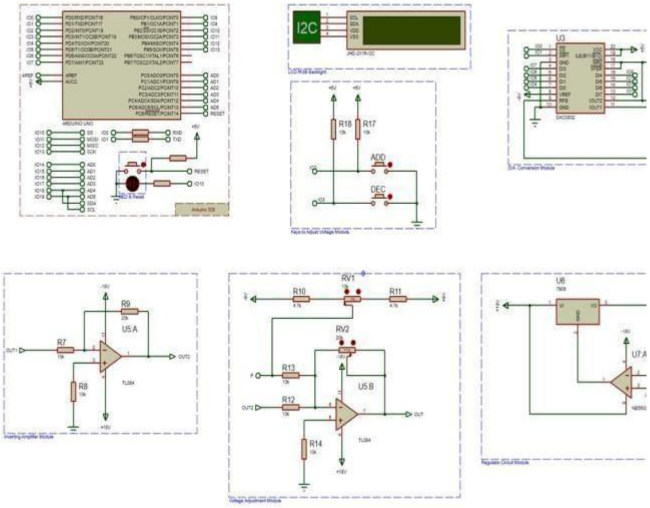
- **Mallik et al. (2024)** proposed a performance analysis modeling framework for Extended Reality applications in edge-assisted wireless networks. Their research high lighted how edge computing reduces delays and im proves responsiveness in immersive environments, which is highly relevant to our sub-100ms latency goal.
- **Łysakowski et al. (2023)** demonstrated real-time onboard object detection for AR using YOLOv8. Their system performed real-time object recognition directly on head mounted displays without cloud reliance, proving the viability of our proposed on-device vision processing approach.
- **Xu, Nagothu, & Chen (2024)** introduced an autonomous and resilient edge computing architecture for smart cities. This architecture demonstrated how edge-based processing improves reliability and security in distributed environments.
- **Walsh et al. (2024)** explored cyber-physical sensing to extend the National Intelligence, Surveillance, and Re connaissance mesh, emphasizing the need for advanced distributed networks in modern tactical systems.
- **Ojha & Gupta (2025)** surveyed the evolving landscape of wireless sensor networks integrated with AI, focusing on data processing and energy efficiency—critical factors for our battery-powered XR nodes.
- **Singh & Bajpai (2025)** proposed an AI-assisted multi sensor fusion architecture for situational awareness, com

bining visual, acoustic, and thermal data to detect drones and human activity accurately.

- **Chaccouet al. (2023)** developed a framework integrating sensing, communication, and AI specifically for XR systems, enabling reliable data collection and real-time immersive interactions.
- **Mallik et al. (2024)** investigated an edge-cloud coordination platform for multi-user AR applications, showcasing collaborative XR systems in distributed environments.



- **Ray (2025)** introduced Edge Agent X-DT, which integrates digital twins and generative AI for resilient edge intelligence in complex tactical networks.
- **Liet al. (2026)** presented an edge vision network-enabled AR monitoring framework for structural systems, pro viding real-time visualization of structural conditions—a concept mirrored in our use of vibration



sensors for structural integrity awareness.

III. IDENTIFICATION OF PROBLEM AND EXISTING SYSTEM

A. Disadvantages of the Existing System

Most current defense field systems rely on basic AR/VR displays that show preloaded maps or static mission data. They suffer from several critical drawbacks:

1) Cloud Dependency Causes Delay: Centralized processing introduces latency, making real-time emergency responses sluggish.

2) No Real-Time AI Threat Detection: Soldiers inside hostile structures receive no automated identification support. Images of suspects are not processed through on-ground AI models.

3) Poor Sensor Data Fusion: Environments are captured through simple cameras without smart verification, meaning no alert generation.

4) One-Way Communication: Communication between field operators and base stations often uses one-way updates, lacking continuous, synchronized intelligence exchange.

5) High Power Consumption and Manual Decision Making: Existing solutions lack integrated situational analysis, leaving soldiers dependent on manual observation.

Fig. 1. Block Diagram of the Existing System Architecture.

Fig. 2. Circuit Diagram of the Existing System.

As shown in Figures 1 and 2, the dependency on cloud infrastructure makes the system highly vulnerable to network dropouts—a fatal flaw in tactical defense scenarios.

IV. PROPOSED SYSTEM AND METHODOLOGY

To overcome the limitations of traditional centralized surveillance, the proposed system introduces a next-generation XR-based tactical platform prioritizing local, real-time response.

- **Objectives Latency Reduction: Achieve sub-100ms response times for threat detection using Edge-AI.**

- **Enhanced Situational Awareness:** Use XR to overlay complex sensor data and AI-detected threats directly onto the operator's field of vision.

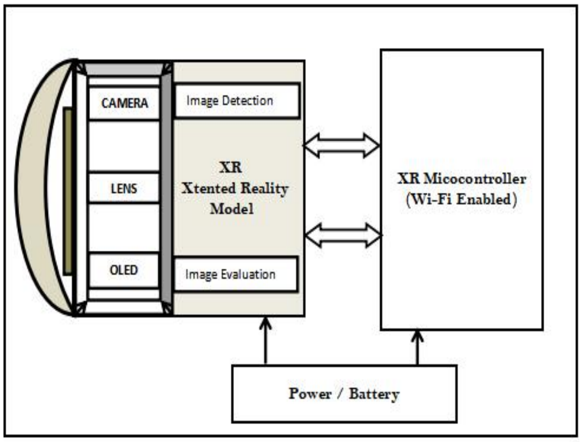
- **Operational Resilience:** Utilize a distributed sensor net work that maintains functionality even offline.

- **Data Sovereignty & Privacy**: Process sensitive tactical data locally to prevent exposure over public networks. B. System Architecture The system consists of two major sections: the Extended Reality Model Node (Field Unit) and the Base Station Node (Monitoring and Alert Unit). Both units communicate via a secure, Wi-Fi-enabled transceiver link.

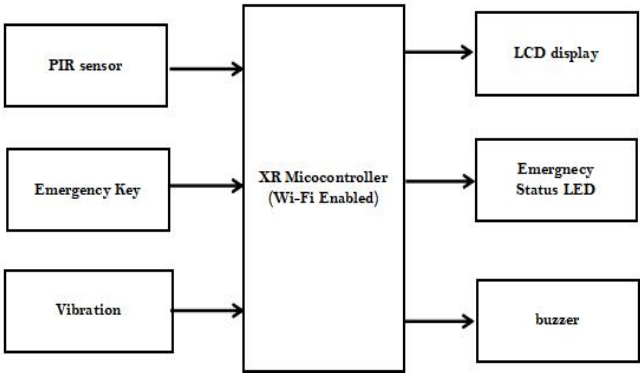
Fig. 3. Block Diagram of the Proposed XR-Based Tactical Support System.

BLOCK DIAGRAM:

Extended Rreality Model Node:



Base Station Node:

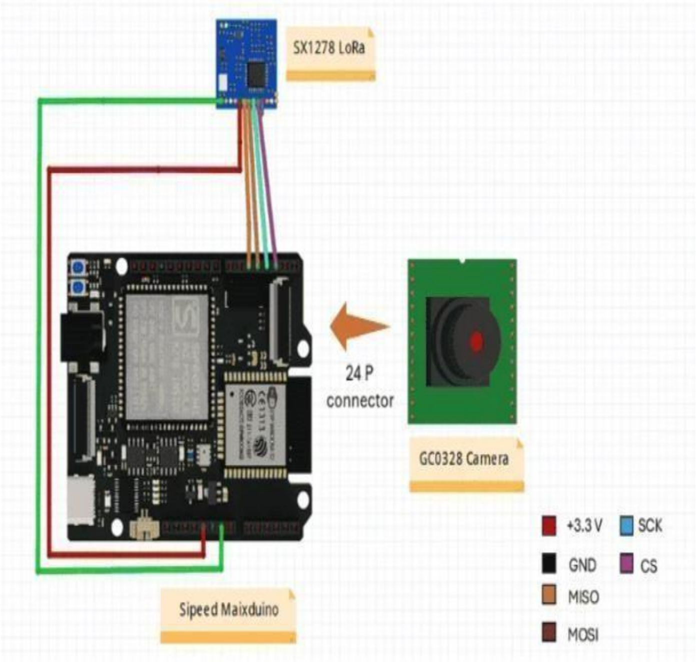


1) **Extended Reality (XR) Model Node (Field Unit):**

This is the primary wearable unit. The camera, equipped with a wide-angle lens, continuously captures real-time video. Edge AI algorithms process this visual data locally to identify suspicious objects or known terrorists via facial recognition. The processed information is rendered on an OLED micro display, acting as the XR interface. An ESP32/ESP8266 microcontroller manages this node, pushing critical alerts back to the base station.

2) **Base Station Node (Monitoring Unit):**

The centralized monitoring system collects peripheral sensor information. It includes a PIR sensor for motion detection, a vibration sensor (SW-420) to detect structural shocks or explosions, and a manual emergency key. If an anomaly is detected, the base station instantly notifies the XR operator, triggering a high decibel buzzer and emergency LEDs, and updating the LCD display for command center personnel.



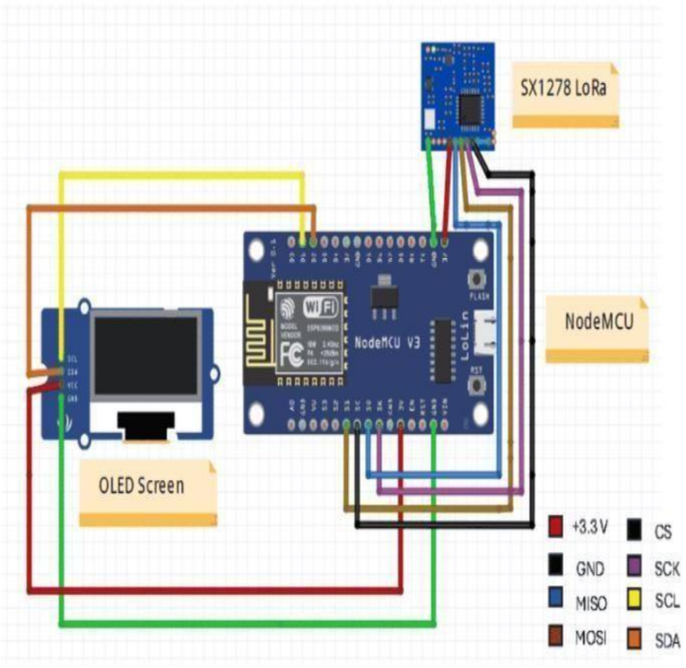


Fig. 4. Circuit Diagram of the Proposed System

V. HARDWARE COMPONENTS AND SPECIFICATIONS

The hardware architecture is designed for low power consumption, high processing power, and robust wireless communication. The detailed bill of materials is outlined below.

TABLE I
DETAILED PRICE LIST AND SPECIFICATIONS OF PROPOSED CIRCUIT COMPONENTS

No.	Component	Specification	Price (INR)
1	ESP32 Microcontroller	32-bit dual-core, 240 MHz, Wi-Fi+BT	600
2	NodeMCU (ESP8266)	32-bit MCU, Wi-Fi enabled	600
3	Camera Module	OV2640, 2-5 MP, up to 30 fps	900
4	Optical XR Lens	Wide-angle, 90-120 degree FOV	600
5	OLED Display Module	0.96 inch, 128x64 pixels, I2C/SPI	500
6	LCD Display Module	16x2 alphanumeric with I2C	450
7	PIR Motion Sensor	HC-SR501, 5-7 m range	250
8	Vibration Sensor	SW-420 Piezo type	250
9	Buzzer	Active buzzer, 80-90 dB	100
10	Power Supply Unit	Rechargeable Li-ion, 3.7V, 3000mAh	1000

A. ESP32 and NodeMCU ESP8266

The ESP32 is a 32-bit dual-core microcontroller running up to 240 MHz, making it highly capable of handling Edge-AI inference tasks alongside network operations. It features built in 802.11 b/g/n Wi-Fi and Bluetooth Classic/BLE. It acts as the brain for the XR node, interfacing via MIPI-CSI (for cameras) and I2C/SPI for displays. The Node MCU ESP8266 handles the Base Station tasks, collecting peripheral sensor data and maintaining the TCP/IP stack for seamless communication.

B. Camera Module and OLED Display

The camera utilizes a CMOS image sensor (like the OV2640) operating at 15-30 fps with a 60-120 degree field of view. The visual interface relies on a 0.96-inch OLED display driven by the SSD1306 IC. This micro-OLED provides high contrast and deep blacks, which is crucial for overlaying digital text (AR) onto transparent visors without obstructing the soldier’s physical view.

C. Peripheral Sensors

The system employs the SW-420 vibration module, which detects abnormal shocks with a response time of < 2 ms. Com bined with HC-SR501 PIR sensors, the base station effectively blankets the operational theater with spatial awareness.

VI. SOFTWARE IMPLEMENTATION AND EMBEDDED SYSTEM DESIGN

An embedded system is a software-driven, real-time control system operating on diverse physical variables. Unlike traditional business applications, embedded code must account for strict throughput, deterministic response times, memory constraints, and high reliability.

A. Embedded system design cycle

The software development follows the ”V-Model” design cycle, beginning with high-level system definition, moving down into rapid prototyping and targeting (loading code onto processors), and climbing back up through hardware-in-the loop testing and final system validation

B. Development Environment

The firmware is developed using Embedded C and compiled using the Arduino IDE. Board Managers were configured specifically for the ESP8266 ecosystem to allow flash coding directly to device.

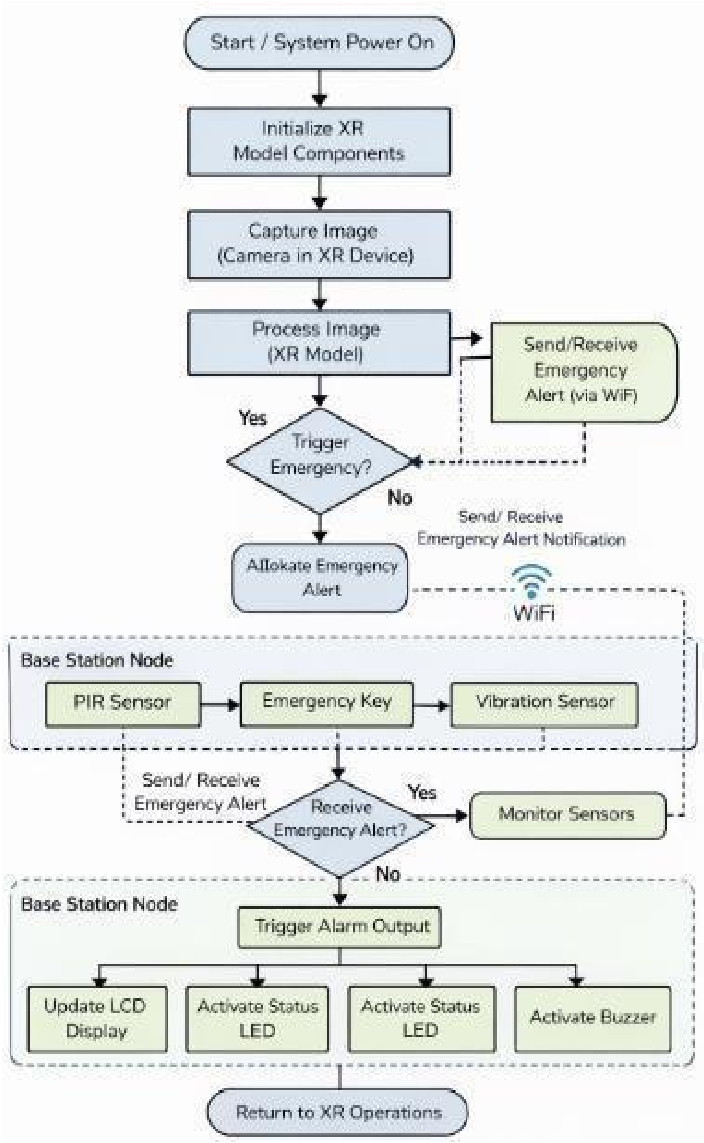


Fig. 5. Operational Flowchart of the Proposed XR Tactical System.

VIII. ADVANTAGES AND APPLICATIONS

A. Advantages

- **Edge-Based Image Processing:** By localizing com put e operations, the system dramatically reduces cloud dependency and response latency.

- **Immersive Visualization:** Real-time XR overlays directly onto OLED displays preserve the operator’s line of sight.

- **Bilateral Synchronization**: Fast wireless communication enables a synchronized intelligence flow between field operatives and command centers.
- **Redundancy**: Combines automated AI surveillance with manual emergency keys and multi-sensor validation(PIR, vibration).
- **Portability**: Features a lightweight, low-power design suitable for wear a bleand mobile acticald employments.

B. Applications

- Defense and military high-risk missions (urban warfare, counter-terrorism).
- Smart wear able safety monitoring for industrial workers in hazardous environments.
- Augmented reality assistance for emergency responders and search – and - rescue teams.
- Advanced smart home and building automation surveilance

IX. CONCLUSION

The proposed Extended Reality (XR)-Based Tactical Support System effectively integrates real-time image processing, Edge-AI, distributed sensor monitoring, and wireless communication to deliver a smart, highly responsive solution. By offloading facial recognition and threat analysis to the edge, the system escapes the latency and reliability pitfalls of traditional cloud-based architectures. The seamless fusion of OLED-driven XR visualization with multi-sensor environmental awareness (motion, vibration) ensures that field operators are continuously protected and informed. Its low-power design, decentralized resilience, and cost-effectiveness make it a cornerstone architecture for modern IoT-based defense, safety, and immersive tactical applications.

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