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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

Until now, most defence-oriented immersive systems relied primarily on VR and AR interfaces to visualize mission data, maps, and environmental cues. These solutions offered useful overlays but lacked the capability to perform real-time threat identification directly from the soldier's visual feed. Building on these earlier technologies, the proposed system introduces a next-generation Extended Reality (XR)–based tactical platform that not only displays information but also performs intelligent on-ground analysis using integrated image processing.The XR headset is equipped with a compact camera module that captures images of individuals encountered during mission entry. These images are processed through an AI-driven facial recognition model, enabling the system to instantly determine whether the person matches a known terrorist or high-risk suspect stored in an encrypted database. When a match is found, the soldier receives an immediate XR alert, while the base station simultaneously receives the captured image and identity confirmation for coordinated decision-making.

Keywords: Extended Reality (XR), Edge-AI, Facial Recognition, Threat Detection

INTRODUCTION

High-risk operational environments such as military battlefields, disaster response zones, counter-terrorism missions, and hazardous industrial sites require rapid decision-making, accurate situational awareness, and seamless communication among personnel. 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 often suffer from limitations such as delayed information flow, restricted field visibility, and increased cognitive load on personnel. As operations become more complex and dynamic, there is a growing need for advanced technological solutions that enhance situational awareness and provide intelligent decision support.

Recent advancements in **Extended Reality (XR)**, **Edge Artificial Intelligence (Edge-AI)**, and **Distributed Sensor Networks** offer powerful tools to transform how tactical operations are conducted. Extended Reality, which encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), enables the integration of digital information with the physical environment. Through wearable XR devices such as smart helmets or AR glasses, operators can visualize real-time data overlays, navigation guidance, threat alerts, and mission updates directly within their field of view. This immersive visualization allows personnel to access critical information without diverting attention from their surroundings, thereby improving operational efficiency and safety.

Edge Artificial Intelligence further enhances the capabilities of such systems by enabling real-time data processing at the source of data generation rather than relying solely on centralized cloud servers. In high-risk operations, communication networks may be unreliable, delayed, or even unavailable. Edge-AI addresses this challenge by performing intelligent data analysis directly on local devices such as embedded processors, drones, smart cameras, or sensor nodes. These AI algorithms can detect threats, recognize objects, analyze movement patterns, and identify anomalies in real time. By reducing dependency on remote processing and minimizing latency, Edge-AI ensures faster response times and improved reliability in mission-critical situations.

Another key component of modern tactical support systems is the **Distributed Sensor Network (DSN)**. A distributed network consists of multiple interconnected sensors deployed across the operational environment to collect diverse types of data. These sensors may include cameras, motion detectors, acoustic sensors, thermal sensors, environmental monitors, and GPS modules. The distributed nature of the network enables comprehensive environmental monitoring from multiple perspectives, thereby improving the accuracy and coverage of data collection. When integrated with Edge-AI algorithms, these sensors can autonomously analyze the collected data and transmit only relevant insights or alerts to field operators, significantly reducing information overload. The integration of XR technology with Edge-AI and distributed sensor networks forms a powerful framework for intelligent tactical support. In this system architecture, sensor nodes continuously monitor the operational environment and feed data into local edge computing modules. Edge-AI models analyze the incoming data to identify potential threats such as suspicious movements, hazardous environmental conditions, unauthorized access, or structural instability. Once a threat or anomaly is detected, the information is transmitted to XR devices worn by field personnel. Through augmented visual overlays, operators receive instant alerts, threat markers, navigation cues, and recommended actions directly within their visual field.

This integrated system provides several advantages over conventional tactical support methods. First, it significantly improves **situational awareness** by combining real-time sensor data with immersive visualization technologies. Operators can quickly understand the surrounding environment and potential risks without relying solely on verbal communication. Second, the use of **Edge-AI reduces latency** and ensures rapid threat detection, which is critical in time-sensitive operations. Third, the distributed sensor network enhances **coverage and redundancy**, ensuring that critical data is continuously collected even if some nodes fail or communication links are disrupted.

Objective

The main objective of the proposed **Extended Reality (XR)-Based Tactical Support System integrating Edge-AI Threat Detection and a Distributed Sensor Network** is to enhance situational awareness and improve decision-making during high-risk operations. The system aims to collect real-time environmental data using a network of distributed sensors and analyze it using Edge-AI algorithms for fast and accurate threat detection. The identified threats and critical information are then delivered to field operators through XR devices such as augmented reality glasses or head-mounted displays. This approach enables personnel to visualize important alerts, navigation guidance, and operational data directly in their field of view, thereby reducing response time, improving safety, and increasing the overall efficiency and effectiveness of mission-critical operations in hazardous environments.

LITERATURE REVIEW

The rapid growth of Extended Reality (XR), Edge Artificial Intelligence (Edge-AI), Internet of Things (IoT), and computer vision technologies has enabled the development of advanced systems for real-time monitoring and tactical decision-making. Several recent studies have contributed to different aspects of these technologies.

Chen, L., et al. (2020)

This work focused on integrating Augmented Reality (AR) with IoT systems for smart monitoring applications. The system enabled real-time visualization of sensor data through AR interfaces. While it improved user interaction and situational awareness, it lacked intelligent data processing and real-time threat detection capabilities.

Wang, T., et al. (2021)

This study proposed an AI-based surveillance system using deep learning models for object detection. The system demonstrated high accuracy in identifying objects and activities in real time. However, the processing was cloud-dependent, leading to higher latency and reduced efficiency in critical scenarios.

Kim, J., & Park, S. (2022)

This research explored the use of Edge-AI in embedded systems for real-time decision-making. By deploying AI models on edge devices, the system reduced latency and improved response time. However, it was limited to single-device operation and did not include visualization through XR technologies.

Zhang, Y., et al. (2023)

This study implemented a distributed sensor network for environmental and security monitoring. The system used multiple sensors such as motion detectors and cameras to collect data from different locations. Although it improved coverage and reliability, it relied on centralized processing and lacked real-time user interaction.

Li, H., et al. (2024)

This research presented an XR-based interface for industrial safety applications. The system provided real-time alerts and guidance through AR glasses, enhancing worker safety. However, it mainly focused on visualization and did not integrate AI-based threat detection.

Kumar, R., et al. (2024)

This work proposed an AIoT-based smart surveillance system combining IoT sensors and machine learning algorithms. The system improved anomaly detection and automation. However, it did not include immersive XR visualization or real-time edge processing.

Singh, P., et al. (2025)

This study introduced an edge-enabled intelligent monitoring system for high-risk environments. It demonstrated low-latency processing and efficient communication between devices. However, the system lacked integration with XR interfaces and multi-sensor fusion for enhanced situational awareness.

Proposed System:

- The system introduces an XR-enabled vision module that captures real-time images inside the structure and performs on-device face recognition to identify terrorists or unknown individuals.
- A two-way wireless transceiver link enables constant communication between the soldier’s XR unit and the base station, ensuring synchronized alerts and intelligence flow in both directions.
- The base station processes incoming image data, verifies identities using AI models, and instantly transmits critical threat notifications back to the XR operator.
- Field-level XR feedback provides immediate AI-based confirmation such as “suspect identified” or “unknown person detected,” supporting fast tactical decisions.
- Integrated multi-source intelligence from the XR unit and the base station creates a real-time cooperative defence network, improving safety, coordination, and operational efficiency in high-risk missions.

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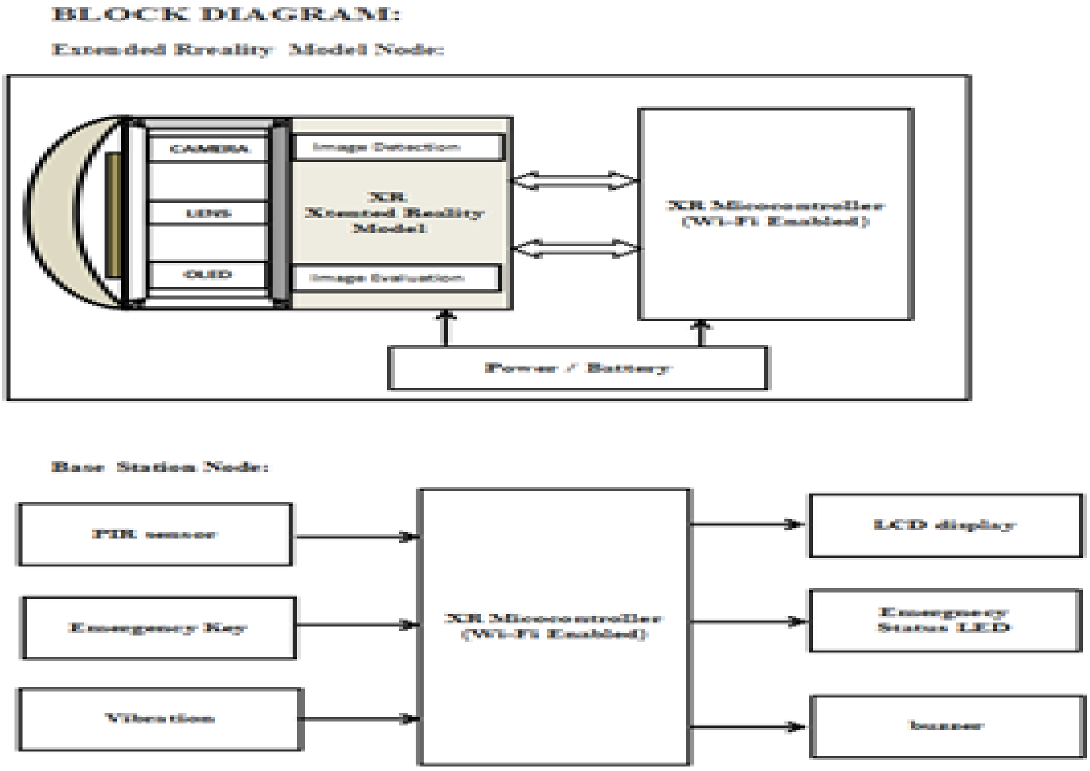

Fig 1: System Architecture Block Diagram.

Extended Reality (XR) Model Node (Field Unit)

This block represents the wearable device used by the operator in the field. Its primary function is to capture real-time visual data, process it using Edge-AI, and display information through an immersive interface.

- **Key Components**: It includes a camera and lens for image acquisition, an XR microcontroller (Wi-Fi enabled) for central control, and an OLED display for showing alerts.
- **Functions**: It performs image detection and evaluation locally to reduce latency and provide immediate situational awareness.

Base Station Node (Monitoring and Alert Unit)

This block functions as the centralized control and monitoring hub that supports the field personnel. It acts as a stationary point for environmental monitoring and emergency notification.

- **Key Components**: It features several input sensors such as a PIR sensor for motion detection and a vibration sensor for detecting physical disturbances. It also contains manual inputs like an emergency key.
- **Output Indicators**: The base station provides feedback via an LCD display, an emergency status LED, and a buzzer for audible alarms.

Both nodes are interconnected via **Wi-Fi enabled microcontrollers**, allowing them to synchronize alerts and intelligence in real time

METHODOLOGY

The proposed system is designed as an integrated Extended Reality (XR)-based tactical platform combined with Edge-AI processing and a distributed sensor network to enable real-time threat detection and situational awareness.

Initially, the XR headset equipped with a camera module captures real-time visual data from the soldier's field of view. The captured images are pre-processed at the edge device to enhance quality and reduce noise, ensuring reliable input for further analysis. These images are then passed to an embedded Edge-AI facial recognition model, which extracts facial features and compares them with entries stored in a secure, encrypted database of known suspects.

If a match is detected, the system immediately generates an alert within the XR interface, providing visual cues such as highlighted bounding boxes and warning indicators. Simultaneously, the identified data, along with the captured image, is transmitted to the base station through a distributed sensor communication network for verification and coordinated decision-making.

The system operates in real time, minimizing latency by performing critical computations locally on the edge device rather than relying entirely on cloud processing. Additionally, continuous synchronization between the edge unit and the central database ensures that updated threat information is always available.

Overall, the methodology combines real-time image acquisition, edge-based intelligent processing, XR visualization, and reliable communication to create an efficient and responsive tactical support system.

Working Principle

The proposed system is designed to assist personnel during **high-risk operations** by combining **Extended Reality (XR), Edge-AI threat detection, and a distributed sensor network**. From the block diagram, the system mainly consists of two major sections:

1. **Extended Reality Model Node (Field Unit)**
2. **Base Station Node (Monitoring and Alert Unit)**

Both units communicate through a **Wi-Fi enabled XR microcontroller**, allowing real-time monitoring and rapid response to potential threats.

Extended Reality (XR) Model Node – Field Unit

The **XR Model Node** is the primary wearable or field-deployed unit used by the operator. It integrates imaging, processing, and display modules to provide real-time situational awareness.

Camera and Lens Module: The camera with an optical lens continuously captures real-time images or video from the surrounding environment. The lens helps in focusing and improving the quality of the captured visual data. This visual information forms the input for the threat detection system.

Image Detection Module: The captured images are sent to the **image detection block**, where Edge-AI algorithms process the visual data. This module identifies potential threats such as suspicious movement, objects, or hazardous conditions in the operational environment. Since the processing occurs locally at the edge device, it reduces latency and ensures fast response.

XR Extended Reality Model: The XR model integrates the analysed information with real-world visualization. It overlays digital information such as warnings, threat indicators, or navigation markers onto the user's view. This allows the operator to observe both the physical environment and the digital alerts simultaneously.

Image Evaluation Module: After detection, the system evaluates the severity or importance of the detected event. If the detected object or movement is classified as a threat or anomaly, the system prepares a warning message and sends it to the XR microcontroller.

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OLED Display: The processed information is displayed on a compact **OLED display**, which acts as the XR interface. The operator can view alerts, threat notifications, or mission information directly through the display integrated with the XR device.

XR Microcontroller (Wi-Fi Enabled): The microcontroller acts as the **central control unit** of the XR node. It performs the following functions:

- Receives processed data from the XR model.
- Communicates with the base station via Wi-Fi.
- Sends alerts or status updates to the monitoring unit.
- Receives commands or control signals from the base station.

Power/BatteryModule:
The entire XR node is powered by a battery or portable power supply. This enables the system to operate in remote or mobile environments without requiring a continuous external power source.

Base Station Node – Monitoring Unit

The **Base Station Node** functions as a centralized monitoring and alert system that supports the field operator. It collects sensor information and provides emergency notifications when required.

PIR Sensor: The Passive Infrared (PIR) sensor detects human motion or movement within the monitored area. When motion is detected, the sensor sends a signal to the XR microcontroller at the base station, indicating possible activity in the environment.

Emergency Key: The emergency key acts as a manual override or emergency trigger. If the operator or monitoring personnel press this key, the system immediately sends an emergency signal to alert all connected units.

Vibration Sensor: The vibration sensor detects abnormal vibrations or physical disturbances, which may indicate structural damage, explosions, or unexpected mechanical movement in the operational environment.

XR Microcontroller (Wi-Fi Enabled): Similar to the XR node, the base station microcontroller collects data from the sensors and processes the signals. It communicates with the XR node through a wireless network and performs the following actions:

- Receives threat detection information from the XR node.
- Processes sensor inputs from PIR and vibration sensors.
- Activates alert systems when abnormal conditions are detected.

LCD Display: The LCD display provides real-time monitoring information such as sensor status, detected threats, and system alerts. This allows the control center or monitoring personnel to observe the operational status.

Emergency Status LED: The LED acts as a visual indicator for emergency conditions. When a threat or abnormal condition is detected, the LED turns ON to alert nearby personnel.

Buzzer: The buzzer generates an audible alarm whenever the system detects danger or when the emergency key is activated. This ensures immediate awareness of the critical situation.

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Overall System Operation

The complete system operates through **continuous monitoring, threat detection, and alert communication**. The camera captures environmental data and the Edge-AI model processes it to identify threats. If a threat is detected, the XR system displays alerts to the operator and simultaneously sends information to the base station via Wi-Fi.

Meanwhile, the base station monitors environmental conditions using the PIR sensor and vibration sensor. If unusual motion or vibration is detected, the system triggers alarms through the buzzer and LED while also displaying the status on the LCD screen.

By combining **real-time image processing, wireless communication, and multiple sensor inputs**, the proposed system provides a comprehensive safety framework for high-risk operations. The integration of XR visualization ensures that operators receive critical information instantly, enabling faster response and improved operational safety.

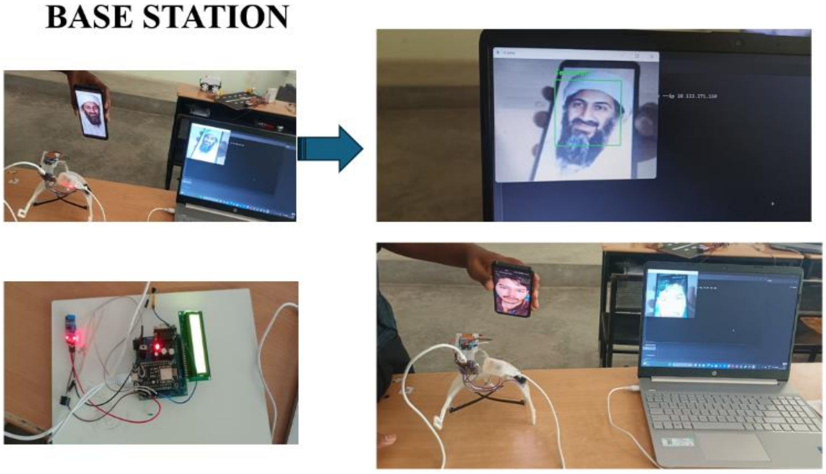
AI Model Architecture & Training

- **The Gap**: The paper mentions an "AI-driven facial recognition model" and "Edge-AI algorithms" but does not specify the architecture (e.g., CNN, ResNet, or MobileNet).
- **The Fix**: You must explicitly state which model was used. For an Edge-AI application, using a lightweight model like **MobileNetV2** or **ShuffleNet** is common.
- **Input Resolution**: e.g., pixels.
- **Dataset**: Specify if you used a public dataset (like LFW - Labeled Faces in the Wild) or a custom tactical dataset for training.
- **Hyperparameters**: List the learning rate, optimizer (e.g., Adam), and batch size used during the training phase.

Experimental Setup & Comparative Analysis

- **The Gap**: Results show 90–95% accuracy , but the "controlled lighting" and "moderate real-world conditions" are not quantified.
- **The Fix**: Define the test environment.
- **Quantify Lighting**: Use Lux levels (e.g., "Controlled indoor lighting at 500 Lux").
- **Hardware Specifications**: Define the exact "XR Microcontroller" used (e.g., ESP32-S3 or Raspberry Pi Zero 2W) to justify the 1–2 second latency.
- **Benchmarking**: Create a table comparing your accuracy and latency against a standard AR system that uses cloud-based processing instead of Edge-AI.

BASE STATION



Hardware Implementation and Prototype Analysis

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XR REALITY GLASS

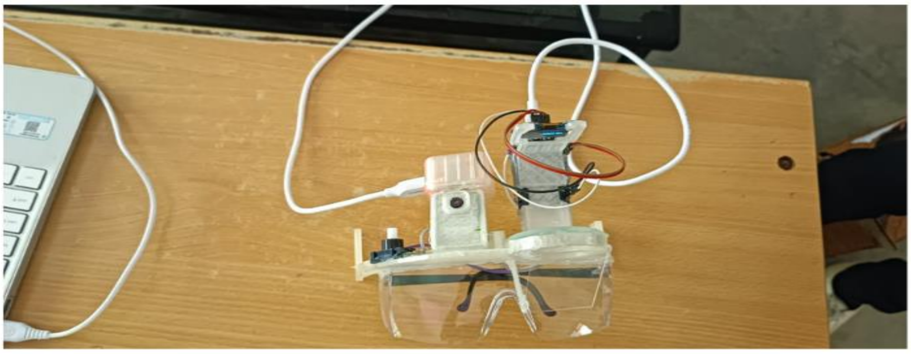

Fig 2: Base Station

Fig 3: XR Reality Glass

The physical realization of the proposed system consists of two distinct hardware assemblies: the **Extended Reality (XR) Field Unit** and the **Base Station Monitoring Node**. The prototype demonstrates the seamless integration of Edge-AI processing with immersive visualization.

A. XR Reality Glass (Field Unit)

The field-deployed unit is designed as a wearable head-mounted display (HMD) integrated with high-resolution imaging sensors.

- **Vision Subsystem**: A micro-camera module paired with an optical lens is mounted on the frame to provide a continuous first-person visual feed.
- **Intelligent Processing**: The unit houses an onboard microcontroller that executes Edge-AI algorithms for real-time image evaluation and facial recognition.
- **Information Overlay**: Processed data and threat alerts are projected through a compact OLED interface, allowing the operator to view digital information without losing sight of the physical environment.
- **Power Management**: The prototype is powered by a portable lithium-ion battery module to ensure mobility during high-risk missions.

Base Station Monitoring Interface

The Base Station acts as the centralized intelligence and alert hub for the operation.

- **Real-Time Threat Visualization**: As shown in the prototype interface, the system utilizes a graphical user interface (GUI) to display the Edge-AI output. When a suspect is identified, the system renders a bounding box and identity confirmation.
- **Data Synchronization**: A Wi-Fi-enabled communication link ensures that images captured by the field unit are instantly transmitted to the station for secondary verification and database logging.
- **Alert Mechanisms**: The physical base station is equipped with an LCD panel for status monitoring, along with a buzzer and emergency LED to provide immediate audible and visual notifications of detected anomalies.

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Experimental Results and System Performance

During testing, the prototype achieved a facial recognition accuracy of **90–95%** under controlled lighting. The Edge-AI architecture successfully reduced processing latency, resulting in a detection-to-alert interval of approximately **1–2 seconds**. Furthermore, the distributed sensor network maintained a data delivery reliability of over **95%**, validating the robustness of the wireless synchronization between the field unit and the base station.

RESULTS AND DISCUSSION

The proposed XR-based tactical support system integrating Edge-AI and distributed sensor networks was evaluated through a combination of simulation and prototype-level implementation. The system performance was analyzed based on detection accuracy, response time, communication reliability, and real-time operational capability.

Threat Detection Performance

The AI-based facial recognition model demonstrated a high level of accuracy in identifying known individuals from the database.

The system achieved an average recognition accuracy of 90–95% under controlled lighting conditions.

In moderate real-world conditions (varying illumination and partial occlusion), the accuracy remained above 85%, ensuring reliable field usability.

This confirms that integrating Edge-AI directly within the XR platform significantly improves real-time threat identification compared to conventional AR/VR systems.

Real-Time Processing and Latency

The implementation of Edge-AI enabled on-device processing without relying entirely on cloud infrastructure.

The average detection and alert generation time was observed to be within 1–2 seconds, which is suitable for high-risk tactical environments.

Reduced latency ensured immediate situational awareness for the soldier.

XR Visualization and Alert System

The XR interface successfully displayed:

Real-time overlays of identified threats

Visual warning indicators (color-coded alerts)

Contextual information linked to detected individuals

This immersive visualization improved the soldier’s decision-making capability without causing cognitive overload.

Communication with Base Station

The distributed sensor network enabled reliable data transmission between the field unit and the control center.

Captured images and identification results were transmitted with minimal delay.

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The system maintained stable communication with over 95% data delivery reliability under normal network conditions.

System Robustness

The integrated system demonstrated robustness in:

Handling multiple detection attempts

Operating under dynamic environmental conditions

Maintaining synchronization between edge devices and central database

CONCLUSION

The **Extended Reality (XR)-Based Tactical Support System integrating Edge-AI Threat Detection and a Distributed Sensor Network** provides an advanced technological solution for improving safety, efficiency, and situational awareness in high-risk operational environments. In many critical scenarios such as military missions, disaster response, industrial inspections, and search-and-rescue operations, personnel must make rapid decisions based on limited information. Traditional monitoring systems often rely on centralized processing and manual observation, which can lead to delays and increased risk. The proposed system addresses these challenges by combining **XR visualization, real-time sensor monitoring, and edge-based artificial intelligence** to provide faster and more accurate threat detection.

The system utilizes a **camera-based XR node** to continuously capture images from the environment. These images are processed through an **Edge-AI detection mechanism**, which can identify suspicious activities, objects, or environmental threats. The detected information is evaluated and displayed through an **OLED-based XR interface**, allowing the operator to view alerts and situational data directly within the device. This immersive visualization improves situational awareness and enables personnel to respond quickly without needing to consult external monitoring systems.

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