ORIGINAL ARTICLE
Electrica 2026; 26: 1-22

Internet of Things–Enabled Sensing and Unmanned Aerial Vehicle Applications for Earthquake Preparedness and Real-Time Response

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Cite this article as: S. Bentaalla-Kaced, N. E. H. Benharkat and D. Yiltas-Kaplan, "Internet of Things–enabled sensing and unmanned aerial vehicle applications for earthquake preparedness and real-time response," *Electrica*, 26, 0029, 2026. doi: 10.5152/electrica.2026.26029.

WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Previous review studies have independently examined UAV applications in disaster management, IoT-based sensing frameworks for seismic monitoring, and other emerging technologies.*
- *IoT-based systems are predominantly utilized for real-time seismic monitoring, early warning dissemination, and structural health monitoring.*
- *UAVs are extensively employed for rapid post-earthquake damage assessment, search and rescue operations, and temporary communication restoration.*
- *Traditional disaster management methodologies are increasingly recognized as insufficient due to their limited capacity to aggregate and process large-scale, heterogeneous data in real time.*

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Received: February 1, 2026
Revision Requested: April 19, 2026
Last Revision Received: April 29, 2026
Accepted: May 4, 2026
Publication Date: September 1, 2026

DOI: 10.5152/electrica.2026.26029

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ABSTRACT

This paper presents a systematic and bibliometric review investigating the role of emerging technologies, specifically the Internet of Things (IoT) and unmanned aerial vehicles (UAVs), in earthquake disaster management. Following the PRISMA 2020 framework, a structured search was conducted in the Scopus database covering publications up to 2025. The retrieved studies were screened and analyzed through quantitative bibliometric techniques to identify research trends, collaboration networks, and keyword co-occurrence patterns. Complementary qualitative content analysis was applied to classify the contributions of IoT and UAV technologies across the three main phases of disaster management: preparedness, response, and recovery. The findings indicate that IoT-based systems are predominantly utilized for real-time seismic monitoring, early warning dissemination, and data communication, while UAVs are extensively employed for rapid damage assessment, communication restoration, and logistics support in post-earthquake scenarios. The integrated use of IoT and UAVs strengthens situational awareness, enhances coordination efficiency, and promotes data-driven decision-making. The study concludes by highlighting research gaps in interoperability, data fusion, and energy efficiency, providing future directions for developing adaptive and collaborative frameworks for earthquake resilience.

Index Terms— Disaster response, earthquake, IoT, real-time monitoring, UAV

I. INTRODUCTION

Disasters are catastrophic occurrences that can arise from both natural and anthropogenic sources. Irrespective of their source, disasters often result in considerable fatalities, economic detriment, and enduring societal consequences. Earthquakes certainly rank among the most violent natural disasters in the world. They can bring extensive destruction, loss of human lives, and immense financial loss. They pose an immense threat to human lives, financial stability, and resilience in infrastructure [1]. Disaster management focuses primarily on minimizing the impact and consequences of such events rather than eliminating the hazards themselves. It encompasses a comprehensive set of activities, including preparedness, mitigation, response, and recovery, aimed at reducing vulnerability before a disaster occurs and enabling effective action during and after the event [2]. In this context, the rapid evolution of wireless communication technologies and the integration of the Internet of Things (IoT) and unmanned aerial vehicles (UAVs), commonly referred to as drones, have introduced transformative capabilities for modern disaster management systems. Disaster-related activities are commonly structured into three temporal phases: pre-disaster, during-disaster (also referred to as intra-disaster) [3], and post-disaster [4]. The pre-disaster phase emphasizes prevention, risk mitigation, and early warning; the during-disaster phase focuses on real-time monitoring, situational awareness, and emergency response; and the post-disaster phase involves damage assessment, recovery, and reconstruction. Certain operations, such as search and rescue missions, span multiple phases, occurring during both the response and recovery stages. Collectively, these phases form the disaster management cycle, as illustrated in Fig. 1 [5].

WHAT DOES THIS STUDY ADD TO THIS TOPIC?

- *It proposes an integrated analytical framework that connects IoT sensing infrastructures, UAV platforms, wireless communication architectures, and AI-enabled tools across the full earthquake disaster-management lifecycle, rather than treating them as isolated domains.*
- *It introduces a phase-oriented taxonomy that systematically maps technological capabilities to specific operational requirements across the pre-disaster, during-disaster, and post-disaster phases.*
- *It identifies critical, previously under-addressed interoperability challenges (across protocol, platform, sensing, and decision-support layers), data fusion issues, and energy efficiency gaps at the IoT–UAV interface.*
- *It provides a structured three-stage R&D roadmap (Foundational Interoperability, Integrated Response Systems, and Autonomous Decision Support) to guide the future design of resilient, adaptive, and phase-persistent earthquake management ecosystems.*

Internet of Things technologies play a pivotal role throughout this cycle by enabling real-time sensing, data acquisition, and information sharing through interconnected networks of sensors, actuators, and communication devices [6, 7]. In earthquake management, IoT-based systems support early seismic detection, structural health monitoring, victim localization in collapsed environments, and coordinated emergency response, thereby enhancing both preparedness and resilience [8]. Complementing these capabilities, UAVs function as agile and mobile sensing platforms capable of rapidly collecting high-resolution data over wide and often inaccessible or hazardous areas. Their deployment is particularly valuable in post-earthquake scenarios, where ground infrastructure may be damaged or inaccessible.

While several review studies have examined UAV applications in disaster management [9-11], IoT-based sensing frameworks for seismic monitoring [12-13], or emerging disaster-management technologies independently [14], this paper proposes an integrated analytical framework that connects sensing infrastructures, aerial platforms, wireless communication architectures, and AI-enabled decision-support tools across the full earthquake disaster-management lifecycle, rather than addressing these technologies as independent or loosely connected domains. Also, it proposes a phase-oriented taxonomy that systematically maps technological capabilities to operational requirements at each stage of the disaster-management lifecycle, thereby supporting the identification and selection of context-appropriate sensing, monitoring, and communication solutions. Furthermore, through the combined application of bibliometric and technical analyses, the study not only synthesizes current research developments but also identifies critical interoperability challenges at the IoT–UAV interface that remain insufficiently addressed in prior literature [11]. It identifies research trends, dominant application areas, and critical technological limitations. The resulting synthesis provides a concise reference framework to guide the design and deployment of resilient, scalable, and efficient IoT–UAV-based disaster management solutions.

The remainder of this paper is organized as follows: Section II details the research methodology, outlining the systematic and bibliometric approaches adopted to identify, classify, and analyze relevant studies. Section III presents the bibliometric results, highlighting publication trends, emerging themes within the domain of IoT- and UAV-based earthquake management. Section IV examines wireless communication technologies and their integration with IoT frameworks for real-time seismic monitoring, early warning, and post-earthquake recovery. Section V discusses UAV applications in earthquake management, classifying UAVs by airframe, range, payload capacity, and propulsion systems, while emphasizing their operational relevance during and after disaster events.

Section VI. Critical Research Gaps and Technical Challenges. Finally, Section VII concludes the paper with a synthesis of findings, highlighting the benefits, limitations, and future research

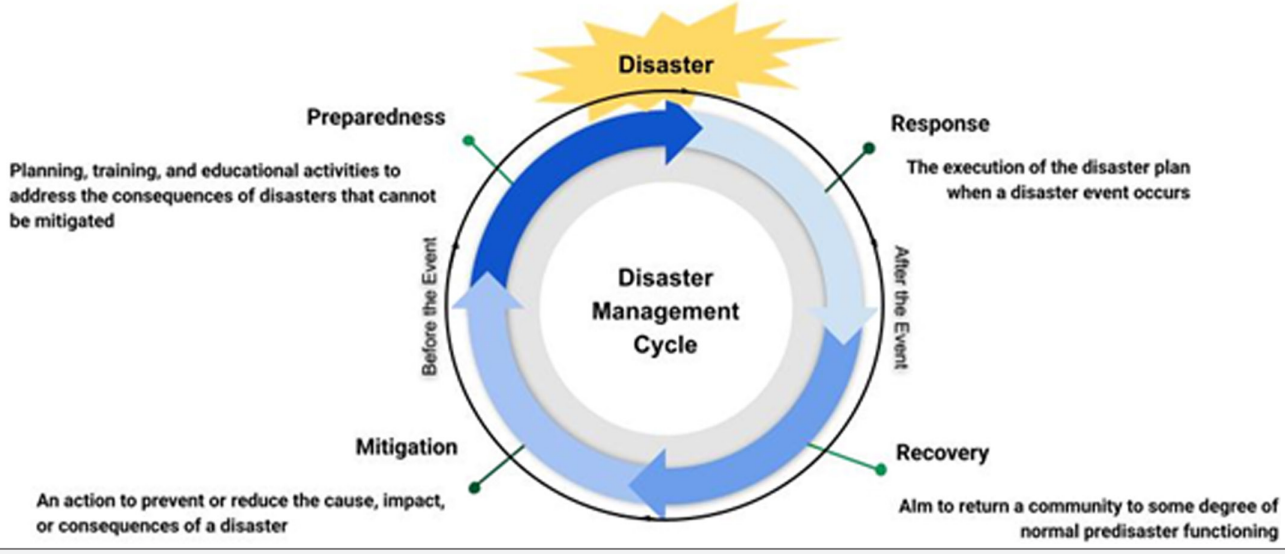

Fig. 1. The four phases of the disaster management cycle.

directions necessary for advancing IoT–UAV integration in next-generation earthquake disaster management systems

II. METHODOLOGY

This study presents a bibliometric and systematic review of emerging technologies applied to earthquake disaster management, with particular emphasis on IoT-enabled sensing and UAV-based applications. The review was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure methodological rigor, transparency, and reproducibility. A comprehensive search was conducted using the Scopus database, which was selected for its extensive coverage of peer-reviewed journals, conference proceedings, and technical literature in the fields of engineering and disaster management. The search was limited to English-language publications and included all available records up to 2025. The search string combined keywords related to disaster type, technology, and application context, using Boolean operators as follows:

TITLE-ABS-KEY ((“earthquake” OR “seismic” OR “aftershock” OR “tremor”) AND (“UAV” OR “drone” OR “unmanned aerial vehicle” OR “IoT” OR “Internet of Things” OR “sensor network*” OR “wireless sensor*”) AND (“monitoring” OR “early warning” OR “damage assessment” OR “structural health monitoring” OR “disaster response” OR “post-earthquake”)).

This strategy yielded a total of 522 journal articles. The selection of studies followed a structured manual screening process carried out by the reviewers. Duplicate records were first identified and removed by comparing titles, authors, and Digital Object Identifiers, resulting in 505 unique publications. The reviewers then examined the titles and abstracts to assess the relevance of each study to the objectives of this review. Studies were retained if they focused explicitly on earthquake or seismic hazards, reported the use of UAVs, IoT systems, or sensor networks, and addressed at least one phase of disaster management, including prevention, early warning, response, or recovery. This stage resulted in the identification of 230 potentially relevant studies. The full texts of these studies were subsequently reviewed to confirm eligibility. To be included, a study was required to present a clearly defined technological framework involving UAVs, IoT systems, or their integration; demonstrate application to a real-world or simulated earthquake scenario; and provide empirical or technical validation through experiments, case studies, or simulations. Following this detailed assessment, a total of 53 met all inclusion criteria. Any discrepancies between reviewers during the screening process were resolved through discussion and consensus. A thematic synthesis was then performed on the final corpus of included studies to identify research patterns and technological orientations. Each study was classified according to its core technology, distinguishing between UAV-based, IoT-based, and integrated UAV–IoT systems, and by its relevance to different phases of disaster management, namely pre-event preparedness and early warning, real-time monitoring during the event, and post-event damage assessment and recovery. In parallel with the systematic review, a bibliometric analysis was conducted using R software and Biblioshiny to map the intellectual and structural evolution of the research field. The analysis explored temporal publication trends and examined co-citation and keyword co-occurrence relationships. This combined systematic and bibliometric approach provided both a quantitative understanding of research evolution and a qualitative perspective on the application of UAV and IoT technologies in earthquake disaster management. The complete selection workflow is summarized in Fig. 2.

Although Scopus provides extensive coverage of engineering and disaster management literature, the exclusive reliance on this single database with English-language filtering constitutes a limitation. This approach may underrepresent regional disaster-response approaches from non-English-speaking countries and specialized

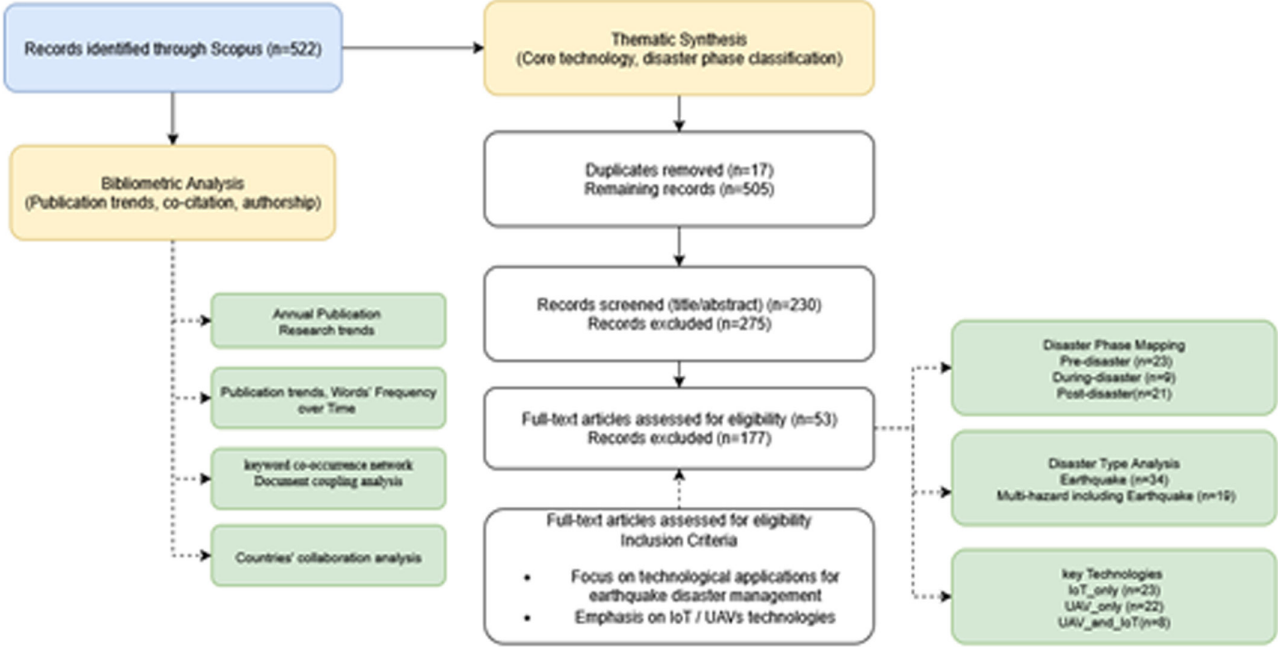

Fig. 2. Research methodology.

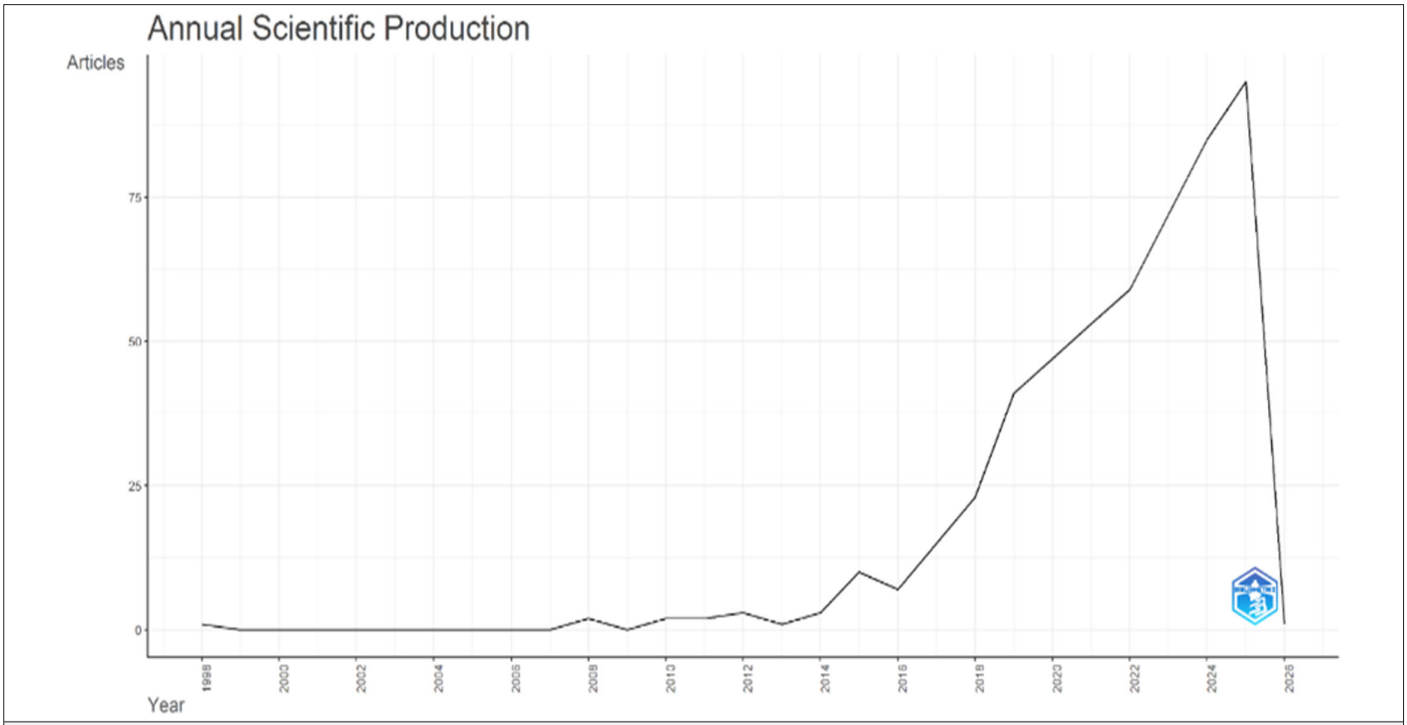

Fig. 3. Annual publication.

engineering venues. This limitation may have resulted in the exclusion of regionally adapted communication restoration techniques, potentially affecting the representativeness of the final set of 53 studies, particularly in the domain of post-disaster communication systems, where regional implementations often adapt global technologies to local infrastructure constraints. Future research should incorporate multiple databases and non-English publications to capture the full spectrum of technological implementations, particularly for communication restoration techniques where regional adaptations of global technologies are common.

III. BIBLIOMETRIC ANALYSIS

A. Publication Trends and Research Growth

The bibliometric analysis of scientific output reveals a clear, accelerating trajectory in research on UAVs and IoT for earthquake disaster management. As illustrated in Fig. 3, the annual publication volume remained minimal from 1998 through 2010, with fewer than five articles per year. A notable inflection point occurred around 2014–2015, marking the beginning of sustained growth. From 2016 onward, publication counts increased exponentially, culminating in over 80 articles in 2024, the highest recorded output to date.

This surge reflects growing global recognition of the critical role that emerging technologies play in enhancing resilience against seismic events. The sharp rise post-2018 coincides with several major earthquakes (e.g., 2018 Sulawesi, 2019 Albania, 2020 Turkiye, 2023 Turkiye–Syria) that catalyzed urgent innovation in rapid damage assessment, real-time monitoring, and automated response systems using UAVs and sensor networks. The spike in 2024 also suggests strong momentum entering the current decade, with academic and industrial interest converging around scalable, data-driven solutions for pre-event preparedness and post-event recovery.

The "Most Relevant Words" analysis (Fig. 4) highlights disaster management, disaster prevention, and disasters as dominant themes, confirming a strong emphasis on both response and preparedness. Technological keywords such as UAVs and IoT emerge as core enablers, while deep learning and remote sensing indicate increasing adoption of AI-driven and data-intensive approaches. The frequent occurrence of antennas underscores the critical role of communication infrastructure in UAV- and IoT-based disaster systems. Overall, the results emphasize the convergence of UAVs, IoT, and AI as central pillars of contemporary disaster management research.

The "Trend Topics" analysis from Bibliometrix (2012–2024) illustrates the temporal evolution of research themes in the field (Fig. 5). The results show that real-time, disaster response, and disaster scenario have become dominant and recent focal points, reflecting the shift toward operational readiness and immediate action. Technological keywords such as UAVs, deep learning, and decision-making display steep growth after 2018, emphasizing the integration of AI-based models and intelligent systems for rapid assessment and decision support. Core concepts like disaster management, disaster prevention, and IoT remain consistently relevant, confirming their foundational role in sensor-based and early warning frameworks. Established tools such as remote sensing, computer vision, and image processing continue to underpin UAV applications, while emerging topics like robotics and autonomous vehicles suggest future research directions. Overall, the trend analysis indicates a clear transition toward real-time, AI-enhanced, and data-driven disaster management systems, positioning UAVs and IoT as the primary enablers of next-generation resilience strategies.

B. Global Research Connectivity and Thematic Linkages

The keyword co-occurrence network (Fig. 6) provides a structural overview of the thematic relationships within literature. The network

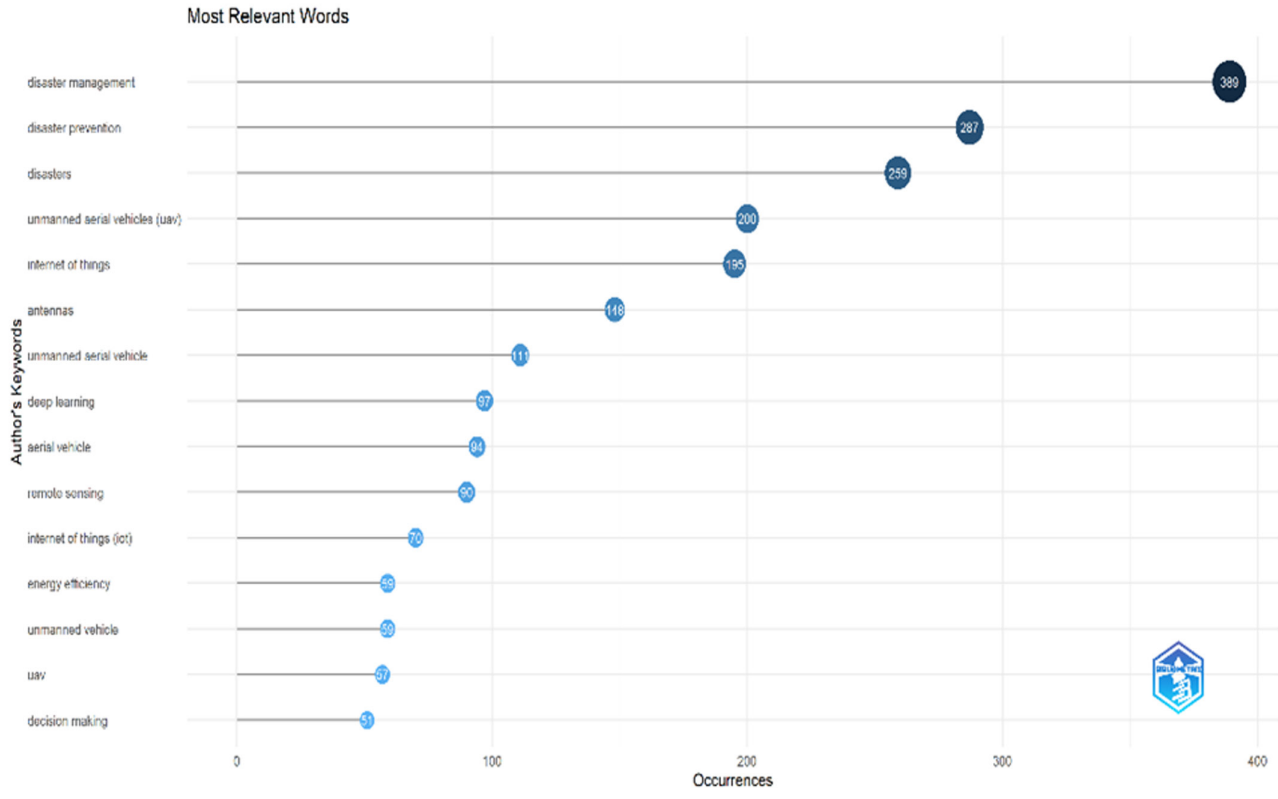

Fig. 4. Most relevant words.

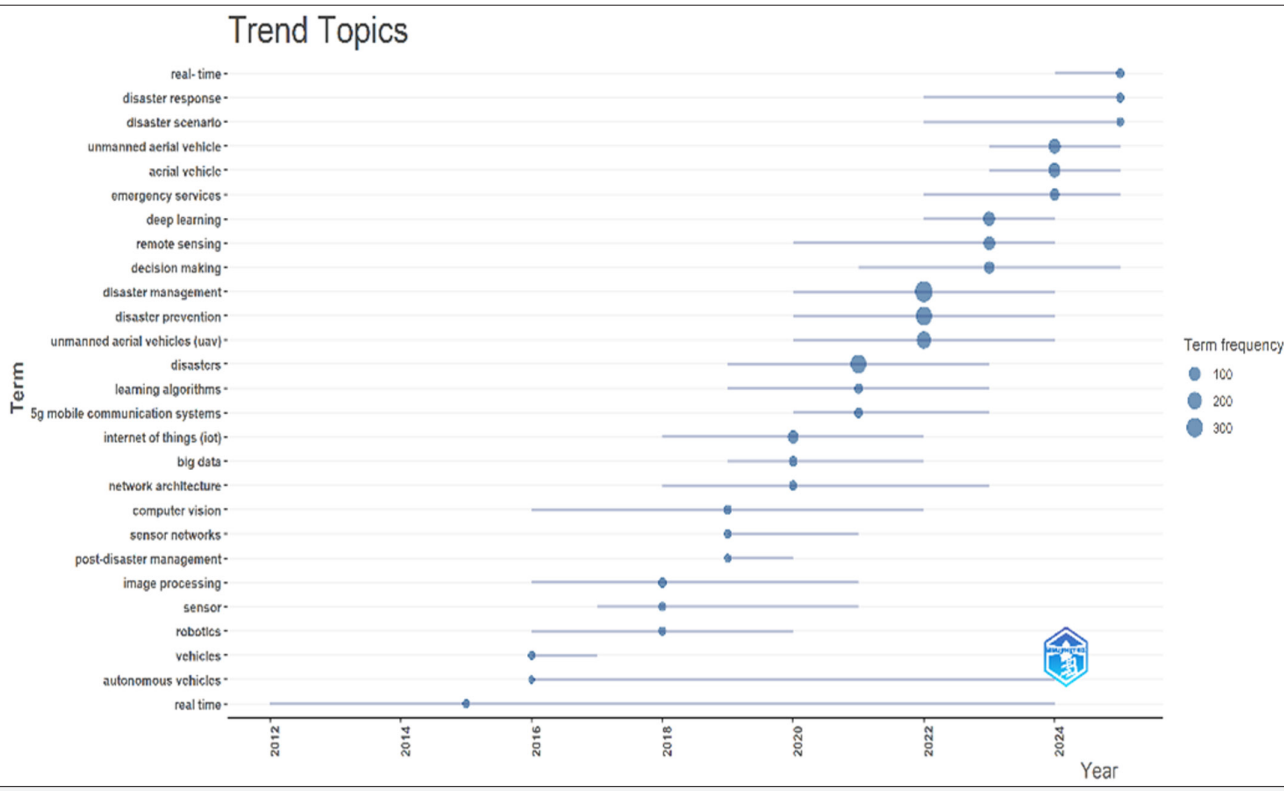

Fig. 5. Trend topics.

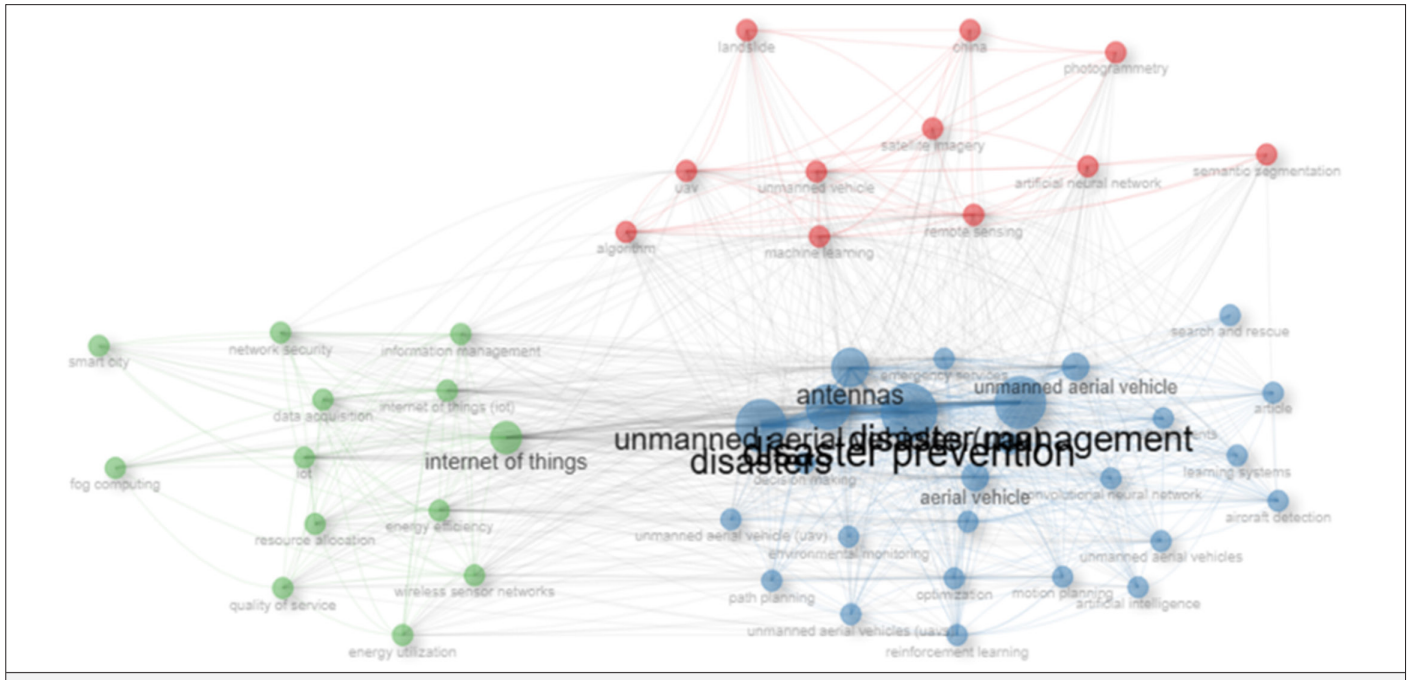

Fig. 6. The keyword co-occurrence network.

reveals three dominant and interrelated thematic pillars: UAVs, disaster management and prevention, and the IoT. These core terms occupy central positions in the map, indicating their strong connectivity and conceptual centrality within the research field. The network further distinguishes three main clusters. The red cluster, focused on remote sensing and AI-driven analysis, connects terms such as landslide, satellite imagery, photogrammetry, and machine learning, emphasizing the growing role of AI and geospatial data in hazard detection and assessment. The green cluster centers on IoT-based systems, encompassing fog computing, smart cities, and wireless sensor networks, highlighting research on resilient and energy-efficient monitoring infrastructures. The blue cluster revolves around UAV operations and mission planning, incorporating terms such as path planning, search and rescue, and reinforcement learning, underscoring UAVs' operational and decision-support roles in disaster contexts. Cross-cutting technologies such as machine learning and artificial neural networks

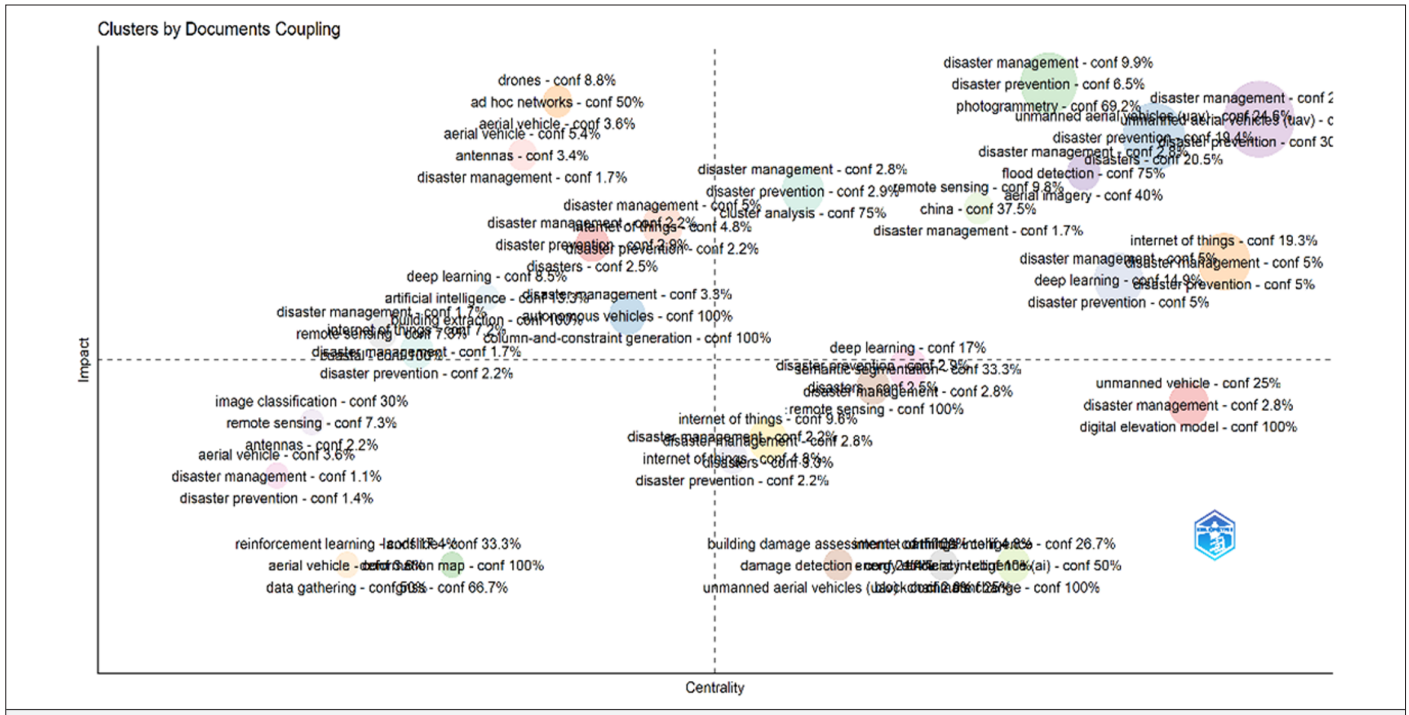

Fig. 7. Document coupling analysis.

bridge multiple clusters, demonstrating AI's integrative role across sensing and response systems. Additionally, geographic references like China and event-related terms such as landslide and earthquake point to strong empirical grounding in case-based studies, particularly in East Asia. Collectively, the network map highlights a mature and interconnected research ecosystem, where UAVs, IoT, and AI converge to advance intelligent, data-driven disaster management solutions. These clusters not only represent thematic groupings but also define distinct functional layers within earthquake management systems, ranging from large-scale sensing (red cluster) to ground-level monitoring (green cluster) and operational response (blue cluster).

The document coupling analysis (Fig. 7) delineates the thematic structure of the research corpus, positioning keywords according to their centrality (the degree of thematic connectivity within the field) and impact (their scholarly influence). The top-right quadrant, characterized by high centrality and high impact, represents the intellectual core of the field, dominated by disaster management, UAVs, disaster prevention, photogrammetry, and deep learning. These themes constitute the primary research anchors, reflecting the integration of AI-based image analysis and UAV-enabled data acquisition in disaster risk assessment and prevention. The bottom-right quadrant highlights central but moderately impactful themes such as IoT, remote sensing, and AI, which serve as enabling technologies underpinning data collection, communication, and automation processes. In contrast, the top-left quadrant identifies niche but high-impact areas, including ad hoc networks, autonomous vehicles, and cluster analysis, suggesting specialized or emerging lines of investigation, particularly relevant to UAV communication and autonomous navigation systems. Finally, the bottom-left quadrant gathers peripheral concepts such as aerial vehicles, antennas, and reinforcement learning, which represent supporting technical components or application-specific approaches. Overall, the coupling structure reveals a coherent "core triad," UAVs, deep learning, and disaster management, that defines the contemporary research focus, while also indicating future opportunities at the intersection of UAV–IoT–AI integration for real-time disaster intelligence.

The collaboration analysis (Fig. 8) shows that research on emerging technologies for earthquake disaster management is highly international and multi-centric. China dominates as the primary hub, maintaining strong ties with India, the United States, and major European countries such as the UK, Germany, and Italy. An active Asia–Pacific network, including Japan, South Korea, and Southeast Asia, reflects regional cooperation driven by shared seismic risks. Europe and North America remain closely linked through long-standing transatlantic collaborations, while emerging contributors like Australia, Brazil, and South Africa show growing participation. Overall, the map highlights a global yet uneven collaboration landscape, emphasizing the need to strengthen partnerships with underrepresented regions (e.g., Africa and Latin America) to enhance global resilience and technological innovation in disaster management.

IV. WIRELESS COMMUNICATION TECHNOLOGIES IN DISASTER MANAGEMENT

The concept of disaster management encompasses the systematic coordination and administration of resources and actions across all phases of a disaster lifecycle, namely mitigation, preparedness, response, and recovery [15]. Central objectives within this framework include the timely dissemination of early warnings, the acquisition of accurate real-time situational data, rapid damage assessment, the identification of viable evacuation routes, and the efficient allocation of emergency resources. Conventional disaster management methodologies are increasingly recognized as insufficient due to their limited capacity to aggregate and process large-scale, heterogeneous data in real time, thereby hindering rapid decision-making during critical response windows [15]. To address these limitations, modern disaster management systems leverage advanced sensor networks integrated with diverse communication technologies for

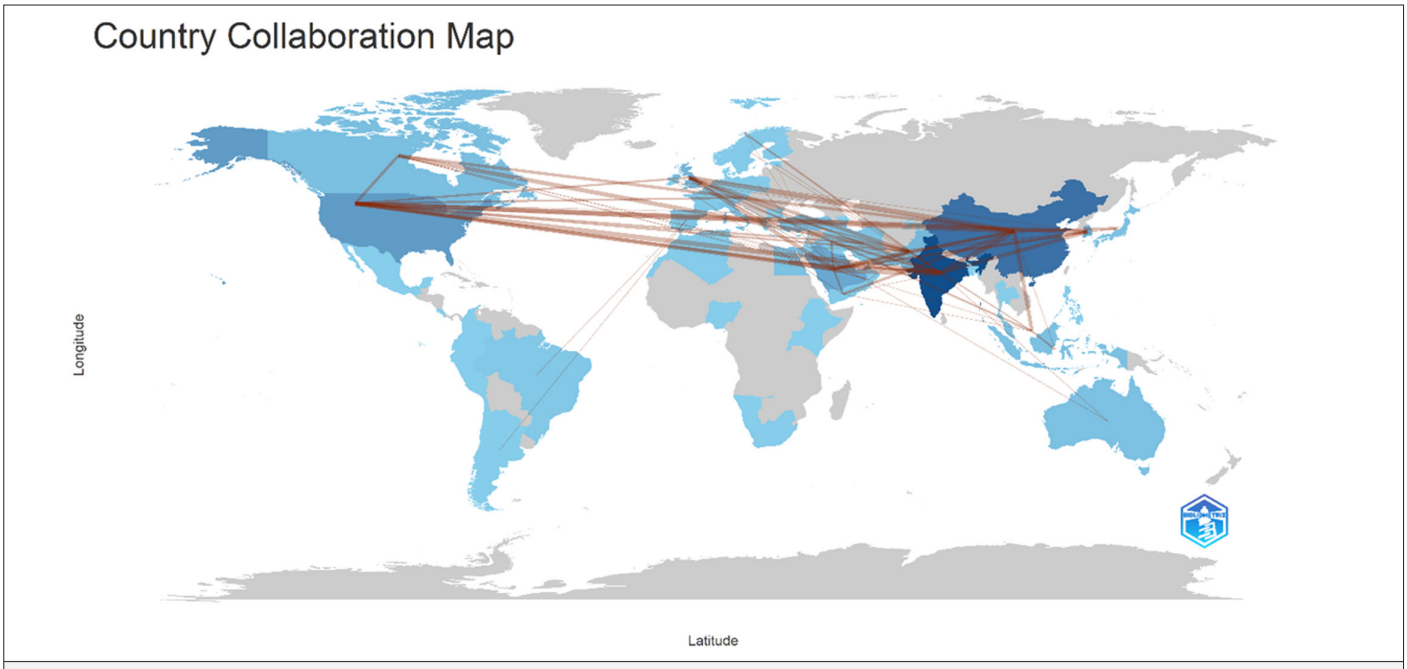

Fig. 8. Countries' collaboration analysis.

data transmission. These include short-range wireless protocols such as Bluetooth and Wi-Fi, wired solutions like Ethernet, as well as long-range options such as cellular networks, radio frequency systems, and conventional radio communication [16].

A variety of communication protocols are employed to ensure reliable and efficient data transfer in disaster scenarios. These include the Choco protocol, User Datagram Protocol, IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN), and IEEE 802.15.4, which are particularly suited for low-power, resource-constrained environments. Additionally, the Message Queuing Telemetry Transport (MQTT) protocol has gained widespread adoption due to its lightweight nature and suitability for unreliable networks [17]. Other protocols, such as Concurrent Multipath Transfer, LoRaWAN, Transmission Control Protocol/Internet Protocol, Hypertext Transfer Protocol, Zigbee, LRWiFi, Cat-M1, Constrained Application Protocol (CoAP), and XBee are also utilized depending on specific application requirements. Before transmission, sensor data is commonly structured in lightweight, machine-readable formats such as JavaScript Object Notation (JSON), facilitating efficient parsing and interoperability across heterogeneous systems [18]. Data storage solutions are implemented at both local and cloud levels. Local storage typically employs SD memory cards for edge-level data buffering, while cloud-based platforms such as MongoDB and Amazon DynamoDB enable scalable, remote data aggregation and analysis [19].

In the context of earthquake monitoring, reliable data transmission is ensured through the use of established communication technologies, including Bluetooth, Ethernet, Wi-Fi, Choco protocol, IEEE 802.15.4, MQTT, and Zigbee [20]. These technologies support real-time monitoring of seismic activity and structural health, enabling timely alerts and post-event assessments. Furthermore, several studies have explored specialized wireless technologies for post-earthquake search and rescue operations. For instance, [21] developed a microwave-based system capable of detecting vital signs, such as breathing and heartbeat, through debris layers up to 10 feet thick. Operating in the L- and S-bands (450 MHz and 1150 MHz), the system utilizes phase-locked oscillators to emit electromagnetic waves that penetrate rubble and reflect off moving human bodies. The reflected signals are modulated by physiological movements and, after demodulation and background noise suppression, yield detectable respiration and cardiac activity. Similarly, [22] proposed a pulsed radar system for life detection by capturing human micro-movements associated with breathing and heartbeat in the time domain. It enables not only the detection of vital signs but also the localization of survivors beneath collapsed structures. However, its operational frequency is constrained by hardware limitations, restricting its adaptability across different scenarios.

The selection of appropriate communication technology depends on specific operational requirements during earthquake response. Table I compares key wireless technologies across critical dimensions relevant to disaster scenarios, highlighting their relative strengths and limitations for different applications. Further, no single communication technology meets all requirements for a comprehensive earthquake response. Instead, resilient systems employ

TABLE I. COMPARATIVE ANALYSIS OF WIRELESS COMMUNICATION TECHNOLOGIES FOR EARTHQUAKE RESPONSE

Technology	Range	Latency	Power Consumption	Robustness to Infrastructure Damage	Best Application Context	Limitations
Bluetooth	<100m	Low	Very low	Low	Short-range device pairing, wearable sensors	Limited range, interference in dense environments
Wi-Fi	<100m	Low	Medium	Low	Local data offloading, temporary hotspots	Requires power source, limited mobility
Zigbee	<100m	Medium	Very low	Medium	Mesh networks for structural monitoring	Low data rate, limited to line-of-sight
LoRaWAN	2-15km	High	Low	High	Wide-area sensor networks, remote monitoring	Low bandwidth, not suitable for video
MQTT	Varies	Medium	Medium	Medium	Sensor data aggregation, IoT platforms	Requires broker infrastructure
CoAP	Varies	Medium	Low	Medium	Constrained IoT devices, low-power networks	Limited security features
Cellular (4G/5G)	Varies	Medium	High	Low-Medium	General communication, video transmission	Infrastructure-dependent, coverage gaps
Ad hoc networks	Varies	Medium-High	Medium	High	Emergency communication restoration	Complex routing, dynamic topology

Wi-Fi: Wireless Fidelity; LoRaWAN: Low Range Wide Area Network; MQTT: Message Queuing Telemetry Transport; IoT: Internet of Things; CoAP: Constrained Application Protocol; 4G: Fourth Generation Mobile Network; 5G: Fifth Generation Mobile Network.

heterogeneous networking approaches that combine short-range, low-power protocols for sensor networks with UAV-based aerial relays for wide-area coverage. The critical transition point occurs when ground infrastructure becomes compromised, requiring rapid reconfiguration to maintain connectivity through ad hoc and UAV-aided networks.

A. Internet of Things for Earthquake Preparedness and Real-Time Response

The concept of IoT was first introduced in 1999 by Kevin Ashton, a British technology pioneer and co-founder of the Auto-ID Center at the Massachusetts Institute of Technology. Ashton coined the term IoT in the context of supply chain management and radio-frequency identification technology. He envisioned a system where physical objects could be uniquely identified and connected to the internet, enabling them to communicate and share data without human intervention. While the term was formally introduced in 1999, the underlying ideas, such as machine-to-machine communication and embedded computing, had been developing for decades prior [23]. However, it wasn't until the 2000s and 2010s, with advances in wireless communication, sensor technology, cloud computing, and miniaturization of electronics, that IoT began to gain widespread traction and practical implementation across industries such as healthcare, transportation, smart homes, and disaster management. The term "things" in such a network denotes any virtual or physical entity, including humans, inanimate items, intelligent software agents, or virtual data [24].

A typical IoT system is built around a sensor network that monitors environmental conditions, as illustrated in Fig. 9. Internet of Things architectures are generally organized into three core layers: the sensor layer, the network layer, and the application layer [25]. The sensor layer forms the foundation of the system and is responsible for real-time data acquisition from the physical environment. Sensors operate autonomously to capture critical parameters, thereby enabling continuous interaction between the physical and digital domains [26]. The collected data is transmitted through the network layer, where communication protocols and gateways ensure reliable data aggregation, preprocessing, and forwarding to higher layers. Finally, the application layer performs data analysis, visualization, and decision support, translating raw sensor data into actionable information for end users and emergency responders [25].

In disaster management, the effectiveness of IoT systems depends strongly on the timeliness, accuracy, and reliability of data delivery across these layers [25]. Real-time information from IoT infrastructure is particularly vital during emergency response operations, where rapid, informed decision-making is required under dynamic, high-pressure conditions. The first 72 hours, known as the "golden rescue period," are essential for search and rescue efforts, as the likelihood of finding survivors decreases after this window [27].

During the pre-disaster phase, IoT sensors are primarily deployed to monitor seismic and environmental parameters. Accelerometers are widely used to detect ground motion and seismic activity [26]. Both triaxial and dual-axis accelerometers are employed depending on accuracy and power requirements. For example, low-power triaxial accelerometers such as ADXL362 offer energy-efficient operation, while high-precision sensors, including EPSON M-A351AU and LSM9DSO, provide enhanced measurement accuracy [28]. Dual-axis accelerometers, such as ADXL203, offer a balance between power consumption and precision [29]. Other triaxial sensors, including L1S3DSH (STMicroelectronics) and EpiSensors, are commonly mounted on buildings and bridges due to their robustness and performance characteristics [13].

These accelerometers are typically mounted on buildings and bridges to detect seismic activity. Single-board computers like Raspberry Pi, CC2420 DBK, [29] and Sparrow v4 [20] are used to process and transmit data. Energy efficiency remains a key design consideration; therefore, many systems employ sleep-mode operation and battery-powered configurations, using energy sources such as D-cell batteries [28] or CR2032 lithium-ion batteries [20] are typically used. Cost-effectiveness is also critical for large-scale deployment, with some earthquake monitoring systems reporting implementation costs of approximately USD 2300 [28].

Reliable real-time data transmission is essential for accurate seismic analysis and rapid response. Traditionally, seismic monitoring stations transmit data to centralized processing centers via a

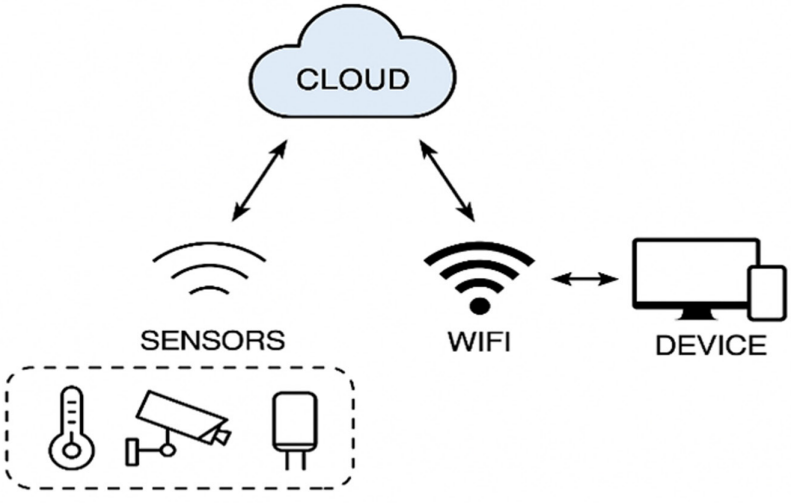

Fig. 9. A general paradigm for Internet of Things systems.

single communication backhaul. However, this approach is vulnerable during disasters, as network infrastructure may be partially or completely damaged. To address this limitation, researchers and emergency agencies advocate for the integration of heterogeneous backhaul technologies within emergency communication networks. Diversifying communication paths reduces dependence on a single point of failure and significantly enhances system resilience and reliability during earthquake events [8]. Recent advances in resilient communication architectures include UAV-mounted Reconfigurable Intelligent Surfaces (RISs) integrated with High Altitude Platform–enabled edge computing in 6G networks, which significantly enhance signal reliability in infrastructure-damaged environments [30].

B. Internet of Things and Post-Earthquake Recovery

In the post-disaster phase, sensors are primarily employed to collect health-related, location, and environmental data, which are critical for enhancing the effectiveness of search and rescue operations. Health monitoring is often enabled through sensors embedded in personal mobile and wearable devices carried by stranded individuals, allowing the collection of physiological parameters such as heart rate, respiratory rate, dizziness, perspiration, chest discomfort, tremors, chills, coughing, and nausea, in addition to precise location information [31]. To further improve operational safety and situational awareness, [31] also emphasized the importance of prioritizing first responder safety through the use of body-worn sensors integrated into wearable smart devices, including smartwatches and smart glasses. These devices enable continuous monitoring of the physical condition of both rescuers and victims during rescue missions. Complementing this approach, [32] developed an IoT-based system designed to detect distressed or trapped individuals and facilitate rapid medical intervention, thereby supporting timely and coordinated post-disaster response.

Accurate positioning data is critical for effective search and rescue operations and typically includes the locations of victims, first responders, and rescue vehicles. The initial positioning of isolated or trapped individuals can be obtained through sensors embedded in personal mobile devices, such as GPS receivers, accelerometers, and gyroscopes, which enable precise localization and motion tracking [16]. In addition, [33] proposed leveraging existing traffic surveillance camera systems to detect individuals trapped in vehicles or under debris. By applying computer vision and video analytics, these systems enhance situational awareness and support rapid survivor identification in urban disaster environments.

Environmental sensing also plays a vital role in post-earthquake recovery. Sensors have been deployed to monitor weather conditions, pollutants, and mobility constraints [27]. Furthermore, [32] installed sensors on buildings and pavements in affected areas to collect environmental and structural data, including building tilt, water levels, temperature, smoke presence, pathway obstructions, visibility range, and sensor location. For post-earthquake structural health assessment, [34] recommended the use of LIS344ALH accelerometers, SHT11 temperature and humidity sensors, and TAOS 2561 light sensors to evaluate damage and safety conditions.

Beyond sensing, IoT systems for earthquake management have evolved to incorporate satellite data and advanced networking technologies to enhance resilience and real-time data exchange. Recent research emphasizes the integration of IoT with Software-Defined Networking (SDN) and Network Function Virtualization (NFV) to improve scalability, flexibility, and adaptability in disaster environments where conventional communication infrastructure may be severely damaged [35]. Through dynamic network reconfiguration and efficient resource allocation, SDN- and NFV-enabled IoT architectures help maintain connectivity and ensure continuous data flow during critical response and recovery phases [36].

In parallel, social networks have emerged as valuable complementary tools for post-earthquake recovery and coordination. Studies have shown that social media platforms can enhance feedback, situational awareness, and relief activities during and after disasters [37]. Platforms such as Twitter and Facebook enable rapid dissemination of warnings, real-time reporting of affected areas, and coordination of rescue and relief efforts [38]. Social media data can support damage mapping, identification of urgent intervention sites, and efficient allocation of resources, while also facilitating the dissemination of information regarding shelters, safe zones, and essential supplies. Integrating social media analytics into IoT-based disaster management frameworks can therefore significantly improve the speed, efficiency, and effectiveness of post-earthquake recovery operations.

C. Artificial Intelligence-Enabled Earthquake Disaster Management Systems

The integration of artificial intelligence (AI) with wireless communication infrastructures represents a paradigm shift in earthquake disaster management systems, transforming raw sensor data into actionable intelligence across all phases of the disaster management cycle. This subsection synthesizes the role of AI within communication frameworks, highlighting specific implementations, operational benefits, and technical constraints that define contemporary research and practice.

Advanced convolutional neural network architectures have demonstrated unprecedented capabilities in automated damage assessment from aerial imagery. For example, [39] implemented a UAV-assisted edge framework deploying CNN-based image classification models on NVIDIA Jetson-series embedded devices to distinguish affected from unaffected areas with high accuracy. These systems process thousands of images per hour, accelerating damage assessment by orders of magnitude compared to manual review. The integration of transfer learning techniques with pretrained models (VGG19, ResNet50, InceptionV3, Xception, EfficientNetB0, and MobileNet) enables adaptation to domain-specific disaster scenarios while maintaining computational efficiency. However, model performance exhibits significant degradation when encountering novel damage patterns not represented in training datasets, particularly in complex urban environments with heterogeneous building types.

AI-powered path planning algorithms optimize UAV trajectories during earthquake response operations. Reinforcement learning approaches enable autonomous navigation through complex urban environments while avoiding obstacles and maintaining communication links. These systems balance multiple objectives including coverage efficiency, battery conservation, and priority area access. Recent advances demonstrate how energy-aware path planning can extend operational availability without compromising mission effectiveness [31]. The Multi-Agent Deep Reinforcement Learning (MADRL) approach for optimizing UAV trajectories represents a paradigm shift in the conceptualization of energy constraints in disaster response systems [40].

Complementing these visual analysis capabilities, AI systems employing multimodal fusion techniques have revolutionized victim localization in post-earthquake scenarios. These systems integrate thermal imagery, audio signatures, and micro-movement detection algorithms to identify potential survivors beneath collapsed structures. Recent advances incorporate signal processing techniques that analyze modulated electromagnetic waves reflected from human bodies, enabling vital sign detection through debris layers up to 10 feet thick [21]. Further, [22] demonstrated pulsed radar systems capable of detecting breathing and heartbeat signals in the time domain, though operational constraints limit these systems to specific frequency bands (10 GHz). The false positive rate remains a critical challenge, with environmental factors such as animal movements and structural vibrations generating misleading signals that require sophisticated filtering algorithms. Equally important is the false negative rate, as missed survivors due to model limitations can have devastating consequences. The optimal threshold for survivor detection must balance these competing concerns, with the acceptable error profile shifting as the disaster evolves from immediate response to extended recovery operations.

Artificial intelligence-powered analytics further integrate heterogeneous data streams from seismic sensors, structural health monitoring systems, population density maps, and real-time UAV footage to generate comprehensive situational awareness. These systems employ multi-criteria decision-making frameworks to prioritize response efforts and allocate resources efficiently [4]. implemented the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to determine optimal UAV base locations for earthquake response in the Marmara region of Türkiye, considering six criteria, including distance to seismic zones, meteorological conditions, and airport traffic density. However, the "black box" nature of many AI models hinders trust among emergency responders who require transparent reasoning behind critical resource allocation decisions.

Training data bias represents a significant limitation in AI-based earthquake response. Models trained primarily on data from developed regions often perform poorly in developing countries due to differences in building typologies, infrastructure density, and environmental conditions. This geographic bias can lead to inaccurate damage assessments in regions underrepresented in training datasets, potentially delaying critical response efforts in vulnerable communities. While transfer learning approaches mitigate this constraint to some extent, they introduce domain adaptation challenges when applying models trained on one geographic region to another with different building typologies and environmental conditions [41].

Resource-limited edge devices deployed in disaster zones face significant challenges running complex AI models. The trade-off between model complexity and inference speed is particularly acute during the critical "golden rescue period" (first 72 hours), where every second counts in search and rescue operations [27]. Recent advances in model quantization and pruning techniques have enabled deployment of lightweight AI models on UAVs and IoT gateways, though often at the expense of accuracy. The lack of model interpretability in deep learning systems creates barriers to adoption by emergency response personnel who require transparent decision-making processes during high-stakes operations. This constraint is particularly problematic in multi-agency coordination scenarios where different organizations must reconcile potentially conflicting AI-generated recommendations [32].

The most promising research trajectories address these constraints through innovative approaches. Federated learning architectures enable collaborative model training across multiple response organizations without sharing sensitive operational data, addressing privacy concerns while improving model robustness through diverse training data [41]. Hybrid human-AI decision frameworks strategically combine machine processing speed with human contextual judgment, preserving human oversight in life-or-death scenarios while leveraging AI for data processing at scale [32]. Explainable AI techniques, such as attention mechanisms and feature importance visualization, provide transparent reasoning for critical decisions, which is essential for building trust among emergency responders and facilitating effective human-AI collaboration [8]. Furthermore, the development of realistic earthquake simulation platforms that generate diverse damage scenarios can address data scarcity challenges while enabling safe testing of AI systems before deployment in real disaster contexts [28].

This integration of artificial intelligence with communication infrastructures represents a critical evolution in disaster management, transitioning from reactive response to predictive and adaptive systems. As these technologies mature, they increasingly enable faster, more accurate, and more coordinated earthquake response operations through enhanced data processing capabilities at the network edge. The convergence of AI with IoT sensing and UAV platforms creates a synergistic effect that significantly enhances situational awareness and decision-making capabilities during all phases of earthquake disaster management.

V. UNMANNED AERIAL VEHICLES FOR EARTHQUAKE

Unmanned aerial vehicles are complex engineering systems that are designed to perform an array of tasks in military and civilian applications. Reliability, effectiveness, and their overall performance depend entirely on their structural layout. The UAV structure must be developed to be aerodynamically efficient while maintaining sufficient strength and stiffness to endure operational stresses. The main structural components of UAVs include fuselage, wings/rotors, control surfaces, landing gear, and internal support structures. Each plays an integral role in how the UAV operates and performs (Fig. 10). The fuselage is the primary structure of the UAV and houses critical systems such as the power source, flight control electronics, sensors, and payload. Advanced composite materials, such as carbon fiber reinforced polymers, are commonly used owing to their excellent strength-to-weight ratio and durability [42].

The design procedure usually proceeds in an orderly fashion in accordance with a methodology of conceptual, preliminary, and detailed designs. Beyond static load-bearing requirements, modern designs incorporate fatigue life prediction and vibration analysis to ensure durability across repeated missions [42]. These structural capabilities enable UAVs to carry sensing payloads such as cameras, LiDAR, thermal imagers, and communication modules for damage assessment, survivor detection, and route planning [43] While UAV-based Earth observation has proven valuable for both short-term rescue and long-term environmental and risk assessment applications [42]. Challenges such as limited payload capacity, restricted flight endurance, and sensitivity to adverse weather conditions remain key constraints on operational performance.

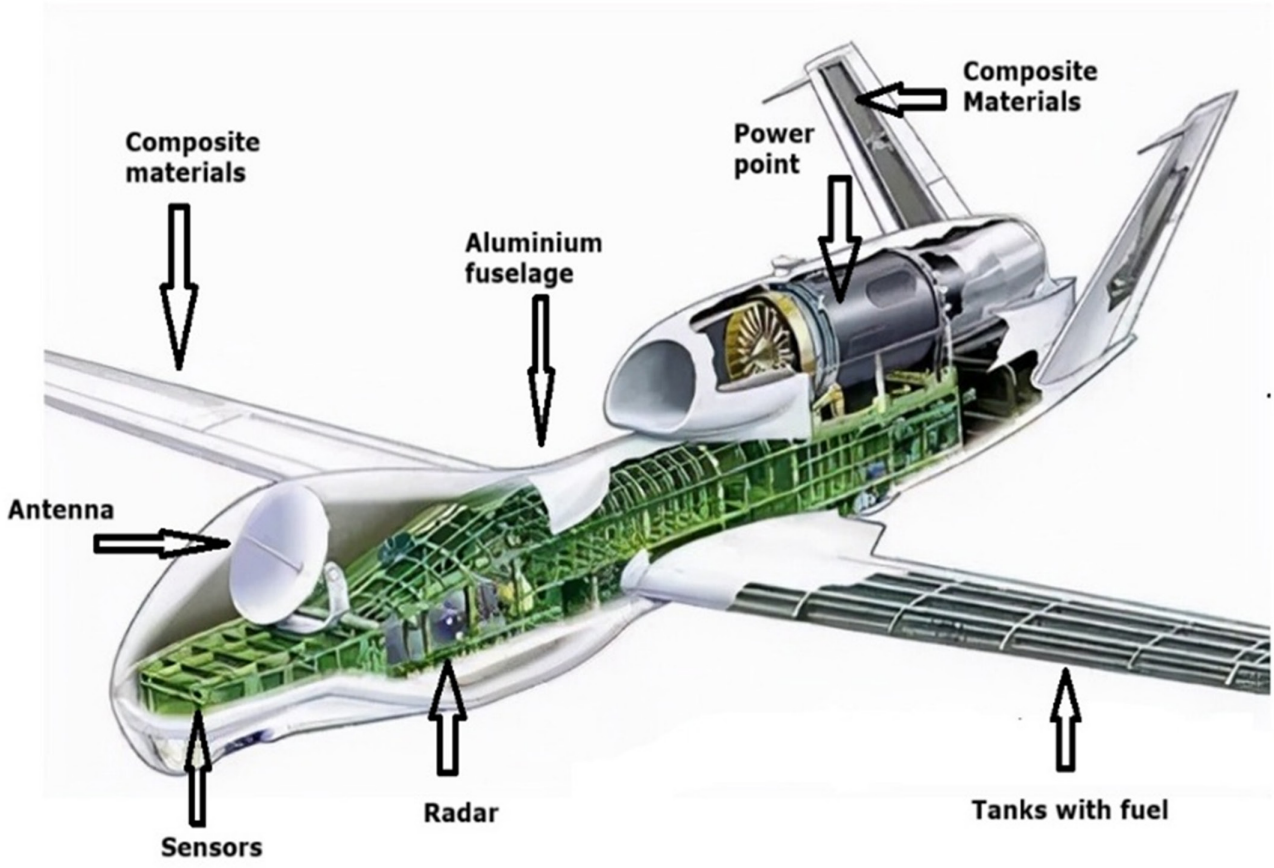

Fig. 10. Schematic structure of an unmanned aerial vehicle.

A. Unmanned Aerial Vehicle Types and Earthquake Response

UAVs have emerged as critical assets in earthquake disaster management due to their operational flexibility, rapid deployment capabilities, and ability to function in hazardous and inaccessible environments. The selection of an appropriate UAV type is a crucial determinant of operational effectiveness in various disaster-related applications, including reconnaissance, structural damage assessment, search and rescue operations, and post-event infrastructure monitoring. The UAVs are commonly categorized according to several technical and functional parameters, such as airframe configuration, propulsion systems, payload capacity, and operational range. Each classification presents distinct advantages and limitations, which significantly influence their suitability and performance in earthquake response and mitigation efforts [44].

1) Unmanned Aerial Vehicle's Airframe-Based Classification:

Unmanned aerial vehicles are commonly classified according to their airframe design, which strongly influences their suitability for earthquake disaster response. The main categories include fixed-wing, rotary-wing, and hybrid (powered-lift) UAVs, each offering distinct operational advantages and constraints.

Fixed-wing UAVs resemble conventional aircraft and generate lift through rigid wings during forward flight. They offer high cruising speeds and long endurance, often several hours, making them well-suited for large-scale post-earthquake surveying and mapping missions [44].Their capability to produce high-resolution orthomosaic maps supports rapid damage assessment and identification of severely affected areas [45]. However, their reliance on runways or open spaces for takeoff and landing limits deployment in dense urban environments or debris-covered zones [46]. Rotary-wing UAVs include single-rotor and multi-rotor platforms. Single-rotor UAVs, similar to manned helicopters, generally provide longer endurance and higher payload capacity than multi-rotor systems [46]. In contrast, multi-rotor UAVs (e.g., quadcopters, hexacopters, and octocopters) offer vertical takeoff and landing and precise hovering, enabling close-range inspection of damaged structures and critical infrastructure [9]. Their maneuverability in confined and obstructed environments makes them particularly effective for urban search-and-rescue operations [4]. Hybrid (powered-lift) UAVs combine features of fixed-wing and rotary-wing platforms, enabling vertical takeoff and landing followed by efficient forward flight [47]. This dual capability allows operation in space-constrained areas while maintaining extended range and endurance. In earthquake scenarios, hybrid UAVs are especially suited for missions requiring both coverage and maneuverability, such as wide-area damage assessment, landslide monitoring, and post-aftershock surveillance [47]. Fig. 11 summarizes the airframe-based classification of UAVs and highlights their structural characteristics and operational relevance across different earthquake response phases.

2) Operational Range-Based Classification:

Unmanned aerial vehicles are also commonly classified according to flight endurance and operational range, which are critical

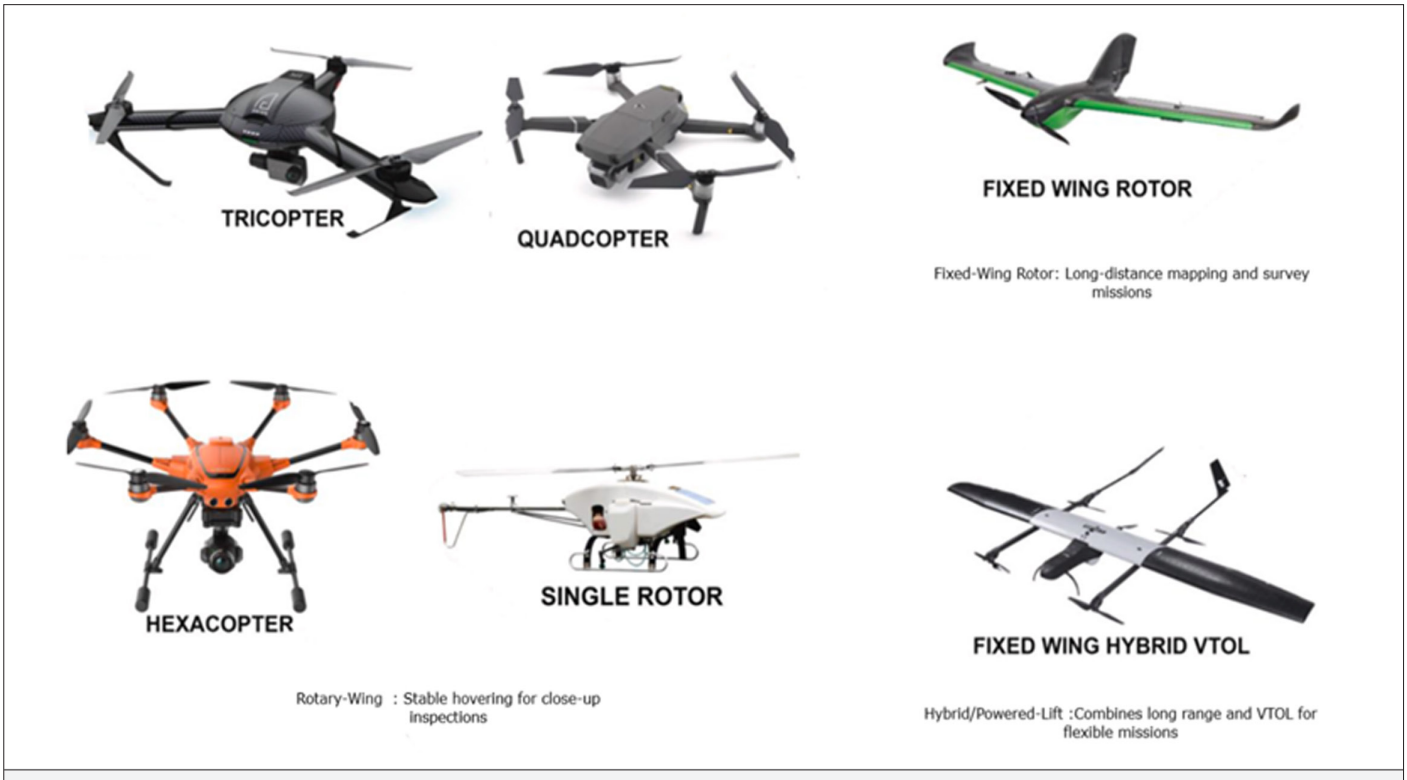

Fig. 11. Classification of unmanned aerial vehicles based on airframe design.

TABLE II. CLASSIFICATION OF UAVS BASED ON OPERATIONAL RANGE, ENDURANCE, AND ALTITUDE

UAV Type	Operational Range	Flight Endurance	Altitude	Typical Applications	Key Features
Very close-range UAVs	<5 km	A few minutes to several hours	Low altitude	Urban search-and-rescue, localized situational awareness, earthquake response	Portable, handheld; ideal for fast visual assessment tasks
Close-range UAVs	5–50 km	1–6 hours	Low-to-medium altitude	Extended local reconnaissance, infrastructure inspection, medium-scale disaster assessment	Greater range than handheld UAVs, good portability
Short-range UAVs	50–150 km	6–12 hours	Up to ~5000–8000 ft	Regional reconnaissance, early damage assessment, communication support	Balanced endurance and mobility; suitable for semi-regional coverage
Medium-range UAVs	150–650 km	Up to 24 hours	Up to 10 000 ft	Extended reconnaissance, border patrol, and wide-area post-disaster monitoring	Capable of carrying heavier payloads; supports communication relay
Long-range UAVs (HALE)	> 650 km	>24 hours (several days)	Up to 30 000 ft	Strategic intelligence, persistent surveillance, and large-scale environmental monitoring	High-altitude long endurance; used for critical communication during recovery
MALE UAVs	~180–200 km	≥12 hours	~6000 m	Sustained observation, seismic event monitoring	Medium-altitude long-endurance; effective for prolonged situational awareness

ft: feet; HALE: High-Altitude Long-Endurance; m: meter; MALE: Medium-Altitude Long-Endurance.

performance parameters for mission planning in reconnaissance, disaster management, and infrastructure surveillance [48]. This classification enables the strategic selection of UAV platforms based on mission scope, environmental constraints, and logistical feasibility (Table II). Very close-range UAVs operate within distances of up to 5 km and typically offer limited endurance, ranging from several

minutes to a few hours. These lightweight and highly portable platforms are well-suited for localized situational awareness tasks, such as rapid visual inspection and urban search-and-rescue operations in post-earthquake environments [45]. Close-range UAVs extend operational coverage to 5–50 km and provide a balance between portability and endurance. With typical flight durations of 1–6 hours at low-to-medium altitudes, they are suitable for neighborhood- or district-level reconnaissance, infrastructure inspection, and medium-scale damage assessment following seismic events [49]. Short-range UAVs cover distances of 50–150 km and offer significantly greater endurance, often exceeding six hours. Operating at altitudes between approximately 5000 and 8000 feet, these platforms are effective for regional reconnaissance, early-stage damage assessment, and temporary communication relay deployment in inaccessible earthquake-affected areas [50]. Medium-range UAVs operate over distances of 150–650 km with endurance reaching up to 24 hours. Their ability to carry heavier payloads and operate at higher altitudes (up to 10,000 feet) makes them suitable for wide-area monitoring and communication support, particularly when ground infrastructure is damaged after an earthquake [51]. Long-range UAVs exceed 650 km in operational range and can sustain flight durations beyond 24 hours. These platforms, commonly classified as High-Altitude Long-Endurance (HALE) UAVs, are primarily used for persistent surveillance, strategic monitoring, and large-scale environmental observation. Some endurance-class systems operate at altitudes up to 30 000 feet, enabling continuous communication and coordination during prolonged disaster recovery phases [45]. Medium-Altitude Long-Endurance (MALE) UAVs, a related subclass, typically operate at around 6000 m altitude with endurance exceeding 12 hours and ranges of approximately 180–200 km, supporting sustained situational awareness across extensive earthquake-affected regions [52].

3) Payload Capacity Classification:

Payload capacity is a defining characteristic that influences the functional utility of UAVs in disaster scenarios. It means the maximum weight that a UAV can carry beyond its operational mass, including sensors, communication modules, medical supplies, or other mission-specific equipment. Based on the literature, Table III categorizes UAVs into three primary groups according to their payload capabilities: Featherweight and Lightweight UAVs, Middleweight UAVs, and Heavy Lift UAVs.

Featherweight and lightweight UAVs typically support payloads below 2 kg and represent the smallest, most portable class of platforms [52]. They are designed for rapid deployment and short-range operations, commonly equipped with basic visual and thermal sensors. These UAVs are particularly effective for immediate post-earthquake reconnaissance, such as inspecting collapsed buildings or navigating rubble in dense urban environments, where rapid situational awareness is critical. However, their limited payload, endurance, and resistance to adverse weather conditions constrain sensor capability and data quality, making them most suitable for preliminary response phases [53].

Middleweight UAVs carry payloads ranging from 2 to 25 kg and offer a balance between mobility and advanced sensing capabilities. This class can support multiple sensors simultaneously, including LiDAR, multispectral cameras, and gas detectors, enabling high-resolution mapping, structural inspection, and hazard detection in post-seismic environments [54]. Their extended endurance and versatility make them suitable for sustained reconnaissance, damage assessment, and decision support across both urban and rural areas during the response and early recovery phases. Heavy-lift UAVs support payloads exceeding 25 kg, with some platforms capable of carrying 60 kg or more. These systems are primarily employed for logistics-intensive and large-scale operations, such as emergency supply delivery, deployment of temporary communication nodes, and transportation of advanced radar or imaging payloads. In earthquake scenarios, heavy-lift UAVs play a critical role in delivering essential resources to isolated areas and supporting wide-area damage assessment and reconstruction planning. Despite their advantages, their deployment is often limited by high operational costs, regulatory constraints, and logistical complexity.

The selection of an appropriate UAV platform requires consideration of both the disaster phase and specific operational requirements within earthquake response scenarios. As detailed in Table IV, UAV suitability extends beyond temporal considerations to encompass environmental constraints and mission-specific demands. Multirotor UAVs excel in GPS-challenged urban canyons for building inspection, while fixed-wing platforms provide optimal coverage for mountainous assessment. Heavy-lift UAVs are essential for medical supply delivery to isolated areas, and hybrid UAVs offer the most versatile solution for temporary communication coverage [18]. This scenario-specific approach, matching platform capabilities to environmental constraints, significantly enhances mission effectiveness across diverse earthquake response operations. As UAV technologies

TABLE III. CLASSIFICATION OF UAVS BASED ON PAYLOAD CAPACITY AND WEIGHT CLASS

UAV Type	Payload Capacity	Weight Class	Key Features	Typical Sensors	Limitations
Featherweight and lightweight UAVs	Up to 2 kg	Micro (<0.1 kg), Very small (0.1–2 kg)	Highly portable, quick deployability, low cost	Visual cameras, thermal sensors	Low endurance, limited sensor capabilities, vulnerable to wind/weather
Middleweight UAVs	2–25 kg	Small (2–25 kg)	Balanced portability and advanced functionality; capable of carrying multiple sensors	LiDAR, multispectral cameras, gas sensors	Higher cost and logistical complexity compared to lightweight UAVs
Heavy-Lift UAVs	>25 kg (up to 60+ kg)	Medium (25–150 kg)	High payload capacity, suitable for logistics and heavy equipment transport	Radar, imaging payloads, communication relays	Regulatory restrictions, high costs, transportation and maintenance challenges

kg: kilogram; LiDAR: Light Detection and Ranging.

TABLE IV. OPERATIONAL SCENARIOS OF EARTHQUAKE RESPONSE AND CORRESPONDING UAV SELECTION GUIDELINES

Response Scenario	Disaster Phase	Most Suitable UAV Type	Specific Capabilities Required	Limitations to Address
Dense urban canyons	Immediate response (0–72 hours)	Multi-rotor (quad/hexacopter)	VTOL capability, obstacle avoidance systems, precise hovering in GPS-challenged environments, thermal imaging payload	GPS signal degradation in urban environments, limited flight time (15–30 minutes), vulnerability to electromagnetic interference
Mountainous areas	Ongoing response (72+ hours)	Fixed-wing or Hybrid UAVs	Long endurance (60–90 minutes), terrain-following capability, wide coverage area (30–50 km^2/hr), weather resistance	Limited takeoff/landing zones in rugged terrain, communication range limitations, and atmospheric interference with sensors
Collapsed-building inspection	Immediate/ongoing response	Middleweight multi-rotor (e.g., DJI M300)	LiDAR and thermal camera payload (2–5 kg), obstacle avoidance, visual-inertial odometry for GPS-denied navigation	Signal interference from building materials, limited operational time in confined spaces, and data processing requirements for structural assessment
Supply delivery operations	Ongoing/recovery phase	Heavy-lift multi-rotor	10–20 kg payload capacity, precision drop capability, weather resistance, and autonomous navigation	Energy constraints limiting delivery range, regulatory restrictions for heavy payloads, and precision landing challenges in disaster zones
Temporary communication coverage	Immediate response	Hybrid or heavy-lift multi-rotor	RF relay equipment payload (5–15 kg), stable hovering capability, multi-band communication support	Energy consumption of communication equipment, limited operational time while providing coverage, and regulatory constraints for communication relays
Regional damage assessment	Ongoing response	Fixed-wing UAVs	Long-range capability (20–30 km), high-resolution imaging, efficient battery usage	Requires clear takeoff/landing zones, is less maneuverable in complex terrain, and has limited hovering capability for detailed inspection

UAV: Unmanned Aerial Vehicle; DJI: Da-Jiang Innovations (manufacturer of the DJI M300 platform); VTOL: Vertical Take-Off and Landing; GPS: Global Positioning System; kg: kilogram; km^2: square kilometer; hr: hour; LiDAR: Light Detection and Ranging; RF: Radio Frequency; km: kilometer.

evolve, their specialized configurations will further address the unique challenges of each operational environment.

4) Classification of Unmanned Aerial Vehicles Based on Propulsion Systems:

Unmanned aerial vehicles are also commonly classified based on their propulsion systems, which strongly influence performance parameters such as endurance, speed, altitude, and payload capacity [55]. Propulsion selection depends on mission requirements, energy efficiency, and environmental constraints, particularly in disaster response scenarios.

Fuel-based propulsion systems rely on internal combustion engines powered by gasoline, diesel, or heavy fuels (e.g., JP-8) and are typically used in large UAVs requiring long endurance and high payload capacity. Platforms equipped with piston or turboprop engines can carry payloads exceeding 50 kg, making them suitable for long-range reconnaissance, strategic surveillance, and cargo delivery missions [56]. While these systems offer high energy density and extended flight duration, they suffer from higher noise levels, mechanical complexity, and maintenance demands compared to electric alternatives [55]. Hybrid propulsion systems combine fuel-based engines with electric motors and battery storage to improve efficiency and operational flexibility. This architecture enables fuel-efficient cruising while supporting electric-powered takeoff, hovering, or low-noise operation [56]. Hybrid systems are particularly advantageous for VTOL and long-endurance missions, including hybrid fixed-wing–rotary configurations, and offer improved reliability and load management in remote or harsh environments [57]. All-electric propulsion systems rely solely on battery-powered motors and are widely used in small and micro-UAVs due to their simplicity, low acoustic signature, and minimal maintenance requirements. Advances in lithium-ion and lithium-polymer battery technologies have improved flight endurance and payload capacity, making electric UAVs well-suited for short-range applications such as urban search-and-rescue, infrastructure inspection, and close-range damage assessment [53]. However, limited energy density remains a major constraint for long-duration or high-altitude missions. A specialized subset of electric UAVs includes solar-powered platforms, which integrate photovoltaic cells to recharge onboard batteries and are mainly deployed in high-altitude, long-endurance (HALE) missions for persistent surveillance and communication relay [57].

In earthquake management, propulsion system selection must align with mission-specific conditions such as terrain complexity, environmental constraints, and the urgency of data acquisition. Rotary-wing

UAVs are typically preferred for rapid urban assessments, while fixed-wing UAVs are more suitable for large-scale regional mapping [44]. Hybrid UAVs are increasingly explored for their ability to bridge the gap between maneuverability and endurance in complex operational environments [47]. Despite regulatory, weather, and energy constraints, ongoing advances in autonomy, sensor miniaturization, and swarm coordination continue to enhance the effectiveness of UAVs in improving the speed, safety, and precision of earthquake response operations [9].

B. Unmanned Aerial Vehicle Usage During and Post-Earthquakes

Unmanned aerial vehicles have been increasingly employed across various phases of disaster management. For instance, [58] proposed a framework for deploying an autonomous drone network to support search and rescue (SAR) operations during disaster events. In this architecture, UAVs operate according to a modular layered structure comprising the network layer, drone control layer, and application layer. The network layer includes functionalities such as medium access control, radio resource management, and self-organizing network protocols to ensure reliable communication. The drone control layer encompasses modules for mobility management, energy optimization, navigation, and flight control, enabling autonomous and adaptive UAV operation. The application layer supports mission-specific tasks, including environmental sensing, real-time mapping, and detection of ground-based devices. Notably, a cognitive module is integrated into the system to facilitate AI-driven decision-making, enhancing situational awareness and operational autonomy. Within this framework, heterogeneous UAVs perform complementary roles: backbone UAVs maintain communication links, mapping UAVs generate aerial imagery for damage assessment, and sensing UAVs detect weak signals from trapped individuals. Coordinated data exchange among these platforms enables robust operation in infrastructure-degraded environments.

Numerous studies have explored the application of UAVs in earthquake response scenarios, emphasizing their critical role in the immediate post-disaster period when survival rates are highest. Various configurations, including fixed-wing UAVs, quadrotors, multicopters, helicopters, and solar-powered aircraft, are selected based on mission requirements such as endurance, payload, and maneuverability. For example, [59]developed a rotary-wing UAV system equipped with a high-resolution camera for SAR operations following an earthquake in China. The system transmits real-time imagery to a ground station, where image analysis and object detection algorithms identify structural damage and potential survivors. Unmanned aerial vehicle flight paths can be updated dynamically, either autonomously using geographic information or manually via ground control, allowing adaptive mission planning. Detection performance can be further enhanced using machine learning-based image analysis and intelligent decision-support mechanisms to prioritize high-risk zones and optimize rescue team deployment. Comprehensive reviews, such as, [10] classify UAV operations according to disaster management phases, highlighting the particular effectiveness of small UAVs in the post-disaster phase for rapid damage assessment and high-resolution mapping. These geospatial products significantly enhance situational awareness and support data-driven SAR coordination. However, such studies often remain broad, offering limited insight into phase-specific implementation challenges.

Unmanned aerial vehicles have also proven critical in restoring communication networks following earthquakes, where conventional infrastructure is frequently compromised. Unmanned aerial vehicle–based systems can function as aerial base stations or relay nodes, rapidly establishing temporary wireless coverage and enabling real-time communication among first responders and command centers [3]. Their integration with heterogeneous networks, including IoT, MANETs, Aeronautical Ad Hoc Networks, and ground sensor networks, combined with cloud, edge, and fog computing paradigms, supports low-latency data processing and improved network responsiveness. Nevertheless, challenges remain related to energy constraints, coverage optimization, latency, and Quality of Service requirements.

Recent studies increasingly integrate AI and edge computing into UAV-based disaster response systems. For instance, [39] employed CNN-based image classification models deployed on embedded edge devices to distinguish disaster-affected areas using aerial imagery. By leveraging transfer learning and on-device inference, the framework achieved high classification accuracy while supporting real-time decision-making, particularly in remote or inaccessible regions.

Real-world deployments further demonstrate the multifaceted role of UAVs. In post-earthquake operations in Japan, drones were used for aerial surveying, 3D surface modeling, emergency supply delivery, and temporary communication restoration [60]. These efforts significantly reduced damage assessment time and improved logistical efficiency. However, operational studies such as [43] highlight persistent challenges, including airspace coordination with crewed aircraft, adverse weather conditions, regulatory constraints, and security concerns.

Finally, decision-support methodologies have been applied to optimize UAV deployment strategies. For example, [4] utilized a multi-criteria decision-making approach (TOPSIS) to identify optimal UAV base locations for earthquake response, considering seismic risk, meteorological conditions, population density, and proximity to emergency services. Similarly, [41] categorized post-disaster UAV operations into information gathering, emergency material delivery, and communication recovery, emphasizing the importance of structured decision-making in maximizing UAV effectiveness.

VI. CRITICAL RESEARCH GAPS AND TECHNICAL CHALLENGES

This study reveals that interoperability challenges manifest across four distinct technical layers requiring differentiated solutions:

- Protocol level: Standardization gaps exist between IoT sensor networks and UAV communication protocols, particularly in disaster scenarios where heterogeneous systems must exchange critical data. Current implementations often require custom middleware for data translation, introducing latency and potential information loss during time-sensitive operations. The lack of universal data formats for structural damage assessment creates barriers to rapid information sharing among response agencies.
- Platform level: Hardware integration challenges persist between diverse UAV platforms and ground-based IoT infrastructure. For instance, mounting specialized sensors on UAVs often requires custom mechanical and electrical interfaces, limiting rapid deployment flexibility. Energy constraints at this level are particularly acute, as highlighted by recent work on energy-aware UAV networking, [40] which demonstrates that conventional UAV operations requiring frequent returns to base stations for

recharging significantly reduce operational availability during critical response windows.

- Sensing level: Cross-calibration difficulties arise when integrating data from fixed seismic sensors, mobile UAV-mounted cameras, and wearable victim monitors. These systems operate with different sampling rates, precision levels, and error characteristics that complicate unified situational awareness. The spatial and temporal misalignment of heterogeneous sensor data streams represents a significant technical barrier to comprehensive damage assessment.
- Decision-support level: The most critical interoperability gap exists in translating processed sensor data into actionable intelligence for incident commanders. Current systems often present raw data without contextual interpretation, forcing responders to manually synthesize information from multiple sources during high-stress situations. This disconnect between data processing and operational decision-making represents a fundamental limitation in current disaster management frameworks.

Energy efficiency challenges span multiple system components and operational phases of disaster response:

- Network-level constraints: Energy consumption in wireless sensor networks is heavily influenced by communication patterns, with data transmission representing the most power-intensive operation. In damaged infrastructure environments, maintaining connectivity often requires increased transmission power, creating a negative feedback loop that rapidly depletes limited energy resources. Recent advances demonstrate that intelligent caching strategies can significantly reduce redundant data transmission [40]. Specifically, the framework proposed by [40] eliminates the need for UAVs to return to base stations for energy replenishment and content reloading through integrated Wireless Power Transfer and RISs. Their Softmax-based probabilistic caching strategy optimizes content placement based on request popularity while preventing redundant storage across UAVs.
- UAV-specific challenges: Traditional UAV operations in disaster scenarios are severely constrained by limited flight endurance, with energy consumption patterns varying dramatically based on payload, weather conditions, and mission profile. The critical insight from recent research is that energy management must be integrated with task planning rather than treated as a separate constraint [40]. The MADRL approach for optimizing UAV trajectories demonstrates how energy-aware path planning can extend operational availability without compromising mission effectiveness.
- System-level coordination: The most promising energy efficiency improvements come from holistic system design that coordinates energy management across IoT sensors, UAV platforms, and ground infrastructure. This requires moving beyond component-level optimization to consider energy flows across the entire response ecosystem. The emerging concept of cooperative energy management, in which UAVs can receive energy and data directly from base stations via line-of-sight links or through ground-vehicle-mounted RISs in non-line-of-sight scenarios, represents a paradigm shift in how we conceptualize energy constraints in disaster response systems [40].

Although disaster management is commonly structured into discrete pre-disaster, during-disaster, and post-disaster phases, the analysis presented in Table V demonstrates that technological applications rarely operate within strict temporal boundaries. Instead, most systems exhibit either phase-specific behavior or phase-persistent functionality, requiring adaptive configurations across the disaster lifecycle. This distinction is essential for understanding not only when technologies are deployed, but how they evolve in response to changing operational demands.

More specifically, the results indicate that IoT-based sensing systems (green cluster) and communication infrastructures tend to exhibit strong phase-persistent characteristics, supporting continuous monitoring and data exchange across all stages. In contrast, UAV-based systems (blue cluster) are primarily phase-specific during the response phase but increasingly transition toward persistent roles in post-disaster assessment and logistics. Meanwhile, remote sensing and AI-driven systems (red cluster) operate as cross-phase enablers, integrating large-scale data acquisition with predictive and decision-support capabilities.

Across all clusters, several recurring challenges emerge, particularly related to interoperability between heterogeneous platforms, real-time multimodal data fusion, and energy constraints in distributed and aerial systems. These limitations highlight the need for integrated architectures capable of maintaining operational continuity without requiring system replacement between phases. Consequently, the convergence of UAV, IoT, and AI technologies represents a critical pathway toward the development of adaptive, resilient, and phase-persistent earthquake management systems.

VII. CONCLUSION

Earthquakes remain among the most destructive natural hazards, requiring rapid, adaptive, and resilient technological solutions to enhance preparedness, response efficiency, and post-disaster recovery. Despite the substantial body of research in literature, significant challenges persist in reducing risks to human life, managing operational constraints during emergencies, and strengthening the resilience of vulnerable urban and infrastructure systems. In this context, the effective integration of rapidly evolving sensing, communication, and aerial monitoring technologies represents a critical priority for advancing earthquake-disaster management strategies.

This study has provided a comprehensive synthesis of recent developments in wireless communication technologies, with particular emphasis on the complementary roles of IoT sensing infrastructures and UAV-based monitoring platforms across the earthquake-management lifecycle. The analysis highlights the important contributions of signal processing techniques, distributed sensor networks, remote sensing systems, robotics, artificial intelligence, social-network–assisted situational awareness, and UAV-enabled aerial operations in supporting both preparedness and response activities. At the same time, the study identifies persistent technical and operational challenges, including regulatory constraints, environmental limitations, hardware resource restrictions, and coordination complexity, that continue to hinder large-scale and reliable deployment of these technologies in real-world earthquake scenarios.

Future work should prioritize the integration of AI-enabled autonomous monitoring systems, edge-computing architectures for low-latency data processing, and hybrid terrestrial–aerial communication frameworks capable of maintaining connectivity under infrastructure-failure conditions. Such developments are essential for improving responsiveness, interoperability, and system-level resilience in next-generation earthquake-management platforms. To support the

TABLE V. INTEGRATED TECHNOLOGY FRAMEWORK ACROSS EARTHQUAKE DISASTER PHASES

Bibliometric Cluster	Technology Category	Pre-disaster Phase	During-disaster Phase	Post-disaster Phase	Phase Characteristic	Critical Technical Requirements	Research Gaps	Deployment Priorities
Remote sensing and AI-driven analysis (Red cluster)	Seismic monitoring	Continuous monitoring with accelerometers (ADXL362, EPSON M-A351AU) Early warning systems Structural health baseline data collection	Real-time seismic activity monitoring Initial damage prediction Alert dissemination	Damage verification Secondary collapse risk assessment	Phase-Specific → Phase-Persistent	Communication: LoRaWAN, MQTT IoT Sensing: Environmental type, 1-10 Hz sampling, Moderate accuracy UAV selection: Fixed wing for regional assessment, Hybrid for mixed terrain	Interoperability: Inconsistent data formats across platforms Data fusion: Spatiotemporal misalignment between sensing modalities Energy: High computational demands on edge devices	1. Standardize data exchange protocols for geospatial disaster data 2. Develop explainable AI interfaces for emergency responders 3. Optimize AI models for edge deployment through quantization
	AI-driven analysis	Risk assessment modeling Simulation and prediction Resource allocation planning	Real-time resource deployment Dynamic path planning Situational awareness	Damage assessment Prioritization of recovery efforts Resource allocation	Phase-Persistent	Communication: LoRaWAN, MQTT IoT Sensing: Environmental type, 1-10 Hz sampling, Moderate accuracy UAV Selection: Fixed-wing for large-area assessment	Interoperability: Limited integration between AI analysis and field systems Data fusion: Balancing computational complexity with response speed Energy: High energy consumption of AI models on edge devices	1. Standardize data exchange protocols 2. Develop explainable AI interfaces 3. Optimize AI models for edge deployment
IoT-based systems (Green cluster)	Seismic sensing	Baseline seismic monitoring Early warning system deployment Network calibration	Real-time seismic wave detection Earthquake characterization Alert generation	Aftershock monitoring Ground stability assessment	Phase-Specific → Phase-Persistent	Sampling Rate:100–200 Hz Reliability: Extreme (life-critical) Power budget: Extreme (must operate continuously for years) Placement strategy: At the bedrock level, fault lines, and critical infrastructure	Protocol level: Fragmented communication protocols for seismic data Platform level: Hardware interface challenges for deep-earth sensors Sensing level: Limited sensor sensitivity at extreme depths Decision level: Delayed alert dissemination due to processing latency	1. Standardize seismic data formats across monitoring networks 2. Implement predictive maintenance for seismic sensors 3. Develop low-power seismic monitoring solutions for remote areas
	Structural health monitoring	Building instrumentation Baseline structural assessment Monitoring system installation	Real-time structural integrity monitoring Damage progression tracking Immediate safety assessment	Detailed structural damage assessment Repair progress monitoring Reconstruction verification	Phase-Specific → Phase-Persistent	Sampling rate: 1–10 Hz Reliability: Very high (safety-critical) Power budget: High (must operate through main power failure) Placement strategy: Strategic points on structural elements (beams, columns, joints) Communication overhead: Medium (event-triggered with periodic checks) Communication: Zigbee, 6LoWPAN UAV selection: Middleweight multi-rotor for structural inspection	Protocol level: Inconsistent structural health data standards Platform level: Hardware interface challenges for embedded sensors Sensing level: Signal interference from building materials Decision level: Disconnect between raw sensor data and actionable structural assessments	1. Implement Software-Defined Networking for dynamic protocol adaptation 2. Establish calibration protocols for disaster-specific sensor networks 3. Develop structural health monitoring standards for earthquake-prone regions

	Human health monitoring	Resource pre-positioning Team training Planning	Initial victim location Immediate rescue operations Situational awareness	Continued victim location Complex rescue operations Logistics support	Phase-Persistent	Sampling rate: 1–5 Hz Reliability: High (life-critical) Power budget: Extreme (wearable constraints) Placement strategy: On victims, responders, and medical teams Communication Overhead: Medium (intermittent transmission with emergency bursts) Communication: BLE, Zigbee UAV selection: Multi-rotor (quad/hexacopter) for urban search and rescue	Protocol level: Lack of standardized victim information formats Platform level: Energy constraints for wearable sensors Sensing level: Environmental interference with biometric readings Decision level: Disconnect between processed data and actionable intelligence	1. Develop unified data-to-decision frameworks for victim location 2. Implement context-aware data fusion techniques for biometric monitoring 3. Optimize energy harvesting for wearable rescue sensors
	Environmental context sensing	Baseline environmental monitoring Weather pattern analysis Pollutant level tracking	Real-time hazard monitoring Smoke detection Water level monitoring Visibility assessment	Environmental recovery monitoring Air quality assessment Water safety verification Pathway obstruction detection	Phase-Persistent	Sampling rate: 1–10 Hz Reliability: Moderate High Power budget: Moderate Placement strategy: Strategic environmental points (water sources, air quality zones, debris fields) Communication Overhead: Medium (event-triggered with periodic checks) Communication: LoRaWAN, MQTT UAV selection: Fixed wing for regional environmental assessment	Protocol level: Inconsistent environmental data standards Platform level: Sensor durability in extreme conditions Sensing level: Crosscalibration of environmental sensors Decision level: Integration of environmental data into operational decisions	1. Standardize environmental data formats for disaster response 2. Develop ruggedized environmental sensors for disaster zones 3. Implement context-aware environmental data fusion techniques
UAV operations and mission planning (Blue cluster)	Communication restoration	Infrastructure hardening Backup network planning Regular system testing	Emergency communication activation Network degradation monitoring Dynamic rerouting	Communication restoration Temporary network deployment Infrastructure repair coordination	Phase-Persistent	Communication: Ad hoc networks, UAV relays IoT Sensing: Environmental type, 1-10 Hz sampling, Moderate accuracy UAV Selection: Hybrid or heavy-lift multi-rotor for communication restoration	Protocol level: Lack of standardized UAV-ground communication Platform level: Energy constraints limiting operational endurance Sensing level: Limited sensor payload capacity Decision level: Manual processes slowing response	1. Develop unified UAV communication protocols 2. Integrate Wireless Power Transfer and RIS technology 3. Implement multi-UAV coordination strategies for energy-aware task allocation
	Search and rescue support	Pre-deployment planning Route mapping Infrastructure baseline imaging	Initial damage assessment Search and rescue initiation Situational awareness establishment	Detailed damage assessment Search and rescue continuation Logistics support	Phase-Specific → Phase-Persistent	Communication: Ad hoc networks, UAV relays IoT sensing: Human health type, 1-5 Hz sampling, High accuracy UAV selection: Multi-rotor (quad/hexacopter) with thermal cameras	Protocol level: Inconsistent data formats across platforms Platform level: Hardware interface challenges Sensing level: Spatiotemporal misalignment between sensing modalities Decision level: Lack of explainability in AI models	1. Develop UAV-swarm coordination protocols for dense urban environments 2. Implement energy-aware mission planning for extended operations 3. Optimize sensor payloads for SAR operations in GPS-denied environments

AI, artificial intelligence; ADXL362 and EPSON M-A351AU, analog devices as a low-power sensor, and a high-precision sensor, respectively; BLE, bluetooth low energy; GPS, global positioning system; Hz, hertz; IoT, internet of things; 6LoWPAN, IPv6 (Internet Protocol version 6) over low-power wireless personal area networks; LoRaWAN, low range wide area network; MQTT, message queuing telemetry transport; RIS, reconfigurable intelligent surfaces; SAR, search-and-rescue; UAV, unmanned aerial vehicle.

transition toward operationally deployable smart disaster-response ecosystems, this review proposes a structured three-stage research and development roadmap: Stage 1: Foundational Interoperability (1–2 years); Development of standardized communication protocols for seamless data exchange between heterogeneous IoT sensor networks and UAV platforms, establishment of common data formats for structural health monitoring, and implementation of energy-aware networking protocols that adapt to infrastructure damage. Stage 2: Integrated Response Systems (2–5 years); Deployment of hybrid terrestrial-aerial communication frameworks that maintain connectivity during infrastructure failure, development of multi-UAV coordination systems with energy-aware task allocation, and implementation of real-time multimodal data fusion for comprehensive situational awareness. Stage 3: Autonomous Decision Support (5+ years); Creation of AI-powered decision support systems with explainable reasoning, predictive models that integrate seismic data with structural assessments to forecast secondary risks, and fully autonomous UAV swarms for coordinated search and rescue operations.

This staged framework reflects the fact that immediate improvements can be achieved through enhanced interoperability and communication resilience, whereas advanced autonomous coordination capabilities will depend on longer-term progress in artificial intelligence, edge intelligence, and distributed aerial robotics. Overall, the convergence of IoT sensing networks with UAV-enabled monitoring platforms represents a significant step toward more resilient, adaptive, and data-driven earthquake management systems. As these technologies continue to mature, they are expected to enable faster situational awareness, more accurate damage assessment, and more coordinated emergency response operations, ultimately contributing to reduced casualties and accelerated recovery processes in earthquake-prone regions worldwide.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Artificial Intelligence Usage Statement: The authors declared that no artificial intelligence tool was used in the preparation, writing, editing, or revision of the manuscript.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – N.E.H.B. and D.Y.-K.; Design – N.E.H.B.; Supervision – S.B.-K. and D.Y.-K.; Resources – S.B.-K., N.E.H.B., and D.Y.-K.; Materials – N.E.H.B. and D.Y.-K.; Data Collection and/or Processing – N.E.H.B. and S.B.-K.; Analysis and/or Interpretation – N.E.H.B.; Literature Search S.B.-K., N.E.H.B., and D.Y.-K.; Writing – N.E.H.B. and D.Y.-K.; Critical Review – S.B.-K.

Declaration of Interests: The authors have no conflict of interest to declare.

Funding: The authors declare that this study has received no financial support.

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