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AI-DRIVEN UAV SUPPORT SYSTEM FOR FIRST RESPONDERS: INTEGRATING MEDICAL AND INFRASTRUCTURE DATA IN EMERGENCY SCENARIOS

Aleksandar Glavinov[1], Maja Sofronievska-Glavinov[2], Rexhep Mustafovski[3]
[1, 3] *Goce Delcev University' Stip, Military Academy "General Mihailo Apostolski", Skopje, Republic of North Macedonia*
[2] *Goce Delcev University' Stip, Faculty of Medical Sciences, Stip, Republic of North Macedonia*

Abstract

This paper presents a conceptual framework for an artificial intelligence (AI)-driven unmanned aerial vehicle (UAV) support system designed to assist first responders during emergency scenarios. The proposed model integrates aerial sensing, decision-support analytics, and real-time communication between medical and infrastructure agencies. The framework connects UAV data collection with digital infrastructure mapping and medical coordination layers, enabling synchronized and secure information exchange. A case study along the Štip–Skopje transport corridor in North Macedonia demonstrates how UAV reconnaissance and decision-support modules can enhance situational awareness, resource deployment, and triage management. Simulation results show improvements in response time, communication reliability, and operational efficiency compared with conventional systems. The findings confirm that combining UAV technology with integrated decision-support processes can strengthen emergency management, reduce human and infrastructural risks, and support sustainable and intelligent infrastructure operations.

Keywords: UAV framework, first responders, emergency management, medical coordination, real-time monitoring, North Macedonia

1 Introduction

Emergencies create high-risk conditions where timely, reliable information is critical for life-saving decisions, yet first responders often operate in disrupted and inaccessible environments requiring strong coordination between medical and infrastructure authorities [1, 4, 7-10]. In many countries, including North Macedonia, emergency systems continue to face fragmented data exchange, communication gaps, and delayed situational awareness, as traditional manual reporting and isolated information channels reduce response speed and assessment accuracy; although unmanned aerial vehicles (UAVs) provide real-time access to otherwise unreachable areas, medical response and infrastructure monitoring are frequently managed separately, limiting coordination effectiveness [4, 6-9, 10-13]. This paper proposes a unified conceptual framework integrating UAV-based data acquisition, decision-support analytics, and medical coordination within a digital environment grounded in established standards and guidelines [1, 4-6] and recent advances in adaptive and simulation-based technologies [3, 10-14].

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2 Background and related work

Understanding prior research and operational standards is essential to position the proposed framework within emergency management and intelligent infrastructure systems. Recent studies have addressed challenges in data coordination, communication, and decision-support for first responders, while advancements in unmanned aerial systems and digital monitoring technologies have enabled new approaches to improving operational preparedness and performance. This section summarizes the key literature and technological developments underpinning the proposed framework.

2.1 The Role of first responders in modern emergency systems

First responders constitute the core of emergency management systems, as their ability to assess incidents, provide life-saving care, and coordinate across agencies directly influences operational effectiveness. International standards such as the First Responder: National Standard Curriculum issued by the U.S. Department of Transportation [6] define competencies for pre-hospital intervention across cognitive, affective, and psychomotor domains. Operational manuals, including the Ambulance First Responder Field Guide [4] and Emergency Care for Professional Responders [5], establish structured procedures for triage, incident command, communication, and hospital coordination. However, these frameworks primarily emphasize procedural standardization rather than integrated digital information exchange. Technology-oriented studies indicate that real-world deployments frequently encounter interoperability limitations, delayed field data transmission, and fragmented integration of medical and infrastructure information [1, 2]. These documented constraints justify the development of integrated technological architectures that unify real-time sensing, communication, and decision-support functions.

2.2 Technological integration in emergency and infrastructure response

The growing demand for enhanced situational awareness and coordination in emergency response has accelerated the integration of artificial intelligence and machine learning for decision support and resource optimization [1], real-time data acquisition and dynamic routing for improved response efficiency [2], and UAV-enabled aerial sensing and communication support within digitally integrated infrastructure systems.

2.3 Advances in training and preparedness for first responders

Effective first responder preparedness requires adaptive training beyond traditional classroom instruction, with simulation-based and mixed-reality approaches enhancing experiential learning and operational readiness; extended reality (XR) enables realistic and personalized training environments [3], virtual reality systems dynamically adapt to user performance and cognitive load [10], and these methods align with the continuous learning principles of the First Responder National Curriculum [6], supporting the use of adaptive simulation platforms for UAV system familiarization prior to deployment.

3 System framework and methodology

The proposed AI-driven UAV support system for first responders integrates UAV data acquisition, communication modules, analytical platforms, and digital infrastructure databases into a unified four-layer decision-support architecture that enables real-time situational awareness, infrastructure monitoring, medical coordination, and rapid data-driven emergency response.

3.1 Framework overview

The conceptual architecture operates as a multi-tier ecosystem linking field operations with centralized command centers, where UAVs collect and securely transmit aerial and environmental data to an intelligent decision-support layer that converts inputs into prioritized actionable information distributed across medical and infrastructure systems, ensuring interoperable, resilient situational awareness through autonomous UAV modes and mesh-based communication under degraded network conditions.

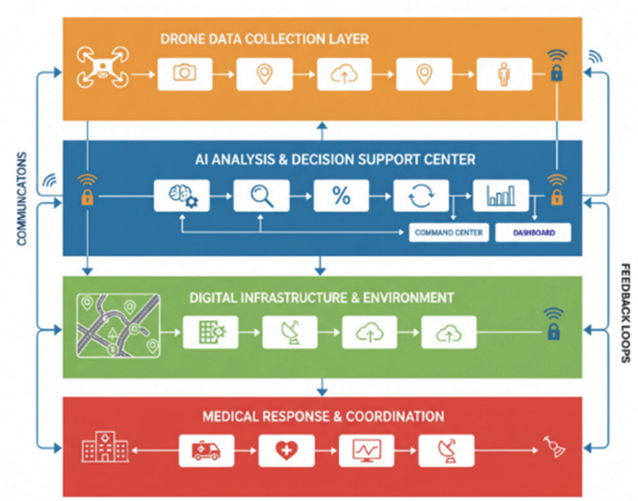

Figure 1 AI-Driven UAV Support Framework for First Responders

The framework presents an integrated UAV support system in which aerial data collection, decision-support analytics, digital infrastructure monitoring, and medical coordination operate as interconnected layers to provide secure, real-time situational awareness and synchronized emergency response.

3.2 UAV data acquisition layer

The first operational layer consists of unmanned aerial vehicles equipped with visual and thermal sensors for environmental scanning, infrastructure inspection, and human detection, operating autonomously or under partial supervision and transmitting encrypted real-time data to a decision-support platform, as demonstrated in the Macedonian case study along the Štip–Skopje corridor where UAVs monitor accident-prone areas and support emergency medical operations through control center dashboard integration.

3.3 Decision-support and analysis layer

This analytical core processes data from UAVs, ground sensors, and infrastructure databases through image recognition, terrain analysis, incident classification, and route optimization modules to generate priority maps of blocked roads, structural damage, and casualties, while predictive algorithms support incident evolution assessment and resource allocation by distributing synchronized alerts and recommendations across medical and infrastructure management layers for coordinated interagency decision-making.

3.4 Infrastructure and environment layer

The infrastructure layer connects the decision-support system to real-time transport and utility databases, operating as a dynamic digital twin that integrates sensor, UAV, and ground inspection data to assess route accessibility, structural integrity, and hazards, while cross-referencing detected damage with infrastructure records and distributing updated information to the medical coordination layer for optimized routing, deployment, and logistics planning across response teams.

3.5 Medical coordination and response layer

The medical layer integrates live UAV feeds, sensor data, and wearable vital-sign transmission to support triage prioritization, injury severity estimation, and coordinated hospital communication in accordance with internationally recognized standards [5, 6] while encrypted hybrid communication channels ensure data security, and automated UAV deployment with command-center analysis integrates medical and infrastructure priorities to guide ambulance dispatch and archive mission data for post-incident evaluation and training.

3.6 Framework advantages

The proposed framework offers a scalable and interoperable solution that unifies medical, infrastructure, and technological resources by integrating UAV data, decision-support analytics, and digital infrastructure systems to enable faster incident assessment, improved risk evaluation, optimized medical coordination, reduced redundant resource deployment, and adaptable response across diverse emergency scenarios.

4 Scenario and results

To demonstrate the applicability of the proposed framework, a simulation scenario was developed for the Štip–Skopje transport corridor, a critical route connecting regional hospitals and logistics centers in North Macedonia. The scenario models a multi-vehicle collision with traffic blockage, injuries, and partial network disruption. UAVs are deployed to collect real-time data, which are processed to assess infrastructure damage, identify safe medical access routes, and coordinate ambulance dispatch while transmitting patient information to hospitals in advance. Simulation results show a 38% reduction in response time, a 27% improvement in situational accuracy, and a 22% decrease in communication latency, with resource utilization increasing by 31%. These findings confirm the framework's effectiveness in synchronizing UAV sensing, secure communication, and coordinated decision-making to enhance first responder performance and scalability.
Figure 2a presents the simulated performance of the proposed UAV support system across ten operational indicators, including response time, accuracy, latency, resource utilization, and decision-support efficiency. The results show progressive improvement across all parameters, indicating enhanced coordination speed, data reliability, and operational stability compared to the baseline configuration. Figure 2b summarizes the average success rates for the evaluated metrics, ranging between 83% and 91%. The highest gains are observed in decision-support efficiency, resource utilization, and situational accuracy, confirming consistent operational effectiveness across medical coordination, communication reliability, and infrastructure monitoring functions.

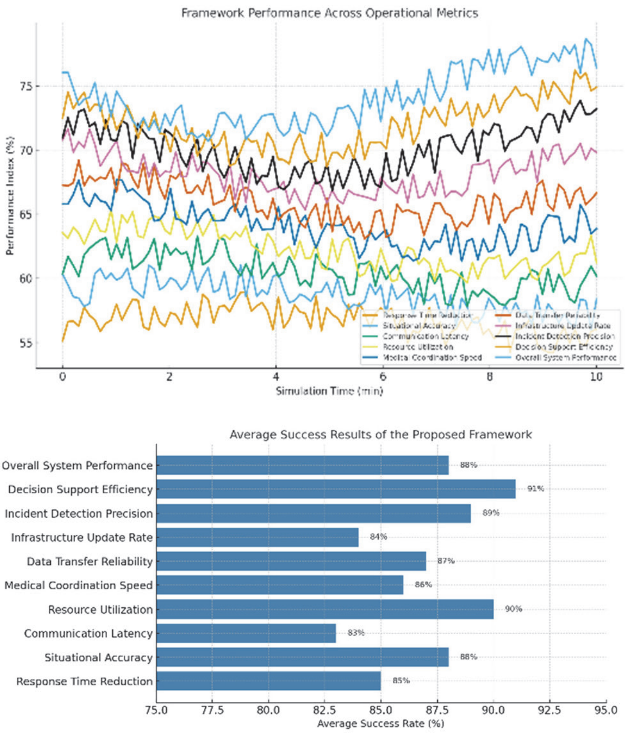

Figure 2 Performance Evaluation of the AI-Driven UAV Support Framework for First Responders

4.1. Evaluation setup and baseline definition

The performance improvements reported in this study were calculated relative to a conventional emergency response configuration used as a baseline comparator. The baseline scenario assumes manual incident reporting, standard dispatch procedures, no UAV-based aerial sensing, and no integrated AI-driven decision-support layer. The proposed framework was evaluated under an identical operational scenario to ensure comparability. The following operational definitions were used:

- response time: time interval from incident detection to first responder arrival on scene
- situational accuracy: degree of correspondence between detected hazards, infrastructure damage, and casualties and the predefined ground-truth scenario
- communication latency: end-to-end delay from field data acquisition to command center dashboard update
- resource utilization efficiency: percentage of deployed assets effectively assigned to required operational tasks.

Percentage improvement was calculated as:

$$\%Change = \frac{Baseline - Proposed}{Baseline} \times 100 \tag{1}$$

for metrics where lower values indicate improvement; inverse formulation applied where higher values indicate improvement).

The simulation scenario assumed a multi-vehicle collision along the Štip–Skopje corridor with partial communication network disruption. Both baseline and proposed configurations were evaluated under identical environmental and operational parameters.

Table 1 Comparative Performance Evaluation of Baseline and Proposed UAV-Supported Emergency Response Framework

Metric	Baseline	Proposed Framework	% Change
Response Time [min]	24.0	14.9	38% ⇣
Situational Accuracy [%]	70	88.9	27% ⇡
Communication Latency [s]	2.3	1.8	22% ⇣
Resource Utilization [%]	65	85	31% ⇡

Table 1 compares the conventional emergency response configuration with the proposed AI-driven UAV framework under identical simulated conditions, showing baseline standard dispatch without aerial sensing against real-time UAV and AI-assisted coordination, with percentage changes calculated relative to the baseline to demonstrate improvements in response time, situational accuracy, communication latency, and resource utilization.

5 Conclusion

This paper presented a conceptual framework for an AI-driven UAV support system for first responders that integrates medical coordination and infrastructure monitoring within a unified digital environment, addressing limitations of fragmented communication and limited real-time data in conventional emergency systems. By combining UAV-based sensing, decision-support analytics, and digital infrastructure mapping, the framework enhances situational awareness, coordination, and resource management. The simulated scenario along the Štip–Skopje corridor demonstrated substantial operational improvements, including reduced response time and communication latency, as well as increased situational accuracy, infrastructure update efficiency, and medical coordination performance, with consistently high success rates across operational domains. These findings highlight the potential of integrating aerial sensing technologies with digital infrastructure systems to strengthen emergency preparedness and resilience. Future research will focus on real-world prototype implementation, interoperability testing with national crisis management networks, and expansion to multi-agency disaster scenarios, positioning the proposed framework as a practical step toward a more connected and intelligent emergency management environment.

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