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# Rescue drone swarm design for innovative disaster management and rescue operations

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## ABSTRACT

Conventional emergency response strategies are often constrained by limited operational coverage, slow resource mobilization, and fragmented data acquisition, which hinder coordination effectiveness during critical phases. This study proposes the design of an autonomous drone swarm system to support innovative disaster management and rescue operations. A coordinated multi-agent-based system was designed to perform real-time monitoring, structured search and rescue, and post-disaster infrastructure evaluation. Rule-based behavioral modeling is used in complex emergency scenarios such as natural disasters. The initial simulation results showed greater area coverage, accelerated response times, and increased mission adaptability under dynamic conditions. The system is also designed to deliver logistical assistance, such as food and medicine, to hard-to-reach areas, such as ravines or steep mountains. The integration of artificial intelligence algorithms improves target identification precision and adaptive swarm response. This model is considered to have the transformational potential to be the foundation for the development of future rapid-response autonomous rescue systems.

**Keywords:** Drone swarms, disaster management, multi-agent systems, artificial intelligence, emergency response

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RESEARCH & PUBLISHING

## 1. INTRODUCTION

The increasing frequency and severity of natural and industrial disasters have exposed the limitations of conventional disaster management systems that rely on human intervention and ground-based resources. Advanced technological solutions are urgently required to enhance the response speed and operational accuracy in hazardous environments. Recent advancements in unmanned aerial vehicles (UAVs) have introduced new possibilities for disaster mitigation using aerial mapping, surveillance, and logistics. Among these, autonomous yet coordinated UAV swarm drone systems offer a transformative approach by enabling real-time communication, dynamic task sharing, and collective adaptation in complex scenarios.

As the frequency and intensity of disasters continue to escalate, the limitations of conventional disaster management systems, which rely on ground-based resources and manual coordination, have become increasingly evident, leading to slow responses and limited coverage in large-scale or complex events (Latue, Manakane, & Rakuasa, 2023). The 2011 Tōhoku Earthquake and tsunami highlighted critical lessons in risk management, emphasizing community engagement through initiatives such as machizukuri as a key component of disaster mitigation (Siawsh, Peszynski, Vo-Tran, & Young, 2023a). Mitigation strategies must integrate both structural measures, such as seawall construction, and nonstructural approaches, such as evacuation planning (Kiyono, 2021). Persistent gaps in preparedness, especially for large-scale disasters, remain a concern (Bachev, 2021). Despite improvements, such as disaster psychiatric teams and enhanced mental health services (Kunii et al., 2022). Knowledge-sharing, child-focused education programs (Ishiwatari, Ranghieri, Taniguchi, & Mimura, 2021) (Nagata, Ikeda, Kimura, & Oda, 2022). Conversely, several post-disaster challenges have been identified, including respiratory infections in evacuation centers (Mavrouli, Mavroulis, Lekkas, & Tsakris, 2021), and weak coordination between governmental bodies and relief organizations (Siawsh, Peszynski, Vo-Tran, & Young, 2023b). Collectively, these lessons serve as a critical foundation for formulating future global disaster preparedness and response strategies (Latue et al. 2023).

In such contexts, the demand for faster and more effective response mechanisms is undeniable and must be addressed. The integration of advanced technologies into emergency operations has emerged as a critical strategic approach to address the urgent need for adaptive and efficient rescue systems. Real-time data acquisition, enhanced coordination, and improved disaster management have been facilitated through the application of the Internet of Emergency Services (IoES) and Uncrewed Aircraft Systems (UAS)(Damaševičius, Bacanin, & Misra, 2023) (Kiyono, 2021). Communication technologies such as near-vertical incidence skywave and drone-based wireless mesh networks have been deployed to maintain connectivity under extreme conditions (Carreras-Coch, Navarro, Sans, & Zaballos, 2022). The adoption of cutting-edge technologies, such as artificial intelligence (AI), the Internet of Things (IoT), and big data analytics, has further optimized planning, resource mobilization, and management during crises (Fosso Wamba et al., 2021). While telehealth services have proven vital in reducing disease transmission, adoption barriers persist(Maleka & Matli, 2024). Smart city frameworks and Internet of Medical Things (IoMT) architectures have also been leveraged to address urban health challenges and medical emergencies ( Ijiga et al., 2024) (Niu et al., 2024). However, critical concerns regarding cost-effectiveness, data security, privacy protection, and digital divides must be urgently addressed to maximize the benefits of these technologies in crisis management (Hassankhani, Alidadi, Sharifi, & Azhdari, 2021). Collectively, these challenges and opportunities underscore the need to develop innovative and adaptive swarm drone rescue systems capable of operating across diverse disaster scenarios.

Moreover, the complexity of modern disasters, often involving cascading threats such as secondary fires or chemical spills, has overwhelmed conventional systems. These scenarios require real-time information, adaptive response strategies, and rapid, precise decision-making that often exceed human operational capacities (Burger, Kennedy, & Crooks, 2021), (Hong, Park, Ju, & Lee, 2024). Traditional approaches have proven inadequate in addressing interconnected physical, social, and environmental risks, highlighting the need for integrated frameworks capable of managing cross-sectoral, multidimensional crises (Kruczkiewicz et al., 2021). In this context, the development of swarm drone rescue systems has emerged as an inevitable technological solution to unresolved systemic challenges in disaster response infrastructure.

Advanced technologies play an increasingly critical role during the recovery phase. Conventional methods of damage assessment, infrastructure restoration, and humanitarian aid distribution remain reliant on slow, error-prone manual inspections (Kang, Fischer, Olsen, Adams, & O'Neil-Dunne, 2024), (Al Shafian & Hu, 2024). Integrating disruptive technologies throughout the disaster management cycle is now considered essential for enhancing post-crisis evaluation and reconstruction processes (Vermiglio, Noto, Rodríguez Bolívar, & Zarone, 2022). While Management Information Systems support strategic decision-making and resource distribution, technical barriers such as data interoperability persist (A.A, n.d.). Consequently, the development of autonomous and precise swarm drone systems for damage mapping has become both relevant and urgent to ensure a strategic and integrated recovery phase (Vermiglio et al. 2022).

Therefore, the integration of advanced technologies, such as swarm drones, artificial intelligence, and real-time data analytics, is now regarded as essential. These technologies enhance situational awareness, accelerate coordination, and enable faster decision-making, collectively strengthening the effectiveness of disaster management (Kang et al., 2024). Studies have demonstrated that multi-unit drone systems equipped with edge intelligence can expedite information processing and adaptively extend communication coverage in the affected areas (Alsamhi et al., 2021). Advanced visual imaging has also improved victim identification accuracy, enabling more rapid and efficient rescue operations (T. Neha, Kavya Panchati, Vaishnavi Mallichetty, Sarika Boyapaty, & Munazza Kausar, 2024). Overall, these technologies have proven instrumental in reinforcing situational awareness, facilitating cross-team coordination, and enabling responsive decision-making, thereby establishing a strategic foundation for innovative swarm-drone-based rescue systems (Kang et al., 2024).

Although technology has long supported rescue operations, its urgency has escalated significantly in recent years. As disasters increase in scale and complexity, the limitations of conventional rescue approaches have become increasingly apparent. Advanced technologies are no longer viewed as supplementary tools but as core components of modern rescue missions. One of the most transformative innovations is the deployment of unmanned aerial vehicles (UAVs) or drones, which enable rapid and precise aerial surveillance, even in areas rendered inaccessible by infrastructure collapse or hazardous conditions (T. Neha et al., 2024) ,(Yucesoy, Balcik, & Coban, 2025). Integrated with artificial intelligence and the Internet of Things, drones are utilized for human detection, environmental monitoring, and real-time data transmission to expedite prioritization and resource allocation during rescue operations(Kumaran, Raj, Raman, & others, 2023) (Alsamhi et al., 2021). In this context, the development of swarm drone rescue systems has emerged as a critical tactical and strategic solution for adaptive, data-driven emergency operations.

Recent advancements in rescue technology have seen drones equipped with thermal imaging cameras emerge as critical components for enhancing search and rescue operations. These systems enable the accurate detection of human body heat concealed beneath debris or dense vegetation, even under hostile environmental conditions (Kumaran et al., 2023). Their effectiveness has been demonstrated globally, including during the 2017 Mexico earthquake, where thermal imaging drones directly contributed to locating survivors (Yucesoy et al., 2025). Overall, the integration of such advanced imaging technologies has accelerated detection processes, expanded mission coverage, and reduced risks for rescue teams, reinforcing the urgency of developing adaptive swarm drone systems for complex disaster scenarios (T. Neha et al., 2024).

Simultaneously, advancements in data analytics and artificial intelligence (AI) have enabled the processing of large, multisource datasets—including from drones, satellites, and ground sensors—for rapid pattern recognition and disaster trajectory prediction (Linardos, Drakaki, Tzionas, & Karnavas, 2022). These predictive capabilities facilitate early evacuation measures before disaster impacts escalate (Abid et al., 2021). The integration of machine learning and remote sensing technologies has further strengthened early warning systems and tactical decision-making in emergencies (Linardos et al., 2022). As a result, AI-driven technologies are no longer supplementary but constitute essential elements of modern intelligent rescue frameworks, underscoring the critical need to develop swarm drone systems as core infrastructure for future disaster response (Velev & Zlateva, 2023)

Robotic technologies have also been deployed to navigate building debris, detect signs of life, and deliver aid to areas inaccessible to human rescuers. Notably, during the 2010 Haiti earthquake, rescue robots were utilized to explore rubble and provide critical data to response teams (Chitikena et al., 2023) . Equipped with thermal sensors, LiDAR, and RGB-D depth cameras, rescue robots—including quadruped and snake-type robots—have demonstrated effectiveness in navigating hazardous environments and detecting life signs. A significant application of this technology was observed during the 2010 Haiti earthquake, where SAR robots were used to search through debris and relay vital data to rescue personnel (Surmann et al., 2024). These experiences confirm that integrating robotics with advanced sensory intelligence forms a vital foundation for developing future intelligent, adaptive, and responsive rescue systems.

Geospatial technologies, such as Geographic Information Systems (GIS), have been integrated into rescue operations to provide detailed maps indicating hazardous areas, evacuation routes, and safe zones. Advancements in communication technologies have significantly enhanced coordination capabilities during rescue missions, particularly through satellite-based systems, mobile command centers, and mesh networks. Communication barriers—previously critical obstacles in rescue operations—can now be substantially minimized through heterogeneous communication architectures combining Ubiquitous Sensor Networks with drone technologies (Carreras-Coch et al., 2022). Integrated platform-based emergency communication approaches have also been recommended to ensure information continuity amid extreme conditions and infrastructure failures (Wang et al., 2023). The synergy between swarm drone systems and the Internet of Things (IoT) further underscores the significant potential of these technologies in maintaining real-time connectivity, a critical factor in rapid decision-making during rescue operations (Alsamhi et al., 2021). Accordingly, designing swarm drone rescue systems with adaptive communication capabilities is an urgent necessity for building resilient and integrated future rescue frameworks.

The integration of GIS with real-time drone data enables dynamic mapping that can rapidly adapt to evolving on-site conditions (Abid et al., 2021). Similarly, combining Geographic Information Systems (GIS) with real-time data collected by drones facilitates dynamic mapping processes that adjust swiftly to changing disaster field conditions (Zangana, Sallow, Alkawaz, & Omar, 2024). Within this framework, swarm intelligence approaches have been applied to address coordination complexity in multi-drone rescue systems, emphasizing decentralized and self-organizing structures (Nguyen, 2024). The ability of drone swarms to perform collective decision-making and efficient task allocation has been recognized as critical in accelerating search, mapping, and data-driven response at disaster sites (Bakar, 2021). With increasing speed, accuracy, and adaptive capacity, UAVs and collective intelligence are no longer supplementary but have become foundational pillars in shaping responsive and predictive modern rescue systems. Thus, technology's role in contemporary rescue operations has become indispensable. Enhancing speed, precision, and coordination, technologies from UAVs to AI are revolutionizing disaster response, with this role expected to grow even more critical as technological advancements continue.

## 2. Understanding Drone Swarm

Drone swarm represents a major advancement in unmanned aerial vehicle (UAV) technology, distinguished by its ability to operate collaboratively in synchronized formations. Unlike single drones functioning independently, swarm systems are designed to act as unified entities, mimicking the collective behaviors observed in nature, such as bird flocks or bee colonies. Through coordinated interaction, these systems can accomplish complex tasks beyond the capabilities of individual drones (Nguyen, 2024). Developed as a significant step in UAV evolution, drone swarm systems emphasize synchronized and autonomous collective operation. In contrast to isolated single-drone missions, swarm drones function as collaborative units that replicate biological swarm behavior using decentralized control principles from swarm robotics (Faria Dias et al., 2021) (Kausar, Ahmad, Zhu, Shahzad, & Eisa, 2023a)(Shahzad et al., 2023) (Kausar, Ahmad, Zhu, Shahzad, & Eisa, 2023b). This dynamic, adaptive interaction allows complex tasks to be executed simultaneously and efficiently, tasks otherwise impractical for single UAVs. Operational efficiency and scalability are further enhanced through swarm intelligence algorithms inspired by natural collective behaviors (Nguyen, 2024) (Lhamo et al., 2024). In modern rescue operations, drone swarms are increasingly recognized not as experimental tools but as critical tactical solutions for large-scale disaster management.

The foundation of drone swarm systems lies in swarm intelligence, a branch of artificial intelligence (AI) that examines the collective behavior of decentralized, self-organizing systems. Natural phenomena, such as ants finding optimal paths to food or birds flying synchronously without centralized leadership, serve as models. Similarly, drones communicate through real-time data exchange and collective behavioral adjustments, enabling rapid adaptation in dynamic operational environments (Nguyen, 2024). Typically, drone swarm systems consist of multiple UAV units equipped with sensors, cameras, and wireless communication modules. These units are interconnected through advanced algorithms that facilitate collective data dissemination and processing. For instance, when one drone detects an obstacle, the information is immediately shared across the swarm, allowing synchronized trajectory adjustments (Brambilla, Ferrante, Birattari, & Dorigo, 2013) (Nguyen, 2024)(Zangana et al., 2024). This interconnection, driven by swarm intelligence algorithms, ensures adaptive, coordinated responses (Nguyen, 2024)(Lhamo et al., 2024). Once any unit detects a hazard, this data is autonomously transmitted throughout the swarm, enabling real-time, decentralized control—modeled after insect colonies or bird flocks (Faria Dias et al., 2021) (Kausar et al., 2023a)(Shahzad et al., 2023)(Kausar et al., 2023b) Given its ability to respond dynamically to changing conditions, drone swarm technology is not only relevant but urgently required for widespread adoption in modern search and rescue missions.

One of the primary advantages of drone swarm systems is scalability. Operational coverage can be expanded by adding more UAV units to the swarm, enabling the system to manage larger areas or more complex tasks. This scalability is particularly relevant in disaster management, where task variability ranges from victim search to wildfire monitoring (Siegwart, Nourbakhsh, & Scaramuzza, 2011). Operational capacity can be significantly extended through the incremental addition of UAV units within the swarm structure, allowing broader area coverage and the management of multidimensional, complex operations. This capability is critical in disaster response scenarios, where tasks vary from locating survivors to tracking the spread of disasters such as fires (Pavitra, Muthukrishnan, Maheswari, Venkatasamy, & Lawrence, 2024). The system's effectiveness arises from simple interactions that generate complex and adaptive collective behavior, eliminating the need for centralized control(Faria Dias et al., 2021). However, despite scalability being a key strength, real-world deployment challenges remain, especially regarding system resilience and simultaneous multitask management (Zangana et al., 2024)

Another essential feature is redundancy. In swarm systems, the failure of one or more units does not disrupt the entire mission, as the remaining units autonomously adjust their formation and assume the missing roles. This inherent robustness makes drone swarms highly suitable for high-risk conditions (Park, Kang, & Choi, 2022). Structural redundancy is embedded within swarm systems, allowing continued operations even if certain units fail. Remaining units dynamically reorganize and compensate for losses without external intervention, enabling high resilience against partial failures—an attribute ideal for deployment in emergency situations and unstructured environments (Wijayathunga, Rassau, & Chai, 2023) (Ding et al., n.d.). This level of robustness has been identified in recent studies as a critical factor for collision-free navigation and sustained long-term mission performance (Belo, Fernandes, Collado, Georgiadis, & Carvalho, 2015).

In addition, drone swarms are designed to operate autonomously with minimal human intervention. Once programmed with mission objectives, the swarm can execute tasks independently. This autonomy is enabled by the integration of AI and machine learning, allowing drones to analyze data, make decisions, and learn from operational experience. For example, in disaster area mapping, the swarm can automatically partition the region into segments, assign tasks to individual drones, and adjust operations according to mission progress (Berman, Halász, Hsieh, & Kumar, 2009). This mechanism allows the swarm to autonomously divide territory, distribute workloads across units, and adapt task execution based on real-time environmental dynamics. Operational resilience has been further enhanced through simultaneous approaches to adaptive task allocation and failure-tolerant mission planning (Faruq, Lacerda, Hawes, & Parker, 2024), as well as predictive models using continuous-time Markov chains to address spatio-temporal uncertainties (Street, Lacerda, Mühlig, & Hawes, 2024). Moreover, reinforcement learning has been effectively applied to optimize large-scale task distribution (Kruczkiewicz et al., 2021), positioning drone swarms as a highly promising AI-driven solution for modern rescue operations. Table 1 presents the key features, descriptions, and operational capabilities of rescue drone swarm systems in disaster management. Each feature is described in terms of its technical function and the corresponding capability contributed to mission effectiveness. The data are structured to highlight how decentralized control, real-time communication, autonomous operation, and advanced sensing collectively enhance system scalability, reliability, and task efficiency during disaster response. Table 1 presents the key features, descriptions, and operational capabilities of rescue drone swarm systems in disaster management. This table was developed to systematically highlight the technological components considered critical for supporting autonomous, scalable, and adaptive multi-drone operations. The inclusion of this table is essential for clarifying the swarm system's role as a core solution in modern disaster response, providing concise insight for both the title and abstract regarding the technological foundation and strategic relevance of drone swarm deployment.

**Table 1. Features, Descriptions, and Capabilities of Rescue Drone Swarms in Disaster Management**

| Feature | Description | Capability |
|---|---|---|
| Swarm Intelligence | Decentralized and self-organizing behavior inspired by biological swarms such as bees or ants. | Enables drones to operate collectively and make data-driven decisions collaboratively without requiring centralized control. |
| Real-Time Communication | Drones communicate and share information instantly via wireless networks. | Facilitates rapid coordination and adjustment among drones in dynamic environments. |
| Scalability | The system can be expanded by adding more drones to the swarm. | Allows wider area coverage or handling of more complex tasks simply by increasing the number of drones. |
| Redundancy | Swarm operation continues even if one or more drones fail. | Mission reliability is enhanced, as remaining drones autonomously reconfigure to compensate for failed units. |
| Autonomy | Missions can be executed with minimal human intervention. | Reduces the need for direct supervision, enabling drones to conduct mapping or search tasks independently. |
| Adaptive Behavior | Drone actions can be adjusted based on environmental changes and real-time data. | Enables drones to respond autonomously to obstacles, mission parameter changes, or unexpected challenges. |
| Task Allocation | Tasks are automatically distributed among swarm members based on data analysis and mission needs. | Optimizes operational efficiency through automatic task assignment tailored to each drone's role and mission demands. |
| Multi-Modal Sensing | Equipped with various sensors such as cameras, thermal imaging, and LiDAR. | Enhances environmental data collection for tasks including mapping, detection, and rescue operations. |
| Coordinated Movementi | Drones move synchronously to maintain formation or target specific areas. | Ensures precise task execution, such as area scanning or perimeter monitoring, through coordinated and synchronized operations. |
| Energy Efficiency | Collective energy management within the swarm optimizes battery usage and mission duration. | Extends operational time, allowing longer missions and reducing the need for frequent recharging. |

In the context of innovative rescue drone swarm design, a high level of autonomy is no longer considered an optional feature but a critical requirement to ensure rapid and effective disaster response. Rescue drone swarms have been engineered for autonomous operation with minimal human intervention through the integration of artificial intelligence and machine learning, enabling intelligent, adaptive, and real-time task allocation. The capability to automatically map affected areas, segment task zones, and adjust the roles of individual drones in real-time positions this technology as essential for dynamic and high-risk environments.System efficiency and resilience are enhanced through simultaneous planning and allocation algorithms designed to respond to unit failures (Faruq et al., 2024), Additionally, proactive allocation frameworks based on Markov chains have demonstrated superior performance in addressing spatial and temporal uncertainties in disaster fields (Street et al., 2024). For large-scale scenarios, reinforcement learning approaches have been strategically implemented to optimize inter-drone role distribution (Kruczkiewicz et al., 2021). Therefore, the development of rescue drone swarms must be regarded as a strategic breakthrough that is not only relevant but urgently needed in addressing increasingly complex disaster scenarios.

## 3. METHOD

In the design framework of rescue drone swarm systems, adaptive search and mapping functions are positioned as the core pillars of disaster response transformation. Conventional approaches relying on human teams or single drones have demonstrated limitations in covering large-scale and high-risk areas. Therefore, the swarm method is developed to enable simultaneous and adaptive multipoint collaboration among drone units. Strategically mounted thermal imaging cameras are utilized to detect human body heat behind debris, as demonstrated during the 2017 Mexico earthquake response. Real-time coordination among drones significantly expands search area coverage while minimizing response time. Additionally, drone swarms are programmed to continuously generate high-resolution maps for damage assessment and data-driven resource allocation prioritization. This model integrates artificial intelligence for automated area segmentation, maximizing efficiency in dynamic mapping and real-time monitoring of on-site developments. Consequently, this approach enhances search effectiveness and strengthens tactical capabilities in modern disaster rescue strategies.

Drone swarm optimization in critical post-disaster phases is realized through functional integration for logistics distribution, secondary risk monitoring, and infrastructure recovery acceleration. When transportation networks collapse, drone swarms function as adaptive airborne distribution networks capable of navigating complex terrain and delivering essential supplies to isolated zones in a coordinated and efficient manner. Through AI-based automatic task allocation algorithms, the swarm system avoids mission redundancy and maximizes delivery speed. Additionally, drones are equipped with atmospheric and hydrological sensors for predictive functions, such as early detection of fire hotspots or river discharge monitoring as part of flood early warning systems. In infrastructure recovery contexts, drone swarms conduct visual and thermal inspections of bridges, power lines, and damaged buildings without exposing personnel to extreme conditions. In rapid recovery scenarios, drone swarms are also employed as equipment carriers to inaccessible high-risk areas. Thus, this method not only reduces risks to human personnel but also accelerates the restoration of essential services, establishing drone swarms as a strategic instrument for precise and sustainable post-disaster reconstruction.

**Figure 1. Visualization of Autonomous Drone Swarm Delivering Medical Aid and Forming Coordinated Formations in Collective Intelligence-Based Rescue Missions.**

Figure 1 strategically illustrates the urgency and capability of drone swarms as intelligent rescue systems capable of collaborative operation in extreme disaster conditions. Their ability to form dynamic formations and simultaneously distribute logistics highlights the transformative value of this technology in enhancing the speed, precision, and sustainability of emergency response operations. The depicted drone swarm implementation is not only relevant for field scenarios such as medical supply delivery to isolated areas but also demonstrates the tangible integration of AI, robotic autonomy, and crisis response directly supporting the methods, research objectives, and the core relevance of the study's title and abstract.

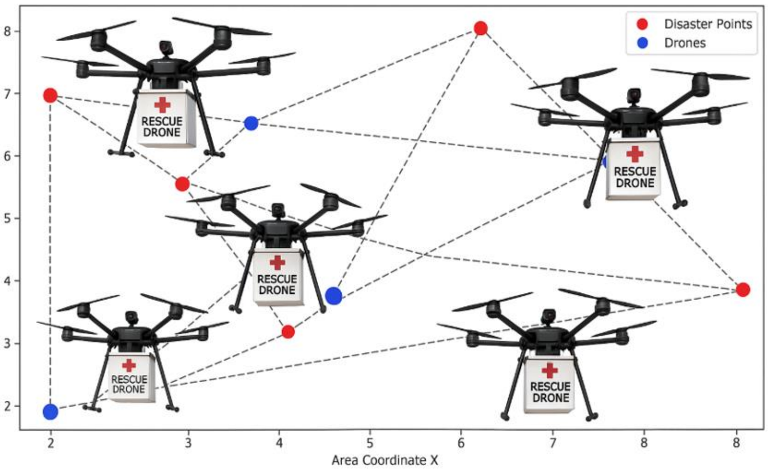

**Figure 2. Drone Swarm in Disaster Management Operations**

Figure 2 illustrates the application of intelligent coordination within drone swarm systems, where disaster points (red) are dynamically mapped and assigned to drone units (blue) via optimal trajectories. This approach represents the practical implementation of swarm intelligence-based task allocation algorithms to enhance response speed and distribution efficiency during rescue operations. Through spatial mapping using area coordinates, drones autonomously and synchronously navigate toward affected sites, even under total infrastructure failure conditions. This figure reinforces the study's methodology and title relevance, emphasizing the strategic urgency of designing drone swarm systems as adaptive and high-precision instruments in disaster management.

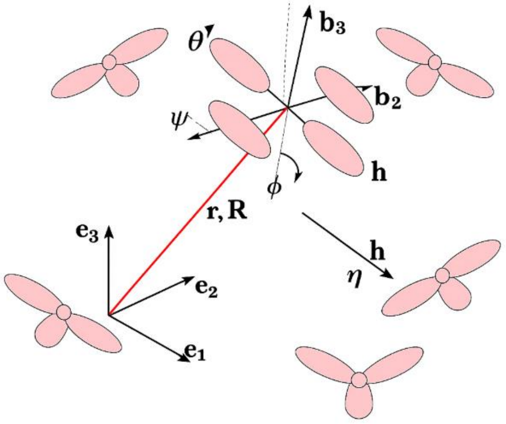

**Figure 3. Reference Coordinate Framework for Rescue Drone Swarm Orientation.**

This diagram illustrates the transformation from the global coordinate system $w = \{\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3\}$, representing spatial translation $\mathbf{r} = [x, y, z]^T$ and rotation $\mathbf{R}(\phi, \theta, \psi)$, to the local coordinate system $b = \{\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3\}$ on each drone. This reference model forms the basis for autonomous position and orientation control of individual rescue drones operating within a swarm formation during emergency missions in dynamic disaster environments.

Figure 3 emphasizes the critical spatial foundation in swarm formation control namely, the transformation from the global coordinate system to each drone's local coordinate frame. Position translation $\mathbf{r} = [x, y, z]^T$ and three-degree-of-freedom rotation $\mathbf{R}(\phi, \theta, \psi)$ enable precise orientation maintenance in rapidly changing disaster scenarios. This model not only supports autonomous navigation algorithms but also serves as a vital component for collective motion synchronization among drones during rescue missions. The visualization underscores the urgency of developing spatial control frameworks based on swarm intelligence, as highlighted in the study's title and abstract, affirming that the effectiveness of future disaster response systems depends on the precision of spatial reference coordinates and the integrated rotational-translational control of each aerial agent. For position and orientation control within 3D space, the position vector **r** and rotation matrix **R** are applied. Position describes the drone's location relative to the world frame, while rotation defines its heading. These notations serve as the foundation for all navigation control within the drone swarm system.

$$\mathbf{r} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \mathbf{R}(\phi, \theta, \psi) \in SO(3) \tag{1}$$

Drones operate in three-dimensional space, requiring orientation to be expressed as rotations about the three axes $(x, y, z)$. The total rotation matrix is obtained by multiplying the individual rotation matrices around each axis. This transformation is essential for converting sensor data from the body frame to the world frame.

$$\mathbf{R} = \boldsymbol{R_z(\psi) R_y(\theta) R_x(\phi)} \tag{2}$$

To ensure directional coordination within a drone swarm, each drone's heading is projected onto the horizontal plane. This heading is utilized in swarm navigation for formation control and collision avoidance.

$$\mathbf{h} = \mathbf{Proj}_{\mathbf{span}(\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2)}(\hat{\mathbf{b}}_1) \tag{3}$$

The heading angle indicates the drone's horizontal orientation relative to the world frame axes. This value is used to estimate the drone's rotation with respect to the virtual north and supports swarm formation control. The atan2 function provides accurate results over the full $360°$ range.

$$\eta = atan2(\hat{\boldsymbol{b}}_1^\top \hat{\boldsymbol{e}}_2, \hat{\boldsymbol{b}}_1^\top \hat{\boldsymbol{e}}_1) \tag{4}$$

Drones possess both translational and rotational velocities. These equations describe position changes based on linear velocity and orientation changes based on angular velocity, forming the core of drone motion in autonomous navigation.

$$\dot{\boldsymbol{r}} = \boldsymbol{v}, \dot{\boldsymbol{R}} = \boldsymbol{R}\hat{\omega} \tag{5}$$

The total forces and torques acting on the drone are described by the Newton-Euler equations. These equations are critical for controller design and maneuver planning, especially when operating under wind disturbances or disaster-induced turbulence.

$$m\ddot{\boldsymbol{r}} = \boldsymbol{f}_{total} + m\boldsymbol{g}, \boldsymbol{J}\dot{\boldsymbol{\omega}} = \boldsymbol{\tau} - \boldsymbol{\omega} \times \boldsymbol{J}\boldsymbol{\omega} \tag{6}$$

Each drone must be optimally assigned to a target location to ensure efficiency. This cost function minimizes the total distance or time required for all drones to reach their assigned rescue points, solved using discrete optimization methods.

$$min \sum_{i=1}^{N} \sum_{j=1}^{M} c_{ij}x_{ij} \text{ s.t. } \sum_j x_{ij} = 1, \sum_i x_{ij} \leq 1 \tag{7}$$

Drones must align their positions or headings with neighboring units to maintain formation. This equation regulates position adjustments based on inter-drone distances, supporting autonomous swarm organization.

$$\dot{\boldsymbol{p}}_i = -\sum_{j \in \mathcal{N}_i} (\boldsymbol{p}_i - \boldsymbol{p}_j) \tag{8}$$

To prevent inter-drone collisions during missions, a repulsive force function is applied when two drones approach too closely. This mechanism is ideal for high-speed, dense, and emergency navigation scenarios.

$$U_{ij} = \begin{cases} \frac{1}{2}\left(\frac{1}{d_{ij}} - \frac{1}{d_0}\right)^2, & \text{if } d_{ij} < d_0 \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

Fuzzy logic-based control is implemented for complex disaster environments. Fuzzy rules can be adapted according to environmental conditions and local sensor data to enhance responsiveness.

$$IF\ (distance_{to_{obstacle}} is NEAR) AND\ (speed\ is\ HIGH) THEN\ (change\ heading\ is\ LARGE) \tag{10}$$

For drone trajectory prediction, machine learning models are employed to estimate future positions. This is essential for automated maneuvering and hazard anticipation.

$$\hat{\boldsymbol{r}}(t + \Delta t) = f(\boldsymbol{r}(t), \boldsymbol{v}(t), \boldsymbol{a}(t)) \tag{11}$$

The orientation of the drone in local and global coordinate systems constitutes a fundamental basis for the navigation and attitude control system. The transformation from the global coordinate frame $w = \{e_1, e_2, e_3\}$ to the drone's local body frame $b = \{b_1, b_2, b_3\}$, through the position translation $r = [x, y, z]^T$ and the Euler rotation $R(\varphi, \theta, \psi)$, serves as an absolute reference for maintaining the drone's orientation while it operates in a disturbance-prone environment. Furthermore, the previously presented framework systematically models the dynamic behavior of the drone swarm, encompassing force, torque, angular momentum, and collective formation control parameters. These equations not only represent real-time changes in the position of each unit but also formalize stability in formation distribution, multi-agent coordination, and simultaneous motion toward the targeted disaster location. The combination of this spatial reference framework (Figure 3) with these formulations facilitates the implementation of swarm control algorithms that are adaptive and robust to dynamic environments. As a result, the swarm-based rescue system is not only responsive to central commands but also capable of evolving autonomously in accordance with situational demands in the field, making it a strategic and innovative solution in modern disaster management..

## 4. RESULTS AND DISCUSSION

Figure 4 illustrates the dynamics of drone orientation changes roll (φ), pitch (θ), and yaw (ψ) as a response to control torques over a 10-second period, based on the mathematical models from formulas 1 to 11. This data confirms that torque and inertia-based control approaches can accurately regulate drone formation movements within rescue swarm scenarios. The combination of spatial translation and rotational models (as shown in Figure 3), along with these simulation results, provides numerical validation of the method's effectiveness in maintaining drone stability and heading in dynamic environments. These findings strongly support the proposed method and reinforce the study's title and abstract within the context of disaster-response drone swarm navigation systems.

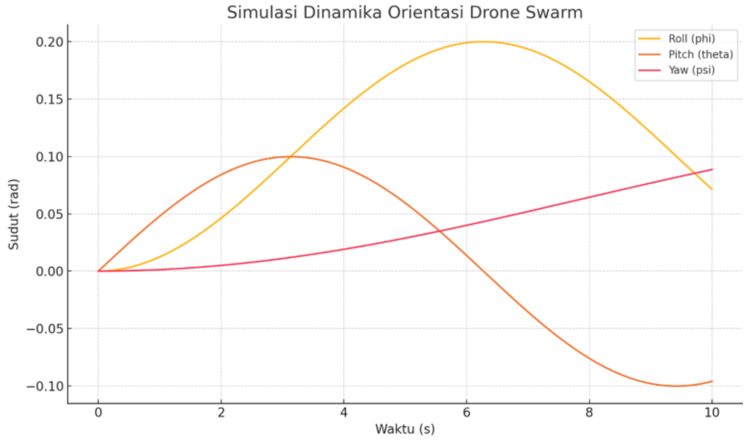

**Figure 4. Simulation of Drone Swarm Orientation Dynamics**

Even in the post-disaster recovery phase, drone swarms remain relevant. Long-term monitoring of affected areas can be conducted to support infrastructure restoration, public health surveillance, and early detection of potential disease outbreaks. This continuous data flow ensures that humanitarian aid remains adaptive to shifting population needs and contributes to more effective and sustainable recovery. The integration of drone swarms in disaster relief and recovery management represents a significant advancement in crisis handling methods. The ability to combine rapid delivery, real-time condition assessment, and adaptation to extreme environments positions this technology as an indispensable element in both emergency response and long-term recovery operations.

Figure 3 underscores the importance of reference coordinate systems in precisely managing drone orientation and positioning within swarm formations, particularly during emergency missions in complex and dynamic disaster zones. While this approach enables autonomous coordination among drones for rapid deployment, operational challenges remain significant. Battery limitations restrict operational duration, while coordination algorithms and inter-drone communication systems remain vulnerable to signal interference in extreme environments. Additionally, adverse weather conditions, such as strong winds and heavy rain, can disrupt navigation stability and reduce data acquisition accuracy. Privacy and data security concerns also necessitate strict regulation regarding the use of high-resolution cameras and advanced sensors. Therefore, the integration of a robust coordinate reference model, as shown in Figure 3, serves not only as a spatial control framework but also as a strategic foundation for addressing technical and ethical constraints—ensuring operational effectiveness, reliability, and sustainability in drone swarm-based disaster response.

Moreover, ethical and legal challenges must be addressed in drone swarm deployment. Privacy issues arise from the use of high-resolution cameras and advanced sensors capable of capturing images of individuals and private property without consent. Strict privacy regulations are required to balance disaster response needs with individual privacy rights. Data security must also be guaranteed to prevent unauthorized access or misuse of collected information. Accordingly, a strong legal framework and ethical guidelines are essential to ensure responsible, secure, and privacy-respecting deployment of this technology, as highlighted in Table 2.

**Table 2. Challenges and Impacts on Drone Swarm Operations in Disaster Management**

| Challenge | Description | Impact on Drone Operations |
|---|---|---|
| Battery Power | Drone operational duration is limited by current battery capacity. | Mission range and duration are constrained. |
| Weather Conditions | Drone stability and navigation are affected by extreme weather such as wind, rain, and snow. | Operational effectiveness and safety are reduced. |
| Privacy Issues | Sensitive data may be captured by high-resolution camera systems installed on drones. | Concerns over data privacy and consent emerge as critical ethical considerations. |

| | | |
|---|---|---|
| Data Security | Risk of unauthorized access to sensitive information collected by drones is significant. | Strict data protection protocols are required to ensure information security. |

Future Prospects

The evolution of swarm drone technology in disaster management appears increasingly promising, driven by deeper integration with artificial intelligence (AI) and machine learning. The technological advantages of autonomous coordination and real-time adaptability are expected to enhance future disaster response capabilities. Accelerated victim detection, damage mapping, and dynamic environmental monitoring can be achieved without direct human intervention. This intelligent adaptation positions drone swarms not merely as auxiliary tools but as autonomous entities capable of responding to crisis dynamics. Beyond disaster management, sectors such as agriculture, infrastructure, and environmental monitoring have demonstrated significant potential for adopting drone swarms to support precision monitoring and data-driven decision-making. In the future, enhancing drone functionality through advanced technologies such as blockchain for data security, long-endurance batteries, and weather-resistant designs is expected to extend operational reach and effectiveness. With continuously evolving flexibility and intelligence, drone swarms are projected to become leading systems for risk mitigation and the resolution of complex global challenges.

## 5. CONCLUSION

The design of swarm drone systems represents a new direction in disaster response transformation, offering significant potential in real-time data acquisition, accurate logistics distribution, and enhanced situational awareness in the field. Powered by artificial intelligence and machine learning algorithms, drones can operate autonomously and in coordination, making them strong candidates as strategic components of modern disaster response architectures. Moreover, their expanding applications in agriculture and infrastructure signal promising industrial opportunities. Nonetheless, technical challenges and ethical legal frameworks remain critical concerns that must be addressed from the early design phase. Therefore, this study currently at the model design stage emphasizes the importance of a responsible and sustainable integration to ensure that swarm drone technology is truly prepared to meet the complexity and urgency of global challenges in the future.

### Ethical Approval

Not Applicable

### Informed Consent Statement

Not Applicable

### Authors' Contributions

SW contributed to the conceptualization, system framework design, and drafting of the manuscript. A supervised the overall research process, contributed to the system modeling and simulation design, and served as the corresponding author during submission and review. PI contributed to the integration of informatics and AI algorithm components within the drone swarm system. BG and MD contributed to the development of the prototype design, data analysis, and visualization of simulation results.

### Disclosure Statement

The Authors declare that they have no conflict of interest

### Data Availability Statement

The data presented in this study are available upon request from the corresponding author for privacy.

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