Coordinated Aerial–Ground Robot Swarms for Urban Disaster Response: Enhancing Resilience Through Collaborative Multi-Terrain Operations

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Abstract: Urban disasters like collapsing buildings, earthquakes, and explosions present major challenges when mapping the affected areas and looking for victims in the rubble. In recent years, the use of heterogeneous aerial-ground swarm robots has evolved into a promising technique due to their adaptability, scalability, and fault tolerance. This paper presents a comprehensive review of the use of such heterogeneous swarms, highlighting their capability of supporting human responders through a synergistic combination between aerial surveying and close-range ground sensing. In doing so, this review traces the evolution of such techniques throughout early robotic deployments, such as in the World Trade Center collapse, to more modern swarm-based approaches. Furthermore, this paper outlines the foundational characteristics and advantages of swarm robots, with a focus on their potential benefits in Search and Rescue scenarios when integrating heterogeneous systems of drones and ground robots. Persistent challenges, such as communication issues, limited resources, and environmental noise, are also discussed. Finally, future prospects and possible solutions for improving autonomy, robustness, and scalability in aerial-ground robot swarms in search and rescue scenarios are reviewed. Therefore, this paper aims to provide a foundation for improving swarm-enabled disaster response strategies, guiding future research and deployments to enhance performance in critical situations.

Keywords: Swarm robotics; UAV–UGV coordination; Disaster response; Sensor fusion; Autonomous systems.

1. Introduction

Urban disasters, whether caused by human actions or natural events, often present complex challenges for rescuers and emergency responders, resulting in widespread destruction, ethical dilemmas, and significant numbers of injuries and fatalities (Waykar, 2021). Therefore, the chaotic and unpredictable nature of disaster environments demands rapid response from public agencies and prompt action in healthcare and rescue efforts, areas that have historically been underdeveloped. In recent years, however, technological advancements have positioned robots as promising revolutionary tools in these scenarios (Murphy, 2012).

As a result of these emerging technologies, in disaster situations, robots offer significant advantages when compared to only using “human” search and rescue teams, since they present increased autonomy, scalability, and replaceability, characteristics that are essential in a rapidly changing, unexpected, and dangerous environment (Abraham et al., 2019). Initially, ground robots started being used for victim detection and ground sensing in regions affected by the presence of large amounts of rubble. Then, drones began being applied for mapping purposes. Following this evolution, recently, a swarm-based approach combining drones and ground robots started being developed for use in these scenarios, representing a huge potential change in efficiency and performance (Chatziparaschis et al., 2020).

Given this recent development, swarm robots have been a relevant topic lately due to their applications in various fields, being defined as large groups of simplistic robots coordinated by environmental rules, acting as one collective agent to efficiently accomplish a certain given task (Navarro & Matía, 2013). Accordingly, these types of robots can be classified as homogenous (all identical or very similar in terms of hardware, software, capabilities, and roles within the swarm) or heterogeneous (diverse agents with different capabilities and specialized roles), with the latter being the focus of this review.

Nonetheless, despite its increasing use, swarm robotic systems still present key operational limitations, such as quick-draining battery life, sensor malfunctions, and poor decision-making under irregular conditions (Şahin, 2005) (Murphy, 2017). Additionally, swarm systems also face numerous organizational and structural challenges, such as communication failures and inefficient task allocation (Brambilla et al., 2013). Therefore, while their benefits are evident, these constraints show that there are many improvements needed to ensure consistent performance during real-world operations

Building on this foundation, this paper explores how heterogeneous aerial–ground robot swarms have contributed to Search and Rescue missions in urban zones, such as in victim detection and mapping in collapsed buildings, and identifies potential developments to enhance their autonomy and reliability in disaster response. By analyzing the collaboration between these swarm systems, this paper hypothesizes that this integrated approach, promising yet underexplored, can significantly increase the speed, coverage, and effectiveness of rescue operations, resulting in fewer deaths and more effective recovery when compared to non-collaborative robotic systems.

In Section 2, the principles, advantages, and applications of swarm robotics in general are discussed. Section 3 continues to present early robotic deployments in disaster scenarios and takeaways from their performance. The use of coordinated aerial-ground swarm robotics in Search and Rescue missions is stated in Section 4. The persistent challenges faced by these robots in disaster scenarios are described in Section 5. Next, Section 6 outlines future directions and opportunities of swarm-based aerial-ground systems. Lastly, in Section 7 the main ideas of this review are synthesized.

2. Swarm Robotics: Advantages and Applications

2.1 Principles of Swarm Intelligence

Swarm robotics is a subfield of collective robotics that applies principles of swarm intelligence, modeled after the behavior of social insects like ants and bees, to accomplish tasks that exceed the capabilities of individual robots. More specifically, it can be defined as the study of how collective intelligent behavior emerges from interactions both among individual agents and with their environment. These agents are typically simple in design and limited in capability when operating alone, but demonstrate efficiency when functioning as a group (Dorigo, 2005).

One of the founding features of swarm robotics is its reliance on decentralized control, where no single unit of the swarm dictates the behavior of the group, and instead every unit functions as a coordinated group, interacting with each other and the environment (Barca & Sekercioglu, 2013). This feature provides a particular resilience and scalability to the swarm, as units can be removed or added without interfering with the performance of the given task (Hu et al., 2018).

Closely tied to decentralization is the concept of redundancy, a critical feature responsible for the reliability of swarm robots. Specifically, redundancy refers to the system's ability to maintain task execution even when individual units fail (Christensen et al., 2009). This characteristic is particularly valuable in dynamic and harsh environments, where failures are expected and continuous operation is essential.

Another fundamental feature of swarm robotics is scalability. This property refers to the system's capacity to maintain effective performance regardless of the size of the swarm, largely enabled by its local communication and decentralized coordination (Bjerknes & Winfield, 2013). As a result, the system can easily adapt to meet the scale of the operation, increasing both the efficiency and the resilience of these swarms.

2.2 Benefits of Swarm Robotics in Dynamic Environments

A key advantage of swarm robotics is grounded in its flexibility and resilience when operating in unpredictable and fast-changing scenarios (Bayındır, 2016). Specifically, due to this system's decentralized control and distributed decision-making, swarm robots can quickly adapt to environmental shifts such as blocked pathways, communication failures, or changing terrain. This allows them to maintain coordinated navigation and reliable task execution even under unpredictable disaster conditions (Khaldi & Cherif, 2015). This flexibility allows the swarm to reconfigure itself in real-time, adjusting its size, role, and trajectories to optimize results.

Furthermore, swarm robots display remarkable fault-tolerance. Originating from its redundancy and local communication within the system, a swarm's fault-tolerancy ensures the task is completed even when facing partial failures in the group (Winfield & Nembrini, 2006). This robustness makes robot swarms particularly suited for high-risk and unpredictable scenarios such as those seen in disaster zones, where timely response, adaptability, and continuity are essential for success.

2.3 *Examples in Related Domains*

Swarm robotics, as a field with potential use in multiple areas where humans act, has also demonstrated promising applications in agriculture. In this regard, swarm robots are mainly used in this area to perform tasks such as crop monitoring, pest control, and irrigation. For example, a coordinated swarm of small electric robots can reach the same field capacity as a single large conventional tractor, while also significantly reducing fuel consumption, soil compaction, and operational costs (Albiero et al., 2020). Moreover, these swarms, by efficiently and homogeneously covering large areas, can reduce the need for extensive human labor and adapt to changing weather conditions, enhancing productivity and minimizing resource waste.

In addition to agriculture, swarm robotics have also demonstrated influence in many other areas, such as in environmental monitoring, planetary exploration, and industrial applications, which we will cover in this paragraph (Dias et al., 2021): in environmental contexts, robot swarms can gather data from multiple sources and areas, offering a wide analysis of the current aspects of the monitored environment, even in extreme conditions; in planetary exploration, these swarms can be used to map and sense the space, covering a much larger area in comparison to other exploration methods; in industrial settings, these systems can perform maintenance in machines and infrastructure without affecting the operations (Schranz et al., 2020). These examples illustrate the flexibility and potential uses of swarm robotic systems in nearly any field, including search and rescue contexts.

2.4 *Relevance to Search and Rescue Contexts*

Linking to this, such missions are often characterized by their uncertainty, time-sensitivity, and instability. Urban disasters, such as collapsing buildings, earthquakes, explosions, floods, and structural fires, give rise to unpredictable and fast-changing environments, unsuited for conventional rescue techniques. Therefore, robustness and flexibility in these situations are essential, as rescue efforts must continue despite any encountered obstacles (Waykar, 2021).

In relation to that, swarm robotics perfectly aligns with the demands of Search and Rescue missions due to its inherent characteristics. Specifically, their redundancy and decentralized control make them highly robust in scenarios where units of the system can fail. Moreover, their autonomy and scalability enable them to rapidly adapt to fast-changing conditions and maintain their operation even in large and complex environments (Moosavi et al., 2024) (Waykar, 2021). Furthermore, these systems can, through collaboration, aid in the exploration of inaccessible or high-risk areas, in the detection of victims, and in the mapping of the affected zones, demonstrating a way better efficiency compared to conventional monitoring systems, making them remarkably suited for such missions.

3. Early Robotic Deployments and Lessons Learned

3.1 Case Studies in Search and Rescue Robotics

In the aftermath of the World Trade Center Collapse in 2001, ground robots were, for the first time, deployed in real urban disaster conditions. In this context, these robots were tasked with searching through the debris, analyzing the structural integrity of the collapsed buildings, and helping human responders locate victims. Moreover, these systems were equipped with cameras and thermal sensors, which were essential for search in the confined, inaccessible, and hazardous areas (Casper & Murphy, 2003). Ultimately, this experience established the foundations for further deployments in many other disaster scenarios, as presented below:

At the La Conchita, California, mudslide, ground robots (Inuktun VGTV Xtreme) were launched into the debris to track missing residents. In doing so, they faced large mobility issues due to the thick and fast-spreading mud. This experience highlighted the need for adaptation in unstable terrains (Murphy, 2012). Moreover, at the Midas Gold Mine collapse in Nevada, a ground robot (an updated Inuktun VGTV-Xtreme) was deployed to search for a missing miner. However, the robot couldn't locate the body because of its insufficient lighting (Murphy, 2012). Furthermore, at Florida's Berkman Plaza collapse, a ground robot (Inuktun VGTV) was deployed to help locate a missing worker. However, the robot failed in locating the victim by itself due to intermittent communication dropouts caused by the collapsed environment (Murphy, 2012).

Together, these deployments show the potential and limitations of robots in Search and Rescue scenarios. The challenges faced demonstrate the need for enhanced locomotion systems, more adaptable modules, and resilient communication to support successful operations in these environments. Building on these insights, the next section explores the specific environmental obstacles and limitations that must be addressed.

3.2 *Environmental Obstacles and Limitations of Early Ground Robots*

Despite their innovative use, many limitations were observed when operating in the World Trade Center's remains. Regarding that, most of the deployed ground robots presented short operational lifespans due to the extreme conditions, which compromised their functionality. Moreover, these systems also faced communication difficulties, reducing their effectiveness in this scenario (Murphy, 2010). Consequently, their deployment demonstrated the need for improvements in robustness and autonomy to enhance robotic capabilities in such disaster environments.

Many hardware characteristics contributed to these limitations. In this regard, many deployed ground robots faced size-related challenges: they were either too big to fit through tight spaces or too small to carry the necessary equipment. Moreover, several of them didn't have the adequate structure required for traversing in unstable terrain, which prevented them from further operating in the disaster scenarios. Additionally, sensors and cameras also struggled when functioning in low-light or obscured areas (Carlson & Murphy, 2005).

Environmental factors must also be considered. In disaster areas, sharp and irregular debris can damage or trap the robots and equipment; suspended dust can obstruct visibility and impair sensor functionality; thick concrete and rebar within the rubble can hinder communication and navigation signals (Tong et al., 2024). Furthermore, high temperatures, moisture, and chemical leaks can degrade hardware and cause malfunctions in the system (Singh et al., 2015).

Collectively, these factors reveal that early ground robots, despite their pioneering use, were very limited in terms of robustness, autonomy, and efficiency, underscoring the importance of new solutions and designs to increase their performance in disaster responses.

3.3 *Lessons Learned and Their Influence*

These insights culminated in the formalization of disaster robotics as an actual subfield within robotics research. In this context, disaster response began to be treated as a relevant and coherent research topic, supported by governments and scientific communities. Consequently, academic labs, public institutions, and independent researchers started working together to develop new designs and technologies that could mitigate the limitations of previous deployments. Building on these foundations, coordinated aerial–ground swarm robotics has emerged as a promising approach, offering increased adaptability, scalability, autonomy, robustness, and efficiency in complex disaster response scenarios.

4. Coordinated Aerial–Ground Swarm Robotics in Disaster Response

4.1 *Functions of UAVs and UGVs*

Unmanned Aerial Vehicles (UAVs) play an important role in disaster scenarios, as they can quickly obtain essential information about the area's circumstances. Specifically, these drones can cover wide areas in real-time, supporting guidance and rescue through the mapping of the affected zone, the detection of areas with the highest likelihood of finding survivors, and the transport of medical supplies (Munasinghe et al., 2024). Moreover, they can also act by extending communication coverage, maintaining connections between different technologies or human teams, even throughout scattered locations (Li et al., 2021).

In contrast, Unmanned Ground Vehicles (UGVs) in disaster scenarios can navigate in inaccessible and high-risk areas, perform close-up detailed inspections, and assist in victim detection and interaction (Munasinghe et al., 2024). Furthermore, as these robots are deployed directly into the collapsed zones and can be equipped with manipulation tools, they can interact with the environment by clearing paths and removing obstacles (Berns et al., 2017). As a result, they enable easier and more effective rescue operations.

Building on these complementary strengths, the next section will explore the underdiscussed yet promising coordination between aerial and ground robots through a swarm-based approach.

4.2 *Swarm-based coordination of aerial-ground robots*

The coordination of aerial-ground robots in disaster scenarios comes with numerous benefits. In these scenarios, UAVs can provide real-time overview data to inform and guide the UGVs' navigation along the safest and most convenient routes. Expanding on that, while drones perform the mapping from above (identifying structural instabilities, survivor hotspots, and areas to avoid), ground robots can use this information to support on-site activities, such as accessing voids, removing obstacles for human rescuers, or delivering medical aid to victims (Munasinghe et al., 2024). These complementary roles, in a chaotic and unpredictable environment, not only systematically and effectively allocate different tasks, but also enable more efficient coverage and faster response times (Queralta et al., 2020). Therefore, by integrating their individual specialities and capabilities, this collaboration can achieve higher autonomy, flexibility, and reliability when compared to their independent use, such as in the World Trade Center rescue operation.

Moreover, implementing this coordinated approach through a swarm-based system presents even more benefits, significantly increasing its general performance.

Specifically, by employing the core principles of swarm intelligence, such as redundancy, local communication, and decentralized decision-making, these aerial-ground systems can naturally adapt to changing conditions, reallocate tasks, and continue operating despite individual unit failures (Brambilla et al., 2013). Moreover, this swarm-based coordination enables UAVs and UGVs to more effectively change their strategy based on the needs and risks of the mission, highlighting their increased adaptability in these environments. This decentralized model also allows scalability, as units of drones or ground robots can be added to increase efficiency and coverage when demanded (Zhang et al., 2025). Therefore, this swarm-based coordination of aerial-ground robotic systems holds promising capabilities that deserve to be further studied and developed, in order to increase resilience, flexibility, and coverage in such unpredictable and chaotic environments.

4.3 *Sensor Implementation for Victim Detection and Mapping*

Implementing sensors into aerial-ground robot systems can increase their performance in disaster scenarios. Through the combination of the capabilities of multiple sensors across these systems, this integration can potentially overcome many limitations. For example, UAVs can use RGB and thermal cameras to collect data and thermal imagery, aiding in the search for victims from above. Moreover, UGVs can use LiDAR and sound sensors for on-site mapping and close-up victim detection, which may be particularly useful in areas blocked from GPS signals. Bultmann et al. (2021) present in their paper a UAV system with LiDAR, RGB, and thermal sensors, showcasing improved object recognition and increased overall reliability. In parallel, Xu et al. (2022) provide a study of a LiDAR-based sensor for SLAM (Simultaneous Localization and Mapping), demonstrating how the implementation of this technology can improve localization and mapping under unpredictable settings.

Considering these studies, it is evident that the use of such sensors in disaster scenarios brings numerous efficiency benefits (Cani et al., 2025). Therefore, their use in aerial-ground swarms can, combined with these systems' innate robustness and flexibility, provide increased precision and reliability in such sensitive settings. In turn, this leads to even fewer injuries and deaths among victims and responders compared to conventional rescue methods that rely solely on human teams or non-coordinated robotic systems. This is because the combination of different sensors can increase the situational awareness of the system, enabling faster and more effective victim detection even in challenging settings (Schichler et al., 2025).

4.4 *Field Deployments and Case Examples*

The ICARUS Project: The EU-FP7 ICARUS project delivered an army of unmanned aerial and ground robots equipped with victim-detection sensors and a radio network to support responders in realistic disaster simulations (Doroftei et al., 2014). In various simulated collapse scenarios, such as destroyed buildings and flood-affected areas, the UAVs managed to conduct aerial reconnaissance and thermal imaging, while the UGVs explored debris piles to perform close-range inspections and payload deliveries. While ICARUS deployments were not robot swarms in the strictest technical sense, they did incorporate swarm-inspired principles. Analyzing their performance, expert end-users evaluated functionality and efficiency, highlighting ICARUS's robots' reduced deployment times, improved situational awareness, and robustness against failures, which are core benefits arising from its decentralized, swarm-inspired design (De Cubber et al., 2013).

Surfside Condo Collapse: During the Champlain Towers South condominium collapse in Surfside, Florida, rescue teams rapidly deployed heterogeneous unmanned systems in what became the largest and longest drone-based disaster response on record. As detailed by Rao et al. (2023), hundreds of UAV missions were demanded to generate orthomosaic maps, digital elevation models, and thermal searches for survivors. At the same time, UGVs were deployed into the standing structure to inspect inaccessible areas and act as communication relays for aerial units. Moreover, these ground robots were also equipped with 360° cameras and thermal sensors in order to improve close-up victim detection in the rubble.

In retrospect, these operations underscored the immense value of integrating aerial and ground platforms, most notably with a swarm-based approach, showing their beneficial and efficient applications in disaster response. However, there are many persistent challenges in these settings that need to be addressed.

5. Persistent Challenges in Rubble Environments

5.1 *Environmental and Perceptual Challenges*

UAVs and UGVs still face many challenges during Search and Rescue missions. For example, many ground robots encounter difficulties when traversing irregular terrain or unstable structures, compromising the mission's safety and navigation. Moreover, in these chaotic settings, uneven surfaces and loose debris can block or trap the robots (Carlson & Murphy, 2005). As described by Solmaz et al. (2024) in their paper, robots and communication equipment can also be damaged by collapsing buildings, leading to decreased or absent functionality and loss of coordination between units, especially when swarm-based approaches are being used. Additionally, complex terrain can cause malfunctions in many of the systems used, which require human intervention and, therefore, can put responders' lives at risk.

Another challenge encountered by aerial-ground robots in rubble environments is perceptual degradation, which significantly limits robotic performance in these scenarios. In relation to that, this term refers to the difficulties faced by vision-based sensors in enclosed and collapsed structures, as they are exposed to suspended dust, complete darkness, smoke, and other occlusion factors (Reich & Sklar, 2006). These factors obstruct visual feeds and sensor readings, and diminish the robot's ability to detect victims and navigate correctly, also hindering the mission's operational success (Cadena et al., 2016). These limitations demonstrate the need for more resistant sensors and new perception strategies, together with more reliable communication networks.

5.2 *Communication and Localization Constraints*

Communication and localization between robots can be hindered in disaster scenarios, as collapsing buildings, rubble, structural fires, and explosions may damage cables and interfere with GPS, Wi-Fi, and other signals, forcing these robots to operate in isolation and largely affecting rescue missions. Seeing that maintaining situational awareness and coordination between units in these GPS-denied and connectivity-scarce zones was difficult, Lajoie et al. (2020) developed DOOR-SLAM, which is a system based on peer-to-peer communication that doesn't require connectivity between units. Similarly, other studies have also discussed ways in which fragmented networks can be preserved in these scenarios. For example, using C-SLAM (Collaborative Simultaneous Localization and Mapping) in multi-robot systems or robotic swarms can prevent communication-related issues (Lajoie et al., 2022), which could otherwise break formation, delay progress, and cause errors in the collective decision-making of the group.

Aiming to overcome the localization constraints in disaster scenarios, various techniques and frameworks were developed by researchers. For example, one related approach is utilizing a landmark-based localization system (LanBLoc) to predict the future state of moving entities along the affected areas, replacing the use of GPS in these isolated settings (Sapkota & Madria, 2024). Moreover, vision-based approaches can help mitigate localization-related problems, as seen in the use of Visual Simultaneous Localization and Mapping (VSLAM) techniques, which use visual data to create 3D maps of the surroundings without the need for external connections (Lu et al., 2022). Together, these locally-based communication and localization strategies form resilient foundations for swarm coordination when traditional connectivity methods fail.

5.3 *Autonomy and Human–Swarm Interaction*

Managing swarm robots during search and rescue missions is both challenging and risky. This can be attributed to the fact that, as units get added to the swarm, more coordination, control, and efficient decision-making are demanded to maintain proper functionality. Aiming to mitigate this difficulty, Hunt et al. (2023) investigate how human-swarm collaboration in the context of Search and Rescue can improve performance and autonomy of swarms, optimizing the reliability and efficiency of these systems, as humans can oversee tasks and decisions. Comparably, Kelly et al. (2024) propose a dynamic hybrid control architecture combining centralized and decentralized control strategies to optimize swarm performance while reducing human cognitive load, offering a solid middle ground between efficiency (centralization) and scalability (decentralization).

Moreover, it is essential for robotic swarms to maintain decision-making in real time to avoid further complications in the disaster areas. From this perspective, Li et al. (2025) propose a Human-in-the-loop Multi-Robot Collaboration Framework (HMCF), which increases adaptability by reallocating tasks and matching capabilities between the swarm, all supervised by humans to ensure safety and reliability. Similarly, Calzolari et al. (2024) present a decentralized collaborative framework based on Reinforcement Learning, enabling faster, smarter, and more efficient decision-making by learning from the environment and operator feedback.

6. Future directions and opportunities

6.1 Adaptive Autonomy and Resilient Communication

Considering the need for autonomous and efficient robots in search and rescue contexts, improvements in decision-making and reliable communication must be further developed. With such an objective, the implementation of Machine Learning strategies presents potential benefits to decision-making, as the system could adjust its actions based on the data collected from the environment (Gielis et al., 2022). This approach would allow for minimal human intervention, enabling the aerial-ground swarms to operate more efficiently and without putting more lives at risk. Moreover, Khatib et al. (2006) propose a coordination strategy enhanced by machine learning-based detection, which improves data integrity and system robustness. This strategy, if used appropriately in search and rescue contexts, could enable faster victim detection and more effective collaboration.

As discussed in Section 5, communication barriers are one of the main obstacles during search and rescue missions, having the power to hinder an entire operation. Therefore, it is necessary to develop more resilient communication networks to guarantee mission success in these scenarios (Sterbenz et al., 2010). For example, Mauthe et al. (2016) present deployable backup networks that integrate heterogeneous communication technologies. This approach could maintain communication between robots and responders even when normal systems break down, guaranteeing that all critical information is received. Moreover, Gorbil & Gelenbe (2013) propose Oppcomms (opportunistic communications), an approach that exchanges messages at a close range by exploiting human mobility, without the use of any infrastructure. This system, similarly to the one presented by Mauthe et al., could also maintain reliable and resilient communication despite any environmental or man-made barriers.

6.2 Multidisciplinary Collaboration and Policy Frameworks

The future success of aerial-ground swarm systems in search and rescue missions will certainly depend on collaboration among multiple groups, such as researchers, manufacturers, ethicists, and policymakers (Alqudsi & Makaraci, 2024). These systems, taking on the responsibility of saving people's lives, need high dependability, ethical grounding, and real-world applicability. Therefore, collaboration between numerous disciplines is needed to ensure safety and reliability in disaster scenarios. Expanding on this, the aerial-ground swarm system must be functional, performing as expected; safe, not putting people's lives at risk during an operation; and ethical, adhering to a set of moral principles that dictate its decision-making (Waykar, 2021).

Moreover, the use of aerial-ground swarm systems should also be discussed at a government level. Therefore, establishing robust policy frameworks is crucial for their effective and ethical use (Winfield et al., 2025). Concerning this, government agencies must develop clear guidelines and regulations to manage accountability in deployments. For example, an article by Pepple (2025) discusses the need for policy and regulation to ensure the humanitarian principles involved with the deployments of such robots. Furthermore, the development of federal policy frameworks for unmanned vehicles emphasizes the importance of safety and transparency in this system (Watts et al., 2012), especially in emergency response contexts.

7. Conclusion

In this paper, we reviewed the operational advantages of heterogeneous aerial-ground swarms for urban search-and-rescue, stemming from their complementary strengths (UAV overhead mapping + UGV close-range sensing), sensor fusion, and decentralized coordination. These capabilities are promising, but they do not erase the hard lessons from field deployments. Fragile communications, sensor degradation in rubble, limited endurance, and gaps in real-time autonomy in complex, dynamic environments still constrain real-world deployment, limiting operational reliability and safety.

Given these gaps, we recommend a focused engineering agenda: prioritize resilient networking, such as opportunistic relays and resistance to degradation; implement robust multimodal perception and SLAM resilient to dust, smoke, darkness, and occlusion; and design autonomous models that are context-aware and confidence-sensitive to enable robust decision-making on when to act autonomously and when to request human oversight. All of this must be validated in realistic field trials, not only in simulations.

Finally, technical advances must go hand in hand with policy and practice. We need interdisciplinary standards; ethical and accountability frameworks; and regular discussions to align development with operational needs and societal values, involving emergency managers, researchers, ethicists, manufacturers, and policymakers. If we coordinate research, policy, and real-world testing now, these swarms can move from promising prototypes to trusted, life-saving tools.

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This paper reviews heterogeneous aerial–ground swarm robotics for urban search-and-rescue (SAR). The manuscript provides a clear introduction and useful historical context. It explains core swarm principles, describes UAV/UGV roles and common sensors, and discusses persistent challenges and future directions. The paper's tone is constructive and the literature coverage is broad, with many recent citations. Overall, the paper is promising but would benefit from a few revisions.

Paper Strengths

The paper demonstrates strong motivation and clear framing of why UAV–UGV swarms are important for urban SAR. It provides useful grounding in real-world deployments (e.g., WTC, ICARUS, Surfside), which helps readers connect theory to practice. The engagement with literature is broad, and includes sensing, SLAM, communication, autonomy, and ethics, with many up-to-date citations.

Comments to the Author

The paper is well written and generally easy to follow. However, much of Sections 2–5 primarily summarize individual works. The review would be more valuable with greater synthesis, highlighting connections, trade-offs, and emerging patterns across studies.Right now, the paper has no figures or tables. Including these would significantly strengthen the clarity of the paper. For example, a table comparing field deployments (platforms, environments, and outcomes) or a schematic of UAV–UGV swarm architectures would add strong pedagogical value.

In addition, extracting quantitative results from cited deployments would be helpful. A short subsection on evaluation metrics and benchmark proposals for future trials could offer practical guidance for both researchers and practitioners. Where possible, highlight areas of and indicate which claims are well-supported versus speculative.

Recommendation

Accept with minor revisions. The manuscript is well written and broadly informed, but it requires the addition of comparative synthesis, figures/tables, and clearer benchmarks to make it worthy of publication.

This paper provides a comprehensive review of heterogeneous aerial–ground swarm robotics for urban disaster response. It summarizes the foundational characteristics and advantages of swarm robotics, discusses current challenges, and outlines future research directions. Despite the importance of the topic, there exists many points that need to be improved, such as insufficient illustration and confused logicality. I would recommend this manuscript to be accepted for publication after major revision.

1. Scope in Section 2: The authors summarize general principles and benefits of swarm robotics (applicable to both homogeneous and heterogeneous systems), but do not clearly introduce the specific principles and advantages of aerial–ground swarm robotics. Please align this section more closely with the manuscript's stated focus.
2. Irrelevant Content (Section 2.3): The discussion of swarm robotics in agriculture is not directly relevant to the theme of urban disaster response. I recommend deleting this subsection.
3. Collaboration Methods (Section 4.2): The authors describe only one method of UAV–UGV collaboration (UAVs guiding UGV navigation). This section should either summarize additional collaboration strategies from the literature (e.g., UAVs acting as communication relays, UGVs supporting UAV landings, cooperative mapping, etc.) or revise the section title to more accurately reflect the limited scope.
4. In Section 5, the authors discuss the current challenges faced by aerial–ground swarm robotics. Please also summarizes the research efforts and attempts that have been made to address these issues.
5. Lack of Figures: No figures are provided in this review, which makes it difficult to follow. Please add illustrative figures to support the text, for example:

    a. Section 2.4: A schematic summarizing types of urban disasters where aerial–ground swarms could be applied.
    b. Section 3: Images or diagrams of robots used in cited case studies.
    c. Section 4.1: Examples of UAVs and UGVs typically deployed in disaster contexts.
    d. Section 4.2: A diagram illustrating how UAVs and UGVs coordinate within a swarm system.
    e. Section 4.3: Examples of sensor payloads for victim detection and mapping.
    f. Section 4.4: Images of aerial–ground swarm robots used in case examples

6. The manuscript occasionally uses informal expressions (e.g., “way better efficiency,” “huge potential change”). A more professional academic expression is recommended.

Decision

Accept with major revisions

Coordinated Aerial-Ground Robot Swarms for Urban Disaster Response: Enhancing Resilience Through Collaborative Multi-Terrain Operations

[redacted]

Abstract: Urban disasters like collapsing buildings, earthquakes, and explosions present major challenges when mapping the affected areas and looking for victims in the rubble. In recent years, the use of heterogeneous aerial-ground swarm robots has evolved into a promising approach due to their adaptability, scalability, and fault tolerance. This paper presents a comprehensive review of the use of such heterogeneous swarms, highlighting their capability of assisting human responders through a synergistic combination between aerial surveying and close-range ground sensing. In doing so, this review traces the evolution of such techniques throughout early robotic deployments, such as in the World Trade Center collapse, to more modern swarm-based approaches. Furthermore, this paper outlines the foundational characteristics and advantages of swarm robots, with a focus on their potential benefits in Search and Rescue scenarios when integrating heterogeneous systems of drones and ground robots. Persistent challenges, such as communication issues, limited resources, and environmental noise, are also discussed. Finally, future prospects and possible solutions for improving autonomy, robustness, and scalability in aerial-ground robot swarms in search and rescue scenarios are reviewed. Therefore, this paper aims to provide a foundation for improving swarm-enabled disaster response strategies, guiding future research and deployments to enhance performance in critical situations.

Keywords: Swarm robotics; UAV-UGV coordination; Disaster response; Sensor fusion; Autonomous systems.

1. Introduction

Urban disasters, whether caused by human actions or natural events, often present complex challenges for rescuers and emergency responders, resulting in widespread destruction, ethical dilemmas, and significant numbers of injuries and fatalities (Waykar, 2021). Therefore, the chaotic and unpredictable nature of disaster environments demands rapid response from public agencies and prompt action in healthcare and rescue efforts, areas that have historically been underdeveloped. In recent years, however, technological advancements have positioned robots as promising transformative tools in these scenarios (Murphy, 2012).

As a result of these emerging technologies, in disaster situations, robots offer considerable advantages relative to traditional human-only search and rescue teams, since they present increased autonomy, scalability, and replaceability, characteristics that are essential in a rapidly changing, unexpected, and dangerous environment (Abraham et al., 2019). Initially, ground robots started being used for victim detection and ground sensing in regions affected by the presence of large amounts of rubble. Then, drones began being applied for mapping purposes. Following this evolution, recently, a swarm-based approach combining drones and ground robots started being developed for use in these scenarios, representing substantial potential improvements in efficiency and performance (Chatziparaschis et al., 2020).

Given this recent development, swarm robots have become an increasingly prominent topic due to their applications in various fields, being defined as large groups of simplistic robots coordinated by environmental rules, acting as one collective agent to efficiently accomplish a certain given task (Navarro & Matía, 2013). Accordingly, these types of robots can be classified as homogeneous (all identical or very similar in terms of hardware, software, capabilities, and roles within the swarm) or heterogeneous (diverse agents with different capabilities and specialized roles), with the latter being the focus of this review.

Nonetheless, despite its increasing use, swarm robotic systems still present key operational limitations, such as quick-draining battery life, sensor malfunctions, and poor decision-making under irregular conditions (Şahin, 2005) (Murphy, 2017). Additionally, swarm systems also face numerous organizational and structural challenges, such as communication failures and inefficient task allocation (Brambilla et al., 2013). Therefore, while their benefits are evident, these constraints show that several improvements are required to ensure consistent performance during real-world operations.

Building on this foundation, this paper explores how heterogeneous aerial–ground robot swarms have contributed to Search and Rescue missions in urban zones, such as in victim detection and mapping in collapsed buildings, and identifies potential developments to enhance their autonomy and reliability in disaster response. By analyzing the collaboration between these swarm systems, this paper hypothesizes that this integrated approach, promising but relatively underexplored, can significantly increase the speed, coverage, and effectiveness of rescue operations, potentially reducing casualties and enhancing recovery outcomes when compared to non-collaborative robotic systems. This review will synthesize findings across multiple studies to identify consistent performance benefits, key trade-offs in system design, and the most pressing gaps between research and real-world deployment.

In Section 2, the principles, advantages, and applications of swarm robotics in general are discussed. Section 3 continues to present early robotic deployments in disaster scenarios and takeaways from their performance. The use of coordinated aerial-ground swarm robotics in Search and Rescue missions is stated in Section 4. The persistent challenges faced by these robots in disaster scenarios are described in Section 5. Next, Section 6 outlines future directions and opportunities of swarm-based aerial-ground systems. Lastly, in Section 7 the main ideas of this review are synthesized.

2. Swarm Robotics: Advantages and Applications

This upcoming section presents the foundational principles, core advantages, and representative applications of swarm robotics in general to establish the base concepts and mechanisms that underlie swarm behavior. The specific and detailed application to heterogeneous aerial–ground systems will be developed in Section 4, where we apply these foundational ideas directly in the search and rescue context.

2.1 Principles of Swarm Intelligence

Swarm robotics is a subfield of collective robotics that applies principles of swarm intelligence, modeled after the behavior of social insects like ants and bees, to accomplish tasks that exceed the capabilities of individual robots. More specifically, it can be defined as the study of how collective intelligent behavior emerges from interactions both among individual agents and with their environment. These agents are typically simple in design and limited in capability when operating alone, but demonstrate efficiency when functioning as a group (Dorigo, 2005).

One of the founding features of swarm robotics is its reliance on decentralized control, where no single unit of the swarm dictates the behavior of the group, and instead every unit functions as a coordinated group, interacting with each other and the environment (Barca & Sekercioglu, 2013). In the context of disaster response, this principle directly supports resilience in communication-disrupted environments, allowing missions to continue even if part of the swarm loses connection. Additionally, this feature provides a particular resilience and scalability to the swarm, as units can be removed or added without interfering with the performance of the given task (Hu et al., 2018).

Closely tied to decentralization is the concept of redundancy, a critical feature responsible for the reliability of swarm robots. Specifically, redundancy refers to the system's ability to maintain task execution even when individual units fail (Christensen et al., 2009). During urban search-and-rescue missions, redundancy ensures operational continuity when robots are lost to rubble collapse or environmental hazards, a pattern repeatedly observed in field reports such as Murphy (2017). This characteristic is particularly valuable in dynamic and harsh environments, where failures are expected and continuous operation is essential.

Another fundamental feature of swarm robotics is scalability. This property refers to the system's capacity to maintain effective performance regardless of the size of the swarm, largely enabled by its local communication and decentralized coordination (Bjerknes & Winfield, 2013). As a result, the system can easily adapt to meet the scale of the operation, increasing both the efficiency and the resilience of these swarms. For example, scaling up a robotic swarm from a small collapsed building to a city block requires only proportional adjustments to communication range and task assignment rather than a complete redesign, which demonstrates practical scalability.

Table 1 summarizes how these core principles correspond to operational advantages in search-and-rescue missions

Table 1

Core Swarm Robotics Principles and Their Operational Roles in Urban Search-and-Rescue Missions

Principle	Operational role in Search-and-Rescue	Evidence type	Sources
Decentralization	Enables continued coordination despite signal loss	Field-tested (WTC, ICARUS)	(Murphy, 2017); (Hu et al., 2018)
Redundancy	Maintains mission progress despite unit failure	Field-tested	(Christensen et al., 2009); (Murphy, 2017)
Scalability	Adjusts team size to mission scale	Simulation-supported	(Bjerknes & Winfield, 2013); (Chatziparaschis et al., 2020)

Note. Data adapted from (Murphy, 2017), (Hu et al., 2018), (Christensen et al., 2009), (Bjerknes & Winfield, 2013), (Chatziparaschis et al., 2020).

2.2 Benefits of Swarm Robotics in Dynamic Environments

A key advantage of swarm robotics is grounded in its flexibility and resilience when operating in unpredictable and fast-changing scenarios (Bayındır, 2016). Specifically, due to this system's decentralized control and distributed decision-making, swarm robots can quickly adapt to environmental shifts such as blocked pathways, communication failures, or changing terrain. This allows them to maintain coordinated navigation and reliable task execution even under unpredictable disaster conditions (Khaldi & Cherif, 2015). This flexibility allows the swarm to reconfigure itself in real-time, adjusting its size, role, and trajectories to optimize results.

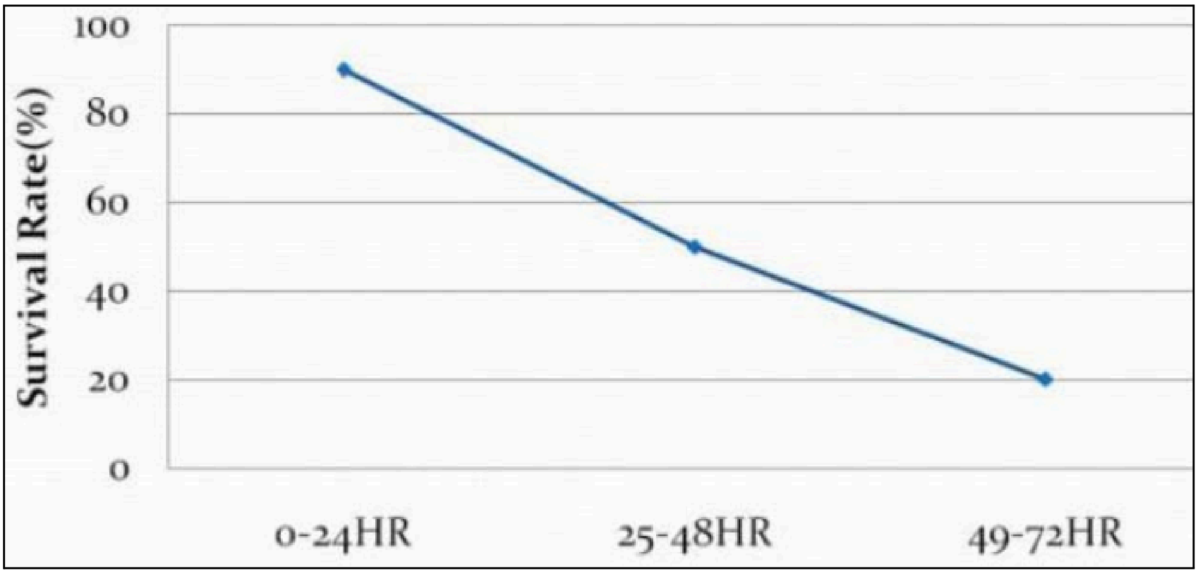
Furthermore, swarm robots display remarkable fault-tolerance. Originating from its redundancy and local communication within the system, a swarm's fault-tolerancy ensures the task is completed even when facing partial failures in the group (Winfield & Nembrini, 2006). This robustness makes robot swarms particularly suited for high-risk and unpredictable scenarios such as those seen in disaster zones, where timely response, adaptability, and continuity are essential for success.

2.3 *Relevance to Search and Rescue Contexts*

Linking to this, such missions are often characterized by their uncertainty, time-sensitivity, and instability. According to research, survival chances for trapped victims are highest within the first 24–48 hours, but start to decline thereafter, often dropping below 20% after 72 hours (see Figure 1)(Zhang et al., 2018).

Figure 1

Statistics of Rescue Time and Survival Rate

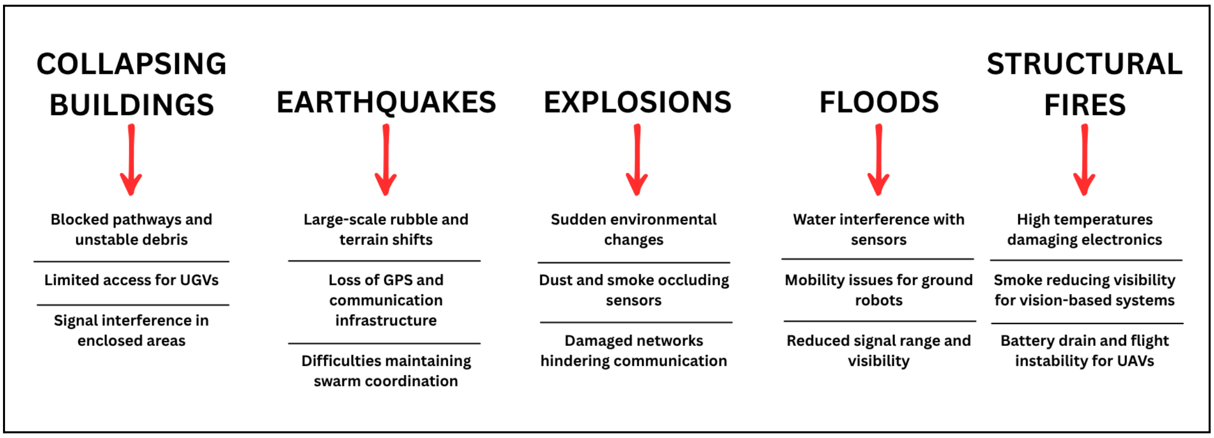


Note. Survival rate declines as time after the event increases, emphasizing the importance of rapid response. Adapted from Hakami, A., Kumar, A., Shim, S. J., & Nahleh, Y. A. (2013). *Application of soft systems methodology in solving disaster emergency logistics problems*. Open access.

Similarly, urban disasters, such as collapsing buildings, earthquakes, explosions, floods, and structural fires, give rise to unpredictable and fast-changing environments, unsuited for conventional rescue techniques (see Figure 2). Therefore, robustness and flexibility are essential in these situations, as rescue efforts must continue despite any encountered obstacles (Waykar, 2021).

Figure 2

Urban Disasters and Their Associated Challenges



Note. This schematic summarizes common urban disasters (collapsing buildings, earthquakes, explosions, floods, and structural fires) and the main operational and environmental challenges they present. Own work.

In relation to that, swarm robotics strongly aligns with the demands of Search and Rescue missions due to its inherent characteristics. Specifically, their redundancy and decentralized control make them highly robust in scenarios where units of the system can fail. Moreover, their autonomy and scalability enable them to rapidly adapt to fast-changing conditions and maintain their operation even in large and complex environments (Moosavi et al., 2024) (Waykar, 2021).

Furthermore, these systems can, through collaboration, aid in the exploration of inaccessible or high-risk areas, in the detection of victims, and in the mapping of the affected zones, demonstrating substantially greater efficiency compared to conventional monitoring systems, making them remarkably suited for such missions. The primary trade-off for these benefits is the increased complexity in coordination and control. However, given the time-critical nature of rescue missions and the high risk of unit loss, the swarm's resilience and scalability present a compelling advantage over more fragile, complex single-robot systems. Therefore, the theoretical foundation of swarm robotics aligns precisely with the practical demands of urban search and rescue.

3. Early Robotic Deployments and Lessons Learned

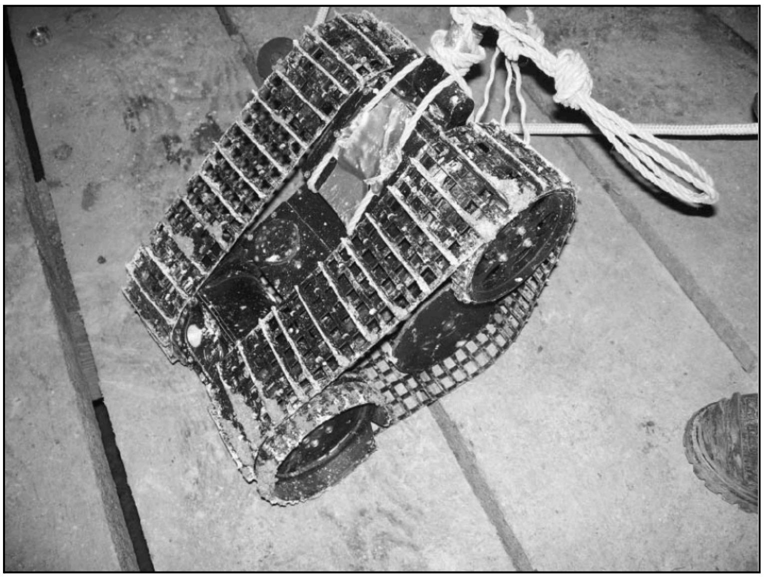
3.1 Case Studies in Search and Rescue Robotics

In the aftermath of the World Trade Center Collapse in 2001, ground robots were, for the first time, deployed in real urban disaster conditions. In this context, these robots were tasked with searching through the debris, analyzing the structural integrity of the collapsed buildings, and helping human responders locate victims. Moreover, these systems were equipped with cameras and thermal sensors, which were essential for search in the confined, inaccessible, and hazardous areas (Casper & Murphy, 2003). Ultimately, this experience established the foundations for further deployments in many other disaster scenarios, as presented below:

At the La Conchita, California, mudslide, ground robots (Inuktun VGTV Xtreme) were launched into the debris to track missing residents. In doing so, they found significant mobility issues due to terrain instability caused by the mud (Murphy, 2008). Moreover, at the Midas Gold Mine collapse in Nevada, a ground robot (an updated Inuktun VGTV Xtreme) was deployed to search for a missing miner (see Figure 3). However, the robot was unable to locate the body because of its insufficient lighting (Murphy, 2012). Furthermore, at Florida's Berkman Plaza collapse, a ground robot (Inuktun VGTV) was deployed to help locate a missing worker. However, the robot failed in locating the victim independently due to communication and locomotion issues caused by the collapsed environment (Murphy, 2012).

Figure 3

The Inuktun Extreme Robot in the Midas Gold Mine Rescue Operation



Note. This figure shows the Inuktun Extreme robot used in the Midas Gold Mine incident to navigate debris and assist rescuers in the confined underground areas. From "Navigational and Mission Usability in Rescue Robots" by R. R. Murphy, 2010, *Journal of the Robotics Society of Japan*, 28(2), 142–146. Open access. https://doi.org/10.7210/jrsj.28.142.

Together, these deployments show the potential and limitations of robots in Search and Rescue scenarios. The specific challenges synthesized in Table 2 demonstrate the need for enhanced locomotion systems, more adaptable modules, and resilient communication to support successful operations in these environments.

Table 2

Synthesis of Challenges in Early Ground Robot Deployments

Deployment scenario	Robot Model	Primary Challenge	Outcome/Impact
World Trade Center (2001)	Various (multiple)	Communication difficulties, extreme environmental conditions	Limited effectiveness; established proof-of-concept but high failure rate
La Conchita Mudslide (2005)	Inuktun VGTV Xtreme	Mobility in unstable, muddy terrain	Severely hampered operations; robot could not traverse key areas
Midas Gold Mine Collapse	Inuktun VGTV Xtreme	Insufficient sensor capability (lighting)	Failed task; unable to locate victim due to poor visibility
Berkman Plaza Collapse	Inuktun VGTV	Locomotion and communication in dense rubble	Failed task; could not reach victim, highlighting terrain limitations

Note. Data adapted from (Murphy, 2008), (Murphy, 2012).

3.2 Environmental Obstacles and Limitations of Early Ground Robots

Despite their innovative use, many limitations were observed when operating in the World Trade Center's remains. This and other deployments showed high failure rates, presenting a Mean Time Between Failures (MTBF) of approximately 24 hours and an availability rate of about 54% (Carlson et al., 2004). Regarding that, most of the deployed ground robots presented short operational lifespans due to the extreme conditions, which compromised their functionality. Moreover, these systems also faced communication difficulties, reducing their effectiveness in this scenario (Murphy, 2010). Consequently, their deployment demonstrated the need for improvements in robustness and autonomy to enhance robotic capabilities in such disaster environments.

Many hardware characteristics contributed to these limitations. In this regard, many deployed ground robots faced size-related challenges: they were either too big to fit through tight spaces or too small to carry the necessary equipment. Moreover, several of them lacked the appropriate structural design required for traversing in unstable terrain, which prevented them from further operating in the disaster scenarios. Additionally, sensors and cameras also struggled when functioning in low-light or obscured areas (Carlson & Murphy, 2005).

Environmental factors must also be considered. In disaster areas, sharp and irregular debris can damage or trap the robots and equipment; suspended dust can obstruct visibility and impair sensor functionality; thick concrete and rebar within the rubble can hinder communication and navigation signals (Tong et al., 2024). Furthermore, high temperatures, moisture, and chemical leaks can degrade hardware and cause malfunctions in the system (Singh et al., 2015).

Collectively, these factors reveal that early ground robots, despite their pioneering use, were highly limited in terms of robustness, autonomy, and efficiency, underscoring the importance of new solutions and designs to increase their performance in disaster responses. The pattern of failure across these cases revealed the fundamental vulnerability of the single-robot, ground-only model, providing a clear rationale for the transition towards heterogeneous, multi-robot systems.

3.3 *Lessons Learned and Their Influence*

These insights culminated in the formalization of disaster robotics as an actual subfield within robotics research. In this context, disaster response came to be recognized as a significant and coherent research area, supported by governments and scientific communities. Consequently, academic labs, public institutions, and independent researchers started working together to develop new designs and technologies that could mitigate the limitations of previous deployments.

Building on these foundations, coordinated aerial–ground swarm robotics has emerged as a promising approach, offering increased adaptability, scalability, autonomy, robustness, and efficiency in complex disaster response scenarios.

4. Coordinated Aerial–Ground Swarm Robotics in Disaster Response

4.1 *Functions of UAVs and UGVs*

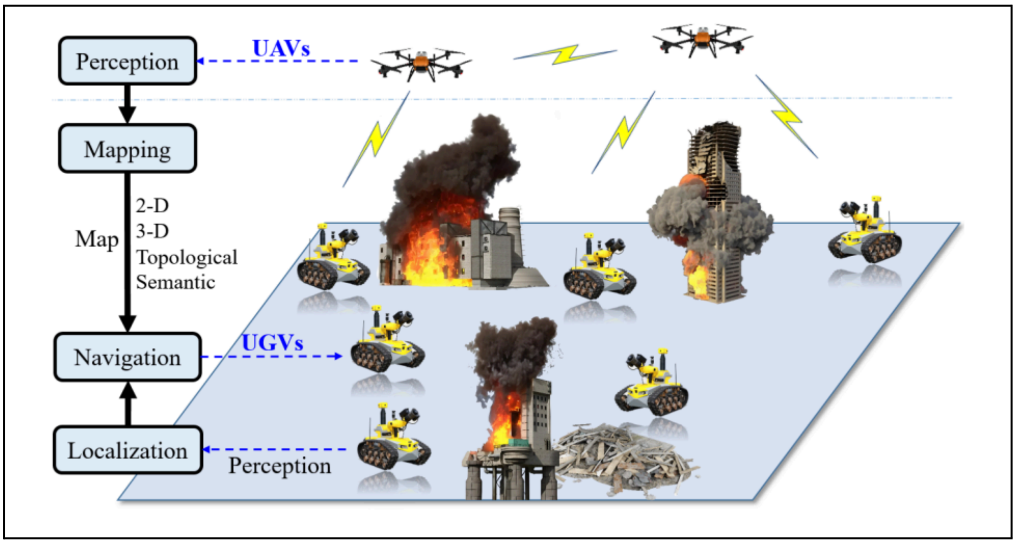
Unmanned Aerial Vehicles (UAVs) play an important role in disaster scenarios, as they can quickly obtain essential information about the area’s circumstances. Specifically, these drones can cover wide areas in real-time, supporting guidance and rescue through the mapping of the affected zone, the detection of areas with the highest likelihood of finding survivors, and the transport of medical supplies (Munasinghe et al., 2024). Moreover, they can also act by extending communication coverage, maintaining connections between different technologies or human teams, even throughout scattered locations (Li et al., 2021).

In contrast, Unmanned Ground Vehicles (UGVs) in disaster scenarios can navigate in inaccessible and high-risk areas, perform close-up detailed inspections, and assist in victim detection and interaction (Munasinghe et al., 2024). Furthermore, as these robots are deployed directly into the collapsed zones and can be equipped with manipulation tools, they can interact with the environment by clearing paths and removing obstacles (Berns et al., 2017). As a result, they facilitate more efficient and effective rescue operations.

A summary of the complementary functions of UAVs and UGVs is shown in Figure 4.

Figure 4

Fundamental Roles of UAVs and UGVs in Search and Rescue Missions



Note. This figure illustrates the key roles of UAV-UGV collaboration. From "Air-Ground Collaborative Robots for Fire and Rescue Missions: Towards Mapping and Navigation Perspective" by Y. Zhang, H. Yan, D. Zhu, J. Wang, C.-H. Zhang, W. Ding, X. Luo, C. Hua, and M. Q.-H. Meng, 2025, arXiv. Open access.

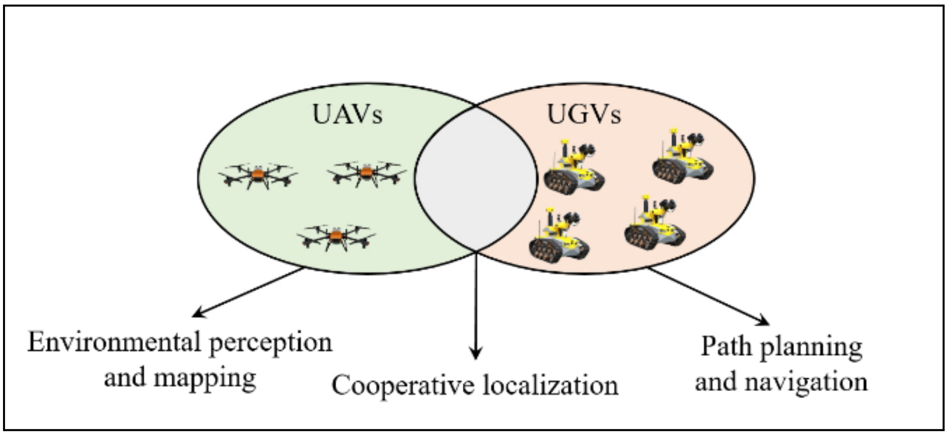
Building on these complementary strengths, the next section will explore the underdiscussed but promising coordination between aerial and ground robots through a swarm-based approach.

4.2 Swarm-based coordination of aerial-ground robots

The coordination of aerial-ground robots in disaster scenarios comes with numerous benefits, as illustrated in Figure 5. In these scenarios, UAVs can provide real-time overview data to inform and guide the UGVs' navigation along the safest and most convenient routes. Expanding on that, while drones perform the mapping from above (identifying structural instabilities, survivor hotspots, and areas to avoid), ground robots can use this information to support on-site activities, such as accessing voids, removing obstacles for human rescuers, or delivering medical aid to victims (Munasinghe et al., 2024). These complementary roles, in a complex and unpredictable environment, not only effectively allocate tasks in a systematic manner, but also enable more efficient coverage and faster response times (Queralta et al., 2020). Therefore, by integrating their individual specialties and capabilities, this collaboration can achieve enhanced autonomy, flexibility, and reliability compared with independent operation (see Table 3), such as in the World Trade Center rescue operation.

Figure 5

Key collaborative functions between UAVs and UGVs in disaster response scenarios



Note. This figure outlines the core areas of cooperation between UAVs and UGVs. From "Air-Ground Collaborative Robots for Fire and Rescue Missions: Towards Mapping and Navigation Perspective" by Zhang et al., 2025, arXiv. Open access. https://doi.org/10.48550/arXiv.2412.20699

Table 3

Performance Metrics for Coordinated vs. Non-Coordinated Systems in Search-and-Rescue Simulations

Metric	Non-Coordinated	Heterogeneous UAV-UGV	Improvement	Source
Mission time	100.0 min	26.7 min	-73.3%	(Chen et al.,

				2025)
Task completion rate (TCR)	Baseline (varies)	+18.42% TCR over baseline	+18.42%	(Lu et al., 2025)
Localization error (GNSS-denied)	1.17 m median error	0.10 m median error	-91.5%	(Sivaneri & Gross, 2017)

Note. TCR = Task Completion Rate; GNSS = Global Navigation Satellite System. Data adapted from (Chen et al., 2025), (Lu et al., 2025), (Sivaneri & Gross, 2017).

Other collaboration strategies reported in the literature include UAVs acting as communication relays to extend connectivity between UGVs and base stations (Johansen et al., 2014), UGVs serving as mobile landing or charging platforms for UAVs (Cheng et al., 2023), cooperative mapping and sensor-fusion workflows in which aerial maps are refined by ground agents for traversal planning (Zhang et al., 2025), and cooperative localization where ground vehicles assist aerial pose estimation via ranging or visual markers (Sivaneri & Gross, 2017) (see Table 4).

Table 4

Collaborative UAV–UGV *Approaches in GPS-Denied or Challenging Environments*

Collaboration Type	Main idea	Source
Communication relay	UAV acts as an aerial relay to extend communication range between UGVs or back to a remote base, enabling coordinated operations in areas with limited connectivity	(Johansen et al., 2014)
UGV as a landing platform	UAV performs autonomous landing or docking on a moving UGV, even in GPS-denied environments, using sensor fusion and dynamic tracking to ensure precision and safety	(Cheng et al., 2023)
Cooperative mapping/sensor fusion	UAV captures aerial maps which are refined and complemented by UGV	(Zhang et al., 2025)

	data for accurate local mapping, helping robots navigate complex or obstructed environments during search and rescue	
Cooperative localization/ranging	UGV assists the UAV in estimating its position and orientation using UWB or vision-based measurements, improving navigation reliability in GNSS-challenged or GPS-denied environments	(Sivaneri & Gross, 2017)

Note. UWB = Ultra-Wideband. Data adapted from (Johansen et al., 2014), (Cheng et al., 2023), (Zhang et al., 2025), (Sivaneri & Gross, 2017).

Moreover, implementing this coordinated approach through a swarm-based system presents even more benefits, significantly increasing its general performance. Specifically, by employing the core principles of swarm intelligence, such as redundancy, local communication, and decentralized decision-making, these aerial-ground systems can naturally adapt to changing conditions, reallocate tasks, and continue operating despite individual unit failures (Brambilla et al., 2013).

This swarm-based coordination also enables UAVs and UGVs to more effectively change their strategy based on the needs and risks of the mission, highlighting their increased adaptability in these environments. This decentralized model also allows scalability, as units of drones or ground robots can be added to increase efficiency and coverage when required (Zhang et al., 2025).

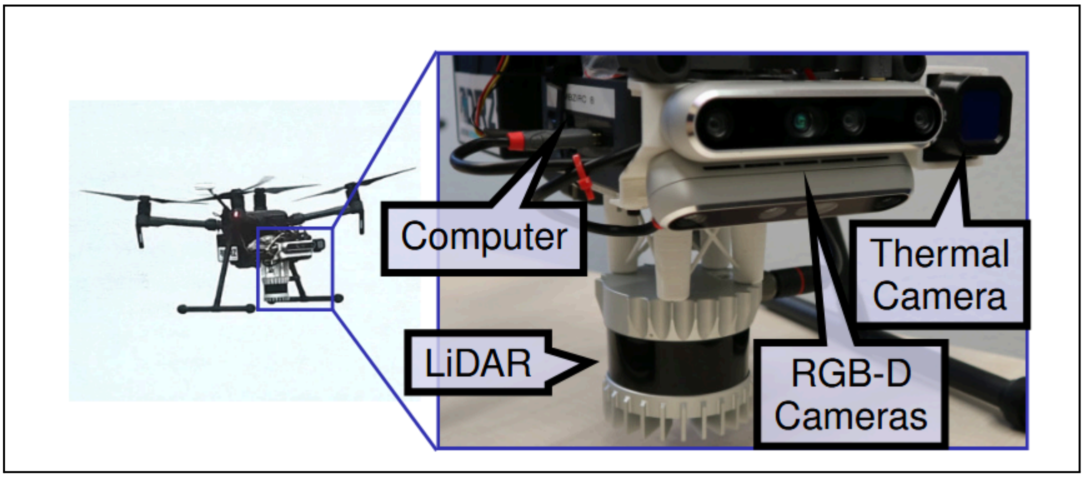
Therefore, this swarm-based coordination of aerial-ground robotic systems holds promising capabilities that deserve to be further studied and developed, in order to increase resilience, flexibility, and coverage in such unpredictable and chaotic environments. The quantitative potential of this approach is demonstrated in realistic simulations. For instance, a study modeling a post-tsunami environment found that a swarm of just five autonomous UAVs could achieve 90% sensor coverage over a 2 km^2 area in under 90 minutes, reaching nearly 99% coverage within two hours (Arnold et al., 2018). This illustrates the potential of swarm-based systems to deliver on the promise of rapid, large-area assessment that is critical in the immediate aftermath of a disaster.

4.3 *Sensor Implementation for Victim Detection and Mapping*

Implementing sensors into aerial-ground robot systems can increase their performance in disaster scenarios. Through the combination of the capabilities of multiple sensors across these systems, this integration can potentially overcome many limitations. For example, UAVs can use RGB and thermal cameras to collect data and thermal imagery, aiding in the search for victims from above. Moreover, UGVs can use LiDAR and sound sensors for on-site mapping and close-up victim detection, which may be particularly useful in areas blocked from GPS signals. Bultmann et al. (2021) present in their paper a UAV system with LiDAR, RGB, and thermal sensors, showcasing improved object recognition and increased overall reliability (see Figure 6). In parallel, Xu et al. (2022) provide a study of a LiDAR-based sensor for SLAM (Simultaneous Localization and Mapping), demonstrating how the implementation of this technology can improve localization and mapping under unpredictable settings.

Figure 6

Multi-Sensor Fusion for UAV Navigation and Perception



Note. This diagram illustrates the types of sensors integrated for advanced perception in UAVs. From "Real-Time Multi-Modal Semantic Fusion on Unmanned Aerial Vehicles" by Bultmann et al., 2021, arXiv. Open access. https://doi.org/10.48550/arXiv.2108.06608

Considering these studies, it is evident that the use of such sensors in disaster scenarios brings numerous efficiency benefits (Cani et al., 2025). Therefore, their use in aerial-ground swarms can, combined with these systems' innate robustness and flexibility, provide increased precision and reliability in such sensitive settings. In turn, this leads to fewer casualties among victims and responders compared to conventional rescue methods that rely solely on human teams or non-coordinated robotic systems. This is because the combination of different sensors can increase the situational awareness of the system, enabling faster and more effective victim detection even in challenging settings (Schichler et al., 2025).

However, it is important to note that while studies like Bultmann et al. (2021) and Xu et al. (2022) provide strong empirical evidence for improved sensor performance and mapping accuracy, the claim of directly reducing casualties remains a projected, outcome-based benefit that requires further validation through large-scale field trials.

4.4 Field Deployments and Case Examples

The ICARUS Project: The EU-FP7 ICARUS project deployed a fleet of unmanned aerial and ground robots equipped with victim-detection sensors and a radio network to support responders in realistic disaster simulations (Doroftei et al., 2014). In various simulated collapse scenarios, such as destroyed buildings and flood-affected areas, the UAVs managed to conduct aerial reconnaissance and thermal imaging, while the UGVs explored debris piles to perform close-range inspections and payload deliveries. While ICARUS deployments were not robot swarms in the strictest technical sense, they did incorporate swarm-inspired principles. Analyzing their performance, expert end-users evaluated functionality and efficiency, highlighting the ICARUS robots' decreased deployment times, improved situational awareness, and robustness against failures, which are core benefits arising from its decentralized, swarm-inspired design (De Cubber et al., 2013).

Surfside Condo Collapse: During the Champlain Towers South condominium collapse in Surfside, Florida, rescue teams rapidly deployed heterogeneous unmanned systems in what became the largest and longest drone-based disaster response on record. As detailed by Rao et al. (2023), hundreds of UAV missions were demanded to generate orthomosaic maps, digital elevation models, and thermal searches for survivors. At the same time, UGVs were deployed into the standing structure to inspect inaccessible areas and act as communication relays for aerial units. Moreover, these ground robots were also equipped with 360° cameras and thermal sensors in order to improve close-up victim detection in the rubble.

In retrospect, these operations underscored the immense value of integrating aerial and ground platforms, most notably with a swarm-based approach, demonstrating their beneficial and efficient applications in disaster response. Across both simulated and real-world deployments, end-users consistently identify the integration of aerial and ground perspectives as the most critical factor for improving situational awareness and reducing operational time, directly supporting this review's thesis. However, there are many persistent challenges in these settings that need to be addressed.

5. Persistent Challenges in Rubble Environments

5.1 Environmental and Perceptual Challenges

UAVs and UGVs continue to face numerous challenges during Search and Rescue missions. For example, many ground robots encounter difficulties when traversing irregular terrain or unstable structures, compromising mission safety and navigation. Moreover, in these chaotic settings, uneven surfaces and loose debris can immobilize or entrap the robots (Carlson & Murphy, 2005). As described by Solmaz et al. (2024) in their paper, robots and communication equipment can also be damaged by collapsing buildings, leading to reduced or lost functionality and loss of coordination between units, especially when swarm-based approaches are being used. Additionally, complex terrain can cause malfunctions in many of the systems used, which require human intervention and, therefore, can put responders' lives at risk.

Another challenge encountered by aerial-ground robots in rubble environments is perceptual degradation, which significantly limits robotic performance in these scenarios. In relation to that, this term refers to the difficulties faced by vision-based sensors in enclosed and collapsed structures, as they are exposed to suspended dust, complete darkness, smoke, and other occlusion factors (Reich & Sklar, 2006). These factors obstruct visual feeds and sensor readings, and diminish the robot's ability to detect victims and navigate correctly, also hindering the mission's operational success (Cadena et al., 2016). These limitations demonstrate the need for more robust sensors and new perception strategies, together with more reliable communications networks.

5.2 *Communication and Localization Constraints*

Communication and localization between robots are often hindered in disaster scenarios, as collapsing buildings, rubble, structural fires, and explosions may damage cables and interfere with GPS, Wi-Fi, and other signals, forcing robots to operate in isolation and largely impairing rescue missions. Given the difficulty of maintaining situational awareness and coordination in GPS-denied and connectivity-scarce zones, Lajoie et al. (2020) developed DOOR-SLAM, which is a system based on peer-to-peer communication that does not require connectivity between units. Similarly, other studies have also discussed ways in which fragmented networks can be preserved in these scenarios. For example, using C-SLAM (Collaborative Simultaneous Localization and Mapping) in multi-robot systems or robotic swarms can prevent communication-related issues (Lajoie et al., 2022), which could otherwise disrupt formations, delay progress, and cause errors in the collective decision-making of the group.

Aiming to overcome the localization constraints in disaster scenarios, various techniques and frameworks were developed by researchers. For example, one related approach is utilizing a landmark-based localization system (LanBLoc) to predict the future state of moving entities along the affected areas, replacing the use of GPS in these isolated settings (Sapkota & Madria, 2024). Moreover, vision-based approaches can help mitigate localization-related problems, as seen in the use of Visual Simultaneous Localization and Mapping (VSLAM) techniques, which use visual data to create 3D maps of the surroundings without the need for external connections (Lu et al., 2022).

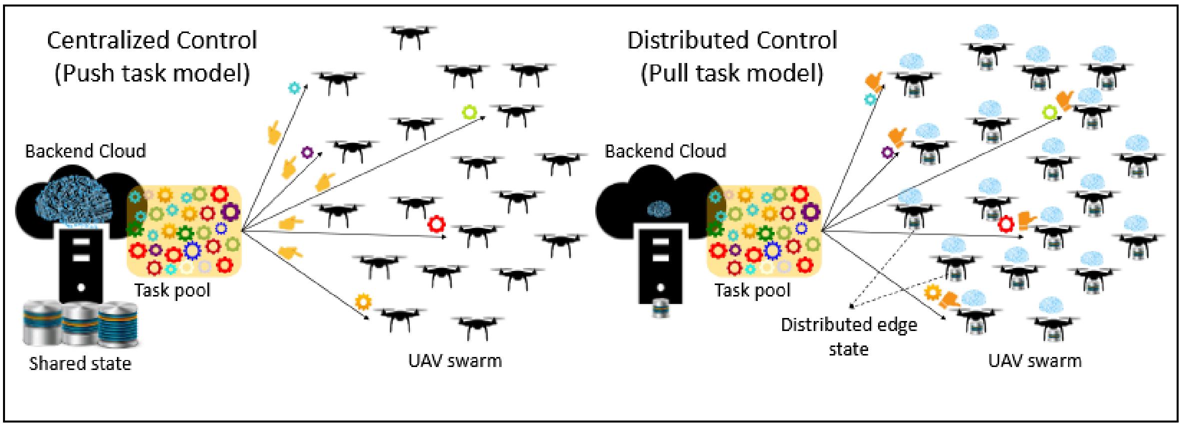
Together, these locally-based communication and localization strategies form resilient foundations for swarm coordination when traditional connectivity methods fail. This collective research effort reveals a clear pattern in the field's evolution: a deliberate shift away from reliance on fragile, pre-existing infrastructure (like GPS and Wi-Fi) and toward self-reliant, onboard solutions. These systems allow robot swarms to generate their own shared understanding of the environment through peer-to-peer communication and collaborative mapping, representing a critical shift for enabling autonomy in GNSS-denied environments.

5.3 *Autonomy and Human–Swarm Interaction*

Managing swarm robots during search and rescue missions is both challenging and risky. This can be attributed to the fact that, as units get added to the swarm, more coordination, control, and efficient decision-making are demanded to maintain proper functionality. Aiming to mitigate this difficulty, Hunt et al. (2023) investigate how human-swarm collaboration in the context of Search and Rescue can improve performance and autonomy of swarms, optimizing the reliability and efficiency of these systems as humans can oversee tasks and decisions. Comparably, Kelly et al. (2024), addressing the main trade-off between centralized and decentralized control illustrated in Figure 7, propose a dynamic hybrid control architecture combining centralized and decentralized control strategies to optimize swarm performance while reducing human cognitive load. This approach offers a solid middle ground between efficiency (centralization) and scalability (decentralization).

Figure 7

Centralized vs. Distributed Control Architectures for Swarm Coordination



Note. This figure contrasts the centralized ("push") and distributed ("pull") models of task allocation and state management in swarm robots. From “To Centralize or Not to Centralize: A Tale of Swarm Coordination” by Hu et al., 2018, arXiv. Open access. https://doi.org/10.48550/arXiv.1805.01786

Moreover, it is essential for robotic swarms to maintain decision-making in real time to avoid further complications in the disaster areas. From this perspective, Li et al. (2025) propose a Human-in-the-loop Multi-Robot Collaboration Framework (HMCF), which increases adaptability by reallocating tasks and matching capabilities between the swarm, all supervised by humans to ensure safety and reliability. Similarly, Calzolari et al. (2024) present a decentralized collaborative framework based on Reinforcement Learning, enabling faster, smarter, and more efficient decision-making by learning from the environment and operator feedback.

To provide a concise overview of the research discussed above, the following table (Table 5) summarizes the main efforts and approaches developed to address the communication, localization, and autonomy challenges faced by aerial–ground swarm robotics in disaster scenarios.

Table 5

Summary of Recent Research in Aerial–Ground Swarm Robotics

Category	Challenge	Approach	Researchers	Outcome
Communication and Localization	Reliance on fragile external infrastructure (GPS, Wi-Fi)	Peer-to-peer communication (DOOR-SLAM), collaborative mapping (C-SLAM)	Lajoie et al. (2020, 2022)	Maintains coordination without central servers; resilient swarm operation
Navigation and Mapping	GPS-denied or signal-limited	Landmark-based localization	Sapkota & Madria (2024),	Robots navigate and

	environments	(LanBLoc), Visual SLAM (VSLAM)	Lu et al. (2022)	map autonomously, ensuring continuous functionality
Autonomy and Human-Swarm Interaction	Managing complex swarms without overloading operators	Dynamic hybrid control models (centralized + decentralized), human-in-the-loop frameworks, decentralized reinforcement learning	Hunt et al. (2023), Kelly et al. (2024), Li et al. (2025), Calzolari et al. (2024)	Enhances real-time decision-making, adaptability, safety, and efficiency of swarms

Note. Data adapted from Lajoie et al. (2020, 2022), Lu et al. (2022), Sapkota & Madria (2024), Hunt et al. (2023), Kelly et al. (2024), Li et al. (2025), Calzolari et al. (2024).

6. Future directions and opportunities

6.1 *Adaptive Autonomy and Resilient Communication*

Considering the need for autonomous and efficient robots in search and rescue contexts, improvements in decision-making and reliable communication must be further developed. With such an objective, the implementation of Machine Learning strategies presents potential benefits to decision-making, as the system could adjust its actions based on the data collected from the environment (Gielis et al., 2022). This approach would allow for minimal human intervention, enabling aerial-ground swarms to operate more efficiently while minimizing risk to human responders. Moreover, Khatib et al. (2006) propose a coordination strategy enhanced by machine learning-based detection, which improves data integrity and system robustness. This strategy, if used appropriately in search and rescue contexts, could enable faster victim detection and more effective collaboration.

As discussed in Section 5, communication barriers are one of the main obstacles during search and rescue missions, having the capacity to hinder an entire operation. Therefore, it is necessary to develop more resilient communication networks to guarantee mission success in these scenarios (Sterbenz et al., 2010). For example, Mauthe et al. (2016) present deployable backup networks that integrate heterogeneous communication technologies. This approach could maintain communication between robots and responders even when normal systems break down, ensuring that all critical information is delivered. Moreover, Gorbil & Gelenbe (2013) propose Oppcomms (opportunistic communications), an approach that exchanges messages at a close range by exploiting human mobility, without the use of any infrastructure. This system, similarly to the one presented by Mauthe et al., could also maintain reliable and resilient communication despite any environmental or man-made barriers.

These two research thrusts (smarter autonomy and resilient networking) are deeply interconnected: reliable communication is necessary for distributing learned behaviors and coordinating decisions, while intelligent autonomy can help manage network resources (Mauthe et al., 2016) (Gorbil & Gelenbe, 2013). Future progress in these areas should be evaluated against standardized metrics, such as communication latency under interference, decision-making speed in novel scenarios, and the rate of successful task completion without human intervention.

6.2 Multidisciplinary Collaboration and Policy Frameworks

The future success of aerial-ground swarm systems in search and rescue missions will certainly depend on collaboration among multiple groups, such as researchers, manufacturers, ethicists, and policymakers (Alqudsi & Makaraci, 2024). These systems, entrusted with life-saving responsibilities, require high dependability, ethical grounding, and real-world applicability. Hence, collaboration between numerous disciplines is needed to ensure safety and reliability in disaster scenarios. Expanding on this, the aerial-ground swarm system must be functional, performing as expected; safe, not putting people's lives at risk during an operation; and ethical, adhering to a set of moral principles that dictate its decision-making (Waykar, 2021).

Moreover, the use of aerial-ground swarm systems should also be discussed at a government level. Therefore, establishing robust policy frameworks is crucial for their effective and ethical use (Winfield et al., 2025). Concerning this, government agencies must develop clear guidelines and regulations to manage accountability in deployments. For example, an article by Pepple (2025) discusses the need for policy and regulation to ensure the humanitarian principles involved with the deployments of such robots.

Furthermore, the development of federal policy frameworks for unmanned vehicles emphasizes the importance of safety and transparency in this system (Watts et al., 2012), especially in emergency response contexts. Expanding on this, it underscores that the path to deployment is not purely technical; successful integration requires parallel progress in technology development, ethical guideline creation, and regulatory framework establishment (Pepple, 2025). The most robust technical system will fail to save lives if policy barriers prevent its timely deployment or if public trust is lacking due to ethical concerns.

7. Conclusion

In this paper, we reviewed the operational advantages of heterogeneous aerial-ground swarms for urban search-and-rescue, stemming from their complementary strengths (UAV overhead mapping + UGV close-range sensing), sensor fusion, and decentralized coordination. These capabilities are promising, but they do not eliminate the hard lessons from field deployments. Fragile communications, sensor degradation in rubble, limited endurance, and gaps in real-time autonomy in complex, dynamic environments still constrain real-world deployment, limiting operational reliability and safety.

Given these gaps, we recommend a focused engineering agenda: prioritize resilient networking, such as opportunistic relays and resistance to degradation; implement robust multimodal perception and SLAM resilient to dust, smoke, darkness, and occlusion; and design autonomous models that are context-aware and confidence-sensitive to enable robust decision-making on when to act autonomously and when to request human oversight. All of this must be validated in realistic field trials, not only in simulations.

Finally, technical advances must go hand in hand with policy and practice. We need interdisciplinary standards; ethical and accountability frameworks; and regular discussions to align development with operational needs and societal values, involving emergency managers, researchers, ethicists, manufacturers, and policymakers. If we coordinate research, policy, and real-world testing now, these swarms can move from promising prototypes to trusted, life-saving tools.

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Coordinated Aerial-Ground Robot Swarms for Urban Disaster Response: Enhancing Resilience Through Collaborative Multi-Terrain Operations

[redacted]

ALL SUBSTANTIVE CHANGES ARE HIGHLIGHTED IN YELLOW. THE ONLY EXCEPTIONS ARE THE GLOBAL LANGUAGE EDITS, WHERE INFORMAL EXPRESSIONS WERE REPLACED WITH MORE FORMAL ACADEMIC TERMINOLOGY THROUGHOUT THE TEXT

Abstract: Urban disasters like collapsing buildings, earthquakes, and explosions present major challenges when mapping the affected areas and looking for victims in the rubble. In recent years, the use of heterogeneous aerial-ground swarm robots has evolved into a promising approach due to their adaptability, scalability, and fault tolerance. This paper presents a comprehensive review of the use of such heterogeneous swarms, highlighting their capability of assisting human responders through a synergistic combination between aerial surveying and close-range ground sensing. In doing so, this review traces the evolution of such techniques throughout early robotic deployments, such as in the World Trade Center collapse, to more modern swarm-based approaches. Furthermore, this paper outlines the foundational characteristics and advantages of swarm robots, with a focus on their potential benefits in Search and Rescue scenarios when integrating heterogeneous systems of drones and ground robots. Persistent challenges, such as communication issues, limited resources, and environmental noise, are also discussed. Finally, future prospects and possible solutions for improving autonomy, robustness, and scalability in aerial-ground robot swarms in search and rescue scenarios are reviewed. Therefore, this paper aims to provide a foundation for improving swarm-enabled disaster response strategies, guiding future research and deployments to enhance performance in critical situations.

Keywords: Swarm robotics; UAV-UGV coordination; Disaster response; Sensor fusion; Autonomous systems.

1. Introduction

Urban disasters, whether caused by human actions or natural events, often present complex challenges for rescuers and emergency responders, resulting in widespread destruction, ethical dilemmas, and significant numbers of injuries and fatalities (Waykar, 2021). Therefore, the chaotic and unpredictable nature of disaster environments demands rapid response from public agencies and prompt action in healthcare and rescue efforts, areas that have historically been underdeveloped. In recent years, however, technological advancements have positioned robots as promising transformative tools in these scenarios (Murphy, 2012).

As a result of these emerging technologies, in disaster situations, robots offer considerable advantages relative to traditional human-only search and rescue teams, since they present increased autonomy, scalability, and replaceability, characteristics that are essential in a rapidly changing, unexpected, and dangerous environment (Abraham et al., 2019). Initially, ground robots started being used for victim detection and ground sensing in regions affected by the presence of large amounts of rubble. Then, drones began being applied for mapping purposes. Following this evolution, recently, a swarm-based approach combining drones and ground robots started being developed for use in these scenarios, representing substantial potential improvements in efficiency and performance (Chatziparaschis et al., 2020).

Given this recent development, swarm robots have become an increasingly prominent topic due to their applications in various fields, being defined as large groups of simplistic robots coordinated by environmental rules, acting as one collective agent to efficiently accomplish a certain given task (Navarro & Matía, 2013). Accordingly, these types of robots can be classified as homogeneous (all identical or very similar in terms of hardware, software, capabilities, and roles within the swarm) or heterogeneous (diverse agents with different capabilities and specialized roles), with the latter being the focus of this review.

Nonetheless, despite its increasing use, swarm robotic systems still present key operational limitations, such as quick-draining battery life, sensor malfunctions, and poor decision-making under irregular conditions (Şahin, 2005) (Murphy, 2017). Additionally, swarm systems also face numerous organizational and structural challenges, such as communication failures and inefficient task allocation (Brambilla et al., 2013). Therefore, while their benefits are evident, these constraints show that several improvements are required to ensure consistent performance during real-world operations.

Building on this foundation, this paper explores how heterogeneous aerial–ground robot swarms have contributed to Search and Rescue missions in urban zones, such as in victim detection and mapping in collapsed buildings, and identifies potential developments to enhance their autonomy and reliability in disaster response. By analyzing the collaboration between these swarm systems, this paper hypothesizes that this integrated approach, promising but relatively underexplored, can significantly increase the speed, coverage, and effectiveness of rescue operations, potentially reducing casualties and enhancing recovery outcomes when compared to non-collaborative robotic systems. This review will synthesize findings across multiple studies to identify consistent performance benefits, key trade-offs in system design, and the most pressing gaps between research and real-world deployment.

In Section 2, the principles, advantages, and applications of swarm robotics in general are discussed. Section 3 continues to present early robotic deployments in disaster scenarios and takeaways from their performance. The use of coordinated aerial-ground swarm robotics in Search and Rescue missions is stated in Section 4. The persistent challenges faced by these robots in disaster scenarios are described in Section 5. Next, Section 6 outlines future directions and opportunities of swarm-based aerial-ground systems. Lastly, in Section 7 the main ideas of this review are synthesized.

2. Swarm Robotics: Advantages and Applications

This upcoming section presents the foundational principles, core advantages, and representative applications of swarm robotics in general to establish the base concepts and mechanisms that underlie swarm behavior. The specific and detailed application to heterogeneous aerial–ground systems will be developed in Section 4, where we apply these foundational ideas directly in the search and rescue context.

2.1 Principles of Swarm Intelligence

Swarm robotics is a subfield of collective robotics that applies principles of swarm intelligence, modeled after the behavior of social insects like ants and bees, to accomplish tasks that exceed the capabilities of individual robots. More specifically, it can be defined as the study of how collective intelligent behavior emerges from interactions both among individual agents and with their environment. These agents are typically simple in design and limited in capability when operating alone, but demonstrate efficiency when functioning as a group (Dorigo, 2005).

One of the founding features of swarm robotics is its reliance on decentralized control, where no single unit of the swarm dictates the behavior of the group, and instead every unit functions as a coordinated group, interacting with each other and the environment (Barca & Sekercioglu, 2013). In the context of disaster response, this principle directly supports resilience in communication-disrupted environments, allowing missions to continue even if part of the swarm loses connection. Additionally, this feature provides a particular resilience and scalability to the swarm, as units can be removed or added without interfering with the performance of the given task (Hu et al., 2018).

Closely tied to decentralization is the concept of redundancy, a critical feature responsible for the reliability of swarm robots. Specifically, redundancy refers to the system's ability to maintain task execution even when individual units fail (Christensen et al., 2009). During urban search-and-rescue missions, redundancy ensures operational continuity when robots are lost to rubble collapse or environmental hazards, a pattern repeatedly observed in field reports such as Murphy (2017). This characteristic is particularly valuable in dynamic and harsh environments, where failures are expected and continuous operation is essential.

Another fundamental feature of swarm robotics is scalability. This property refers to the system's capacity to maintain effective performance regardless of the size of the swarm, largely enabled by its local communication and decentralized coordination (Bjerknes & Winfield, 2013). As a result, the system can easily adapt to meet the scale of the operation, increasing both the efficiency and the resilience of these swarms. For example, scaling up a robotic swarm from a small collapsed building to a city block requires only proportional adjustments to communication range and task assignment rather than a complete redesign, which demonstrates practical scalability.

Table 1 summarizes how these core principles correspond to operational advantages in search-and-rescue missions

Table 1

Core Swarm Robotics Principles and Their Operational Roles in Urban Search-and-Rescue Missions

Principle	Operational role in Search-and-Rescue	Evidence type	Sources
Decentralization	Enables continued coordination despite signal loss	Field-tested (WTC, ICARUS)	(Murphy, 2017); (Hu et al., 2018)
Redundancy	Maintains mission progress despite unit failure	Field-tested	(Christensen et al., 2009); (Murphy, 2017)
Scalability	Adjusts team size to mission scale	Simulation-supported	(Bjerknes & Winfield, 2013); (Chatziparaschis et al., 2020)

Note. Data adapted from (Murphy, 2017), (Hu et al., 2018), (Christensen et al., 2009), (Bjerknes & Winfield, 2013), (Chatziparaschis et al., 2020).

2.2 *Benefits of Swarm Robotics in Dynamic Environments*

A key advantage of swarm robotics is grounded in its flexibility and resilience when operating in unpredictable and fast-changing scenarios (Bayındır, 2016). Specifically, due to this system's decentralized control and distributed decision-making, swarm robots can quickly adapt to environmental shifts such as blocked pathways, communication failures, or changing terrain. This allows them to maintain coordinated navigation and reliable task execution even under unpredictable disaster conditions (Khaldi & Cherif, 2015). This flexibility allows the swarm to reconfigure itself in real-time, adjusting its size, role, and trajectories to optimize results.

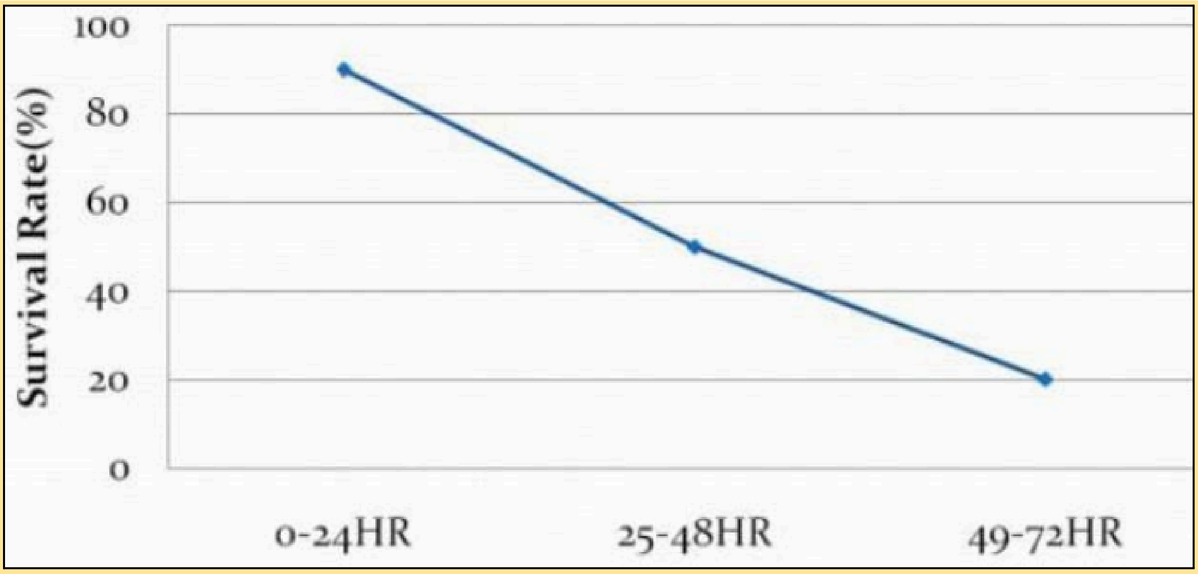
Furthermore, swarm robots display remarkable fault-tolerance. Originating from its redundancy and local communication within the system, a swarm's fault-tolerancy ensures the task is completed even when facing partial failures in the group (Winfield & Nembrini, 2006). This robustness makes robot swarms particularly suited for high-risk and unpredictable scenarios such as those seen in disaster zones, where timely response, adaptability, and continuity are essential for success.

2.3 *Relevance to Search and Rescue Contexts*

Linking to this, such missions are often characterized by their uncertainty, time-sensitivity, and instability. According to research, survival chances for trapped victims are highest within the first 24–48 hours, but start to decline thereafter, often dropping below 20% after 72 hours (see Figure 1)(Zhang et al., 2018).

Figure 1

Statistics of Rescue Time and Survival Rate

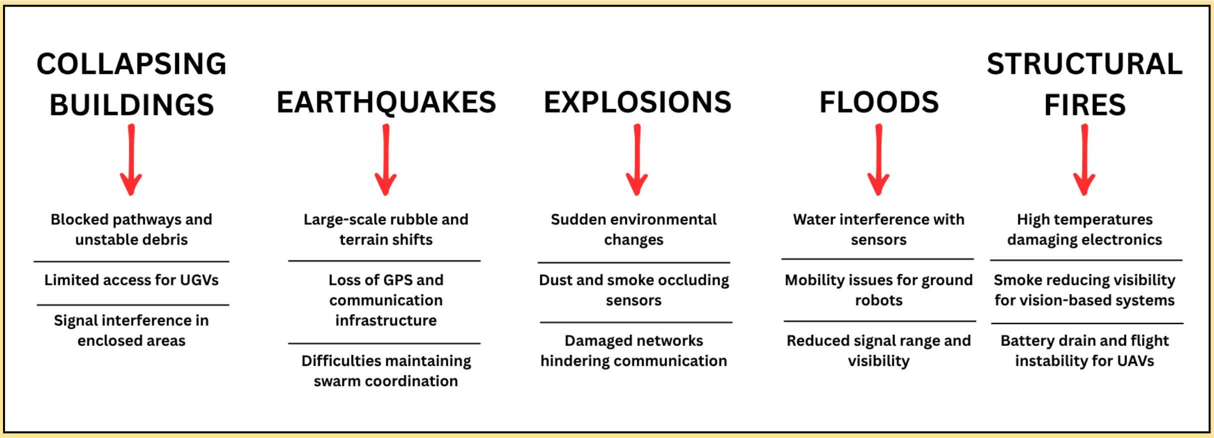


Note. Survival rate declines as time after the event increases, emphasizing the importance of rapid response. Adapted from Hakami, A., Kumar, A., Shim, S. J., & Nahleh, Y. A. (2013). *Application of soft systems methodology in solving disaster emergency logistics problems*. Open access.

Similarly, urban disasters, such as collapsing buildings, earthquakes, explosions, floods, and structural fires, give rise to unpredictable and fast-changing environments, unsuited for conventional rescue techniques (see Figure 2). Therefore, robustness and flexibility are essential in these situations, as rescue efforts must continue despite any encountered obstacles (Waykar, 2021).

Figure 2

Urban Disasters and Their Associated Challenges



Note. This schematic summarizes common urban disasters (collapsing buildings, earthquakes, explosions, floods, and structural fires) and the main operational and environmental challenges they present. Own work.

In relation to that, swarm robotics strongly aligns with the demands of Search and Rescue missions due to its inherent characteristics. Specifically, their redundancy and decentralized control make them highly robust in scenarios where units of the system can fail. Moreover, their autonomy and scalability enable them to rapidly adapt to fast-changing conditions and maintain their operation even in large and complex environments (Moosavi et al., 2024) (Waykar, 2021).

Furthermore, these systems can, through collaboration, aid in the exploration of inaccessible or high-risk areas, in the detection of victims, and in the mapping of the affected zones, demonstrating substantially greater efficiency compared to conventional monitoring systems, making them remarkably suited for such missions. The primary trade-off for these benefits is the increased complexity in coordination and control. However, given the time-critical nature of rescue missions and the high risk of unit loss, the swarm's resilience and scalability present a compelling advantage over more fragile, complex single-robot systems. Therefore, the theoretical foundation of swarm robotics aligns precisely with the practical demands of urban search and rescue.

3. Early Robotic Deployments and Lessons Learned

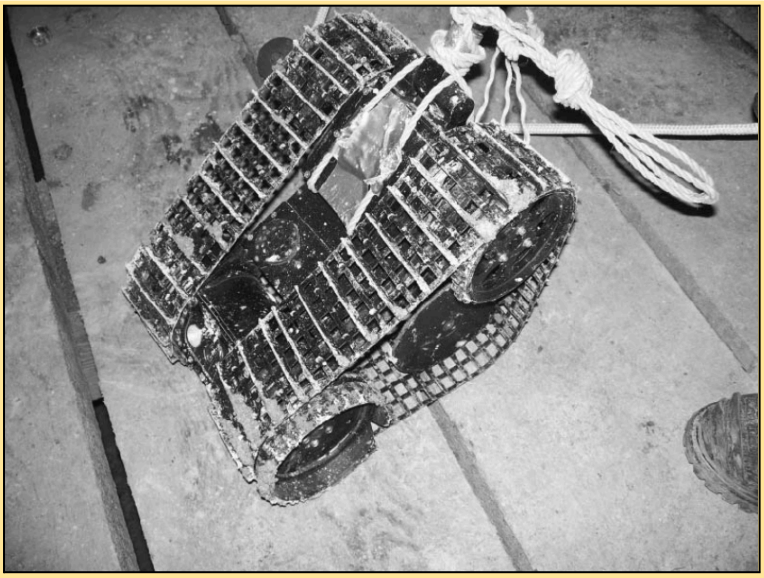
3.1 Case Studies in Search and Rescue Robotics

In the aftermath of the World Trade Center Collapse in 2001, ground robots were, for the first time, deployed in real urban disaster conditions. In this context, these robots were tasked with searching through the debris, analyzing the structural integrity of the collapsed buildings, and helping human responders locate victims. Moreover, these systems were equipped with cameras and thermal sensors, which were essential for search in the confined, inaccessible, and hazardous areas (Casper & Murphy, 2003). Ultimately, this experience established the foundations for further deployments in many other disaster scenarios, as presented below:

At the La Conchita, California, mudslide, ground robots (Inuktun VGTV Xtreme) were launched into the debris to track missing residents. In doing so, they found significant mobility issues due to terrain instability caused by the mud (Murphy, 2008). Moreover, at the Midas Gold Mine collapse in Nevada, a ground robot (an updated Inuktun VGTV Xtreme) was deployed to search for a missing miner (see Figure 3). However, the robot was unable to locate the body because of its insufficient lighting (Murphy, 2012). Furthermore, at Florida's Berkman Plaza collapse, a ground robot (Inuktun VGTV) was deployed to help locate a missing worker. However, the robot failed in locating the victim independently due to communication and locomotion issues caused by the collapsed environment (Murphy, 2012).

Figure 3

The Inuktun Extreme Robot in the Midas Gold Mine Rescue Operation



Note. This figure shows the Inuktun Extreme robot used in the Midas Gold Mine incident to navigate debris and assist rescuers in the confined underground areas. From "Navigational and Mission Usability in Rescue Robots" by R. R. Murphy, 2010, *Journal of* *the Robotics Society of Japan*, 28(2), 142–146. Open access. https://doi.org/10.7210/jrsj.28.142.

Together, these deployments show the potential and limitations of robots in Search and Rescue scenarios. The specific challenges synthesized in Table 2 demonstrate the need for enhanced locomotion systems, more adaptable modules, and resilient communication to support successful operations in these environments.

Table 2

Synthesis of Challenges in Early Ground Robot Deployments

Deployment scenario	Robot Model	Primary Challenge	Outcome/Impact
World Trade Center (2001)	Various (multiple)	Communication difficulties, extreme environmental conditions	Limited effectiveness; established proof-of-concept but high failure rate
La Conchita Mudslide (2005)	Inuktun VGTV Xtreme	Mobility in unstable, muddy terrain	Severely hampered operations; robot could not traverse key areas
Midas Gold Mine Collapse	Inuktun VGTV Xtreme	Insufficient sensor capability (lighting)	Failed task; unable to locate victim due to poor visibility
Berkman Plaza Collapse	Inuktun VGTV	Locomotion and communication in dense rubble	Failed task; could not reach victim, highlighting terrain limitations

Note. Data adapted from (Murphy, 2008), (Murphy, 2012).

3.2 *Environmental Obstacles and Limitations of Early Ground Robots*

Despite their innovative use, many limitations were observed when operating in the World Trade Center's remains. This and other deployments showed high failure rates, presenting a Mean Time Between Failures (MTBF) of approximately 24 hours and an availability rate of about 54% (Carlson et al., 2004). Regarding that, most of the deployed ground robots presented short operational lifespans due to the extreme conditions, which compromised their functionality. Moreover, these systems also faced communication difficulties, reducing their effectiveness in this scenario (Murphy, 2010).

Consequently, their deployment demonstrated the need for improvements in robustness and autonomy to enhance robotic capabilities in such disaster environments.

Many hardware characteristics contributed to these limitations. In this regard, many deployed ground robots faced size-related challenges: they were either too big to fit through tight spaces or too small to carry the necessary equipment. Moreover, several of them lacked the appropriate structural design required for traversing in unstable terrain, which prevented them from further operating in the disaster scenarios. Additionally, sensors and cameras also struggled when functioning in low-light or obscured areas (Carlson & Murphy, 2005).

Environmental factors must also be considered. In disaster areas, sharp and irregular debris can damage or trap the robots and equipment; suspended dust can obstruct visibility and impair sensor functionality; thick concrete and rebar within the rubble can hinder communication and navigation signals (Tong et al., 2024). Furthermore, high temperatures, moisture, and chemical leaks can degrade hardware and cause malfunctions in the system (Singh et al., 2015).

Collectively, these factors reveal that early ground robots, despite their pioneering use, were highly limited in terms of robustness, autonomy, and efficiency, underscoring the importance of new solutions and designs to increase their performance in disaster responses. The pattern of failure across these cases revealed the fundamental vulnerability of the single-robot, ground-only model, providing a clear rationale for the transition towards heterogeneous, multi-robot systems.

3.3 *Lessons Learned and Their Influence*

These insights culminated in the formalization of disaster robotics as an actual subfield within robotics research. In this context, disaster response came to be recognized as a significant and coherent research area, supported by governments and scientific communities. Consequently, academic labs, public institutions, and independent researchers started working together to develop new designs and technologies that could mitigate the limitations of previous deployments.

Building on these foundations, coordinated aerial–ground swarm robotics has emerged as a promising approach, offering increased adaptability, scalability, autonomy, robustness, and efficiency in complex disaster response scenarios.

4. Coordinated Aerial–Ground Swarm Robotics in Disaster Response

4.1 *Functions of UAVs and UGVs*

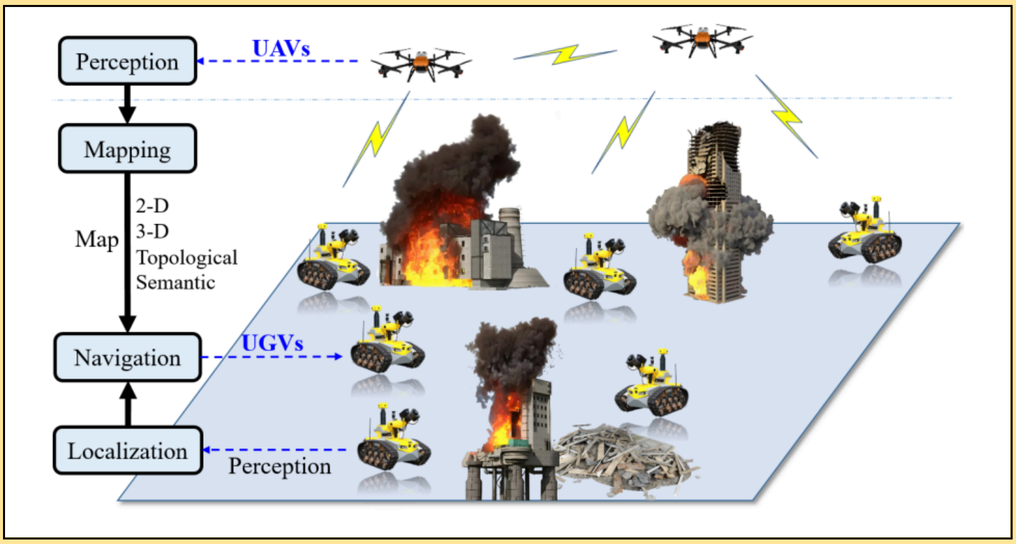
Unmanned Aerial Vehicles (UAVs) play an important role in disaster scenarios, as they can quickly obtain essential information about the area's circumstances. Specifically, these drones can cover wide areas in real-time, supporting guidance and rescue through the mapping of the affected zone, the detection of areas with the highest likelihood of finding survivors, and the transport of medical supplies (Munasinghe et al., 2024). Moreover, they can also act by extending communication coverage, maintaining connections between different technologies or human teams, even throughout scattered locations (Li et al., 2021).

In contrast, Unmanned Ground Vehicles (UGVs) in disaster scenarios can navigate in inaccessible and high-risk areas, perform close-up detailed inspections, and assist in victim detection and interaction (Munasinghe et al., 2024). Furthermore, as these robots are deployed directly into the collapsed zones and can be equipped with manipulation tools, they can interact with the environment by clearing paths and removing obstacles (Berns et al., 2017). As a result, they facilitate more efficient and effective rescue operations.

A summary of the complementary functions of UAVs and UGVs is shown in Figure 4.

Figure 4

Fundamental Roles of UAVs and UGVs in Search and Rescue Missions



Note. This figure illustrates the key roles of UAV-UGV collaboration. From "Air-Ground Collaborative Robots for Fire and Rescue Missions: Towards Mapping and Navigation Perspective" by Y. Zhang, H. Yan, D. Zhu, J. Wang, C.-H. Zhang, W. Ding, X. Luo, C. Hua, and M. Q.-H. Meng, 2025, arXiv. Open access.

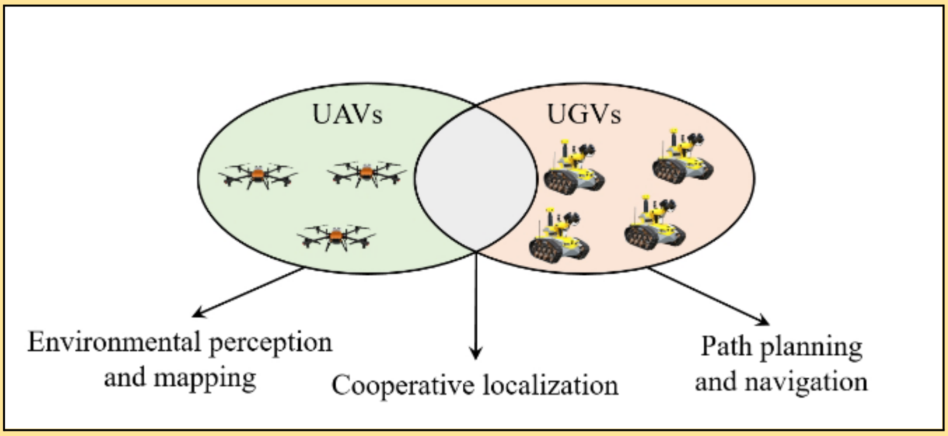
Building on these complementary strengths, the next section will explore the underdiscussed but promising coordination between aerial and ground robots through a swarm-based approach.

4.2 Swarm-based coordination of aerial-ground robots

The coordination of aerial-ground robots in disaster scenarios comes with numerous benefits, as illustrated in Figure 5. In these scenarios, UAVs can provide real-time overview data to inform and guide the UGVs' navigation along the safest and most convenient routes. Expanding on that, while drones perform the mapping from above (identifying structural instabilities, survivor hotspots, and areas to avoid), ground robots can use this information to support on-site activities, such as accessing voids, removing obstacles for human rescuers, or delivering medical aid to victims (Munasinghe et al., 2024). These complementary roles, in a complex and unpredictable environment, not only effectively allocate tasks in a systematic manner, but also enable more efficient coverage and faster response times (Queralta et al., 2020). Therefore, by integrating their individual specialties and capabilities, this collaboration can achieve enhanced autonomy, flexibility, and reliability compared with independent operation (see Table 3), such as in the World Trade Center rescue operation.

Figure 5

Key collaborative functions between UAVs and UGVs in disaster response scenarios



Note. This figure outlines the core areas of cooperation between UAVs and UGVs. From "Air-Ground Collaborative Robots for Fire and Rescue Missions: Towards Mapping and Navigation Perspective" by Zhang et al., 2025, arXiv. Open access. https://doi.org/10.48550/arXiv.2412.20699

Table 3

Performance Metrics for Coordinated vs. Non-Coordinated Systems in Search-and-Rescue Simulations

Metric	Non-Coordinated	Heterogeneous UAV-UGV	Improvement	Source
Mission time	100.0 min	26.7 min	-73.3%	(Chen et al., 2025)
Task completion rate (TCR)	Baseline (varies)	+18.42% TCR over baseline	+18.42%	(Lu et al., 2025)
Localization error (GNSS-denied)	1.17 m median error	0.10 m median error	-91.5%	(Sivaneri & Gross, 2017)

Note. TCR = Task Completion Rate; GNSS = Global Navigation Satellite System. Data adapted from (Chen et al., 2025), (Lu et al., 2025), (Sivaneri & Gross, 2017).

Other collaboration strategies reported in the literature include UAVs acting as communication relays to extend connectivity between UGVs and base stations (Johansen et al., 2014), UGVs serving as mobile landing or charging platforms for UAVs (Cheng et al., 2023), cooperative mapping and sensor-fusion workflows in which aerial maps are refined by ground agents for traversal planning (Zhang et al., 2025), and cooperative localization where ground vehicles assist aerial pose estimation via ranging or visual markers (Sivaneri & Gross, 2017) (see Table 4).

Table 4

Collaborative UAV–UGV Approaches in GPS-Denied or Challenging Environments

Collaboration Type	Main idea	Source
Communication relay	UAV acts as an aerial relay to extend communication range between UGVs or back to a remote base, enabling coordinated operations in areas with limited connectivity	(Johansen et al., 2014)
UGV as a landing platform	UAV performs autonomous landing or docking on a moving UGV, even in GPS-denied environments, using sensor fusion and dynamic tracking to ensure precision and	(Cheng et al., 2023)

	safety	
Cooperative mapping/sensor fusion	UAV captures aerial maps which are refined and complemented by UGV data for accurate local mapping, helping robots navigate complex or obstructed environments during search and rescue	(Zhang et al., 2025)
Cooperative localization/ranging	UGV assists the UAV in estimating its position and orientation using UWB or vision-based measurements, improving navigation reliability in GNSS-challenged or GPS-denied environments	(Sivaneri & Gross, 2017)

Note. UWB = Ultra-Wideband. Data adapted from (Johansen et al., 2014), (Cheng et al., 2023), (Zhang et al., 2025), (Sivaneri & Gross, 2017).

Moreover, implementing this coordinated approach through a swarm-based system presents even more benefits, significantly increasing its general performance. Specifically, by employing the core principles of swarm intelligence, such as redundancy, local communication, and decentralized decision-making, these aerial-ground systems can naturally adapt to changing conditions, reallocate tasks, and continue operating despite individual unit failures (Brambilla et al., 2013).

This swarm-based coordination also enables UAVs and UGVs to more effectively change their strategy based on the needs and risks of the mission, highlighting their increased adaptability in these environments. This decentralized model also allows scalability, as units of drones or ground robots can be added to increase efficiency and coverage when required (Zhang et al., 2025).

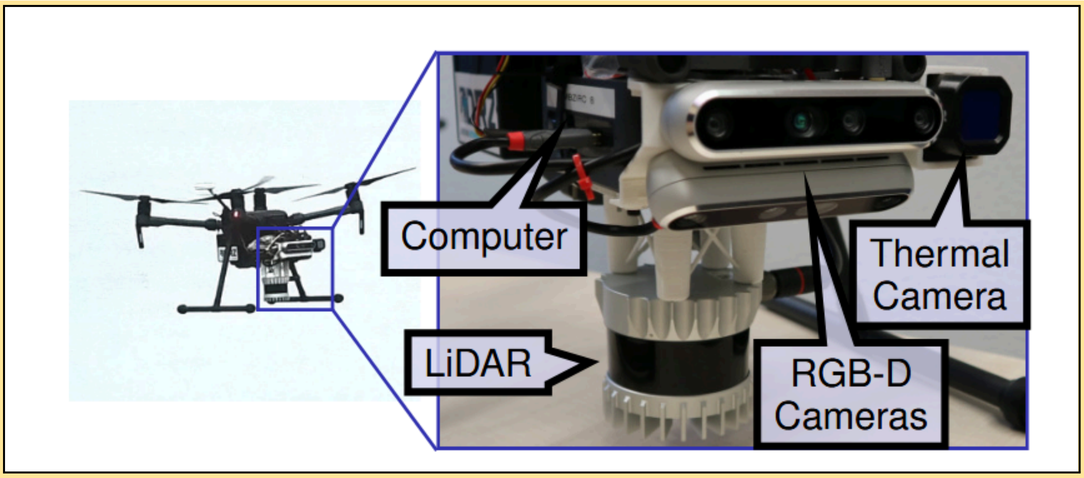
Therefore, this swarm-based coordination of aerial-ground robotic systems holds promising capabilities that deserve to be further studied and developed, in order to increase resilience, flexibility, and coverage in such unpredictable and chaotic environments. The quantitative potential of this approach is demonstrated in realistic simulations. For instance, a study modeling a post-tsunami environment found that a swarm of just five autonomous UAVs could achieve 90% sensor coverage over a 2 km^2 area in under 90 minutes, reaching nearly 99% coverage within two hours (Arnold et al., 2018). This illustrates the potential of swarm-based systems to deliver on the promise of rapid, large-area assessment that is critical in the immediate aftermath of a disaster.

4.3 Sensor Implementation for Victim Detection and Mapping

Implementing sensors into aerial-ground robot systems can increase their performance in disaster scenarios. Through the combination of the capabilities of multiple sensors across these systems, this integration can potentially overcome many limitations. For example, UAVs can use RGB and thermal cameras to collect data and thermal imagery, aiding in the search for victims from above. Moreover, UGVs can use LiDAR and sound sensors for on-site mapping and close-up victim detection, which may be particularly useful in areas blocked from GPS signals. Bultmann et al. (2021) present in their paper a UAV system with LiDAR, RGB, and thermal sensors, showcasing improved object recognition and increased overall reliability (see Figure 6). In parallel, Xu et al. (2022) provide a study of a LiDAR-based sensor for SLAM (Simultaneous Localization and Mapping), demonstrating how the implementation of this technology can improve localization and mapping under unpredictable settings.

Figure 6

Multi-Sensor Fusion for UAV Navigation and Perception



Note. This diagram illustrates the types of sensors integrated for advanced perception in UAVs. From “Real-Time Multi-Modal Semantic Fusion on Unmanned Aerial Vehicles” by Bultmann et al., 2021, arXiv. Open access. https://doi.org/10.48550/arXiv.2108.06608

Considering these studies, it is evident that the use of such sensors in disaster scenarios brings numerous efficiency benefits (Cani et al., 2025). Therefore, their use in aerial-ground swarms can, combined with these systems’ innate robustness and flexibility, provide increased precision and reliability in such sensitive settings. In turn, this leads to fewer casualties among victims and responders compared to conventional rescue methods that rely solely on human teams or non-coordinated robotic systems. This is because the combination of different sensors can increase the situational awareness of the system, enabling faster and more effective victim detection even in challenging settings (Schichler et al., 2025).

However, it is important to note that while studies like Bultmann et al. (2021) and Xu et al. (2022) provide strong empirical evidence for improved sensor performance and mapping accuracy, the claim of directly reducing casualties remains a projected, outcome-based benefit that requires further validation through large-scale field trials.

4.4 *Field Deployments and Case Examples*

The ICARUS Project: The EU-FP7 ICARUS project deployed a fleet of unmanned aerial and ground robots equipped with victim-detection sensors and a radio network to support responders in realistic disaster simulations (Doroftei et al., 2014). In various simulated collapse scenarios, such as destroyed buildings and flood-affected areas, the UAVs managed to conduct aerial reconnaissance and thermal imaging, while the UGVs explored debris piles to perform close-range inspections and payload deliveries. While ICARUS deployments were not robot swarms in the strictest technical sense, they did incorporate swarm-inspired principles. Analyzing their performance, expert end-users evaluated functionality and efficiency, highlighting the ICARUS robots' decreased deployment times, improved situational awareness, and robustness against failures, which are core benefits arising from its decentralized, swarm-inspired design (De Cubber et al., 2013).

Surfside Condo Collapse: During the Champlain Towers South condominium collapse in Surfside, Florida, rescue teams rapidly deployed heterogeneous unmanned systems in what became the largest and longest drone-based disaster response on record. As detailed by Rao et al. (2023), hundreds of UAV missions were demanded to generate orthomosaic maps, digital elevation models, and thermal searches for survivors. At the same time, UGVs were deployed into the standing structure to inspect inaccessible areas and act as communication relays for aerial units. Moreover, these ground robots were also equipped with 360° cameras and thermal sensors in order to improve close-up victim detection in the rubble.

In retrospect, these operations underscored the immense value of integrating aerial and ground platforms, most notably with a swarm-based approach, demonstrating their beneficial and efficient applications in disaster response. Across both simulated and real-world deployments, end-users consistently identify the integration of aerial and ground perspectives as the most critical factor for improving situational awareness and reducing operational time, directly supporting this review's thesis. However, there are many persistent challenges in these settings that need to be addressed.

5. Persistent Challenges in Rubble Environments

5.1 Environmental and Perceptual Challenges

UAVs and UGVs continue to face numerous challenges during Search and Rescue missions. For example, many ground robots encounter difficulties when traversing irregular terrain or unstable structures, compromising mission safety and navigation. Moreover, in these chaotic settings, uneven surfaces and loose debris can immobilize or entrap the robots (Carlson & Murphy, 2005). As described by Solmaz et al. (2024) in their paper, robots and communication equipment can also be damaged by collapsing buildings, leading to reduced or lost functionality and loss of coordination between units, especially when swarm-based approaches are being used. Additionally, complex terrain can cause malfunctions in many of the systems used, which require human intervention and, therefore, can put responders' lives at risk.

Another challenge encountered by aerial-ground robots in rubble environments is perceptual degradation, which significantly limits robotic performance in these scenarios. In relation to that, this term refers to the difficulties faced by vision-based sensors in enclosed and collapsed structures, as they are exposed to suspended dust, complete darkness, smoke, and other occlusion factors (Reich & Sklar, 2006). These factors obstruct visual feeds and sensor readings, and diminish the robot's ability to detect victims and navigate correctly, also hindering the mission's operational success (Cadena et al., 2016). These limitations demonstrate the need for more robust sensors and new perception strategies, together with more reliable communications networks.

5.2 Communication and Localization Constraints

Communication and localization between robots are often hindered in disaster scenarios, as collapsing buildings, rubble, structural fires, and explosions may damage cables and interfere with GPS, Wi-Fi, and other signals, forcing robots to operate in isolation and largely impairing rescue missions. Given the difficulty of maintaining situational awareness and coordination in GPS-denied and connectivity-scarce zones, Lajoie et al. (2020) developed DOOR-SLAM, which is a system based on peer-to-peer communication that does not require connectivity between units. Similarly, other studies have also discussed ways in which fragmented networks can be preserved in these scenarios. For example, using C-SLAM (Collaborative Simultaneous Localization and Mapping) in multi-robot systems or robotic swarms can prevent communication-related issues (Lajoie et al., 2022), which could otherwise disrupt formations, delay progress, and cause errors in the collective decision-making of the group.

Aiming to overcome the localization constraints in disaster scenarios, various techniques and frameworks were developed by researchers. For example, one related approach is utilizing a landmark-based localization system (LanBLoc) to predict the future state of moving entities along the affected areas, replacing the use of GPS in these isolated settings (Sapkota & Madria, 2024). Moreover, vision-based approaches can help mitigate localization-related problems, as seen in the use of Visual Simultaneous Localization and Mapping (VSLAM) techniques, which use visual data to create 3D maps of the surroundings without the need for external connections (Lu et al., 2022).

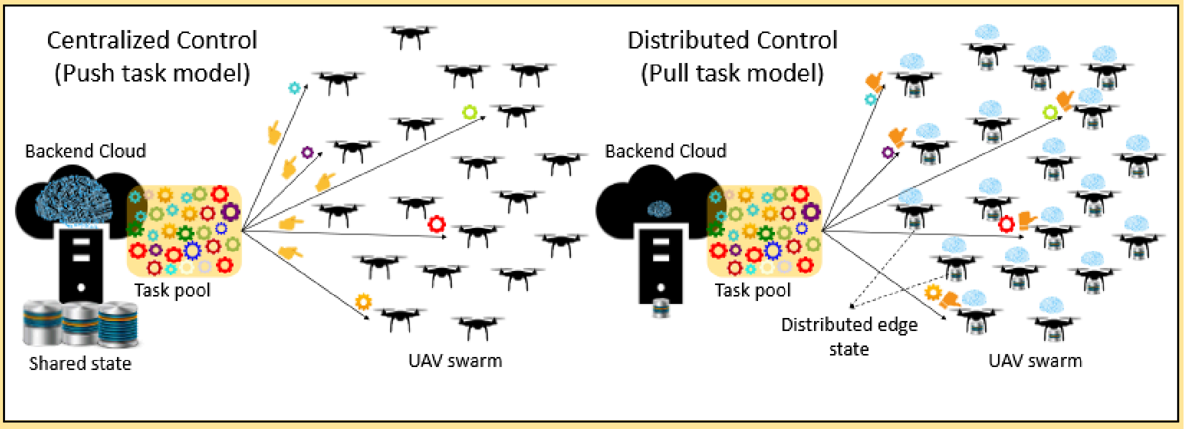
Together, these locally-based communication and localization strategies form resilient foundations for swarm coordination when traditional connectivity methods fail. This collective research effort reveals a clear pattern in the field's evolution: a deliberate shift away from reliance on fragile, pre-existing infrastructure (like GPS and Wi-Fi) and toward self-reliant, onboard solutions. These systems allow robot swarms to generate their own shared understanding of the environment through peer-to-peer communication and collaborative mapping, representing a critical shift for enabling autonomy in GNSS-denied environments.

5.3 *Autonomy and Human–Swarm Interaction*

Managing swarm robots during search and rescue missions is both challenging and risky. This can be attributed to the fact that, as units get added to the swarm, more coordination, control, and efficient decision-making are demanded to maintain proper functionality. Aiming to mitigate this difficulty, Hunt et al. (2023) investigate how human-swarm collaboration in the context of Search and Rescue can improve performance and autonomy of swarms, optimizing the reliability and efficiency of these systems as humans can oversee tasks and decisions. Comparably, Kelly et al. (2024), addressing the main trade-off between centralized and decentralized control illustrated in Figure 7, propose a dynamic hybrid control architecture combining centralized and decentralized control strategies to optimize swarm performance while reducing human cognitive load. This approach offers a solid middle ground between efficiency (centralization) and scalability (decentralization).

Figure 7

Centralized vs. Distributed Control Architectures for Swarm Coordination



Note. This figure contrasts the centralized ("push") and distributed ("pull") models of task allocation and state management in swarm robots. From “To Centralize or Not to Centralize: A Tale of Swarm Coordination” by Hu et al., 2018, arXiv. Open access. https://doi.org/10.48550/arXiv.1805.01786

Moreover, it is essential for robotic swarms to maintain decision-making in real time to avoid further complications in the disaster areas. From this perspective, Li et al. (2025) propose a Human-in-the-loop Multi-Robot Collaboration Framework (HMCF), which increases adaptability by reallocating tasks and matching capabilities between the swarm, all supervised by humans to ensure safety and reliability. Similarly, Calzolari et al. (2024) present a decentralized collaborative framework based on Reinforcement Learning, enabling faster, smarter, and more efficient decision-making by learning from the environment and operator feedback.

To provide a concise overview of the research discussed above, the following table (Table 5) summarizes the main efforts and approaches developed to address the communication, localization, and autonomy challenges faced by aerial–ground swarm robotics in disaster scenarios.

Table 5

Summary of Recent Research in Aerial–Ground Swarm Robotics

Category	Challenge	Approach	Researchers	Outcome
Communication and Localization	Reliance on fragile external infrastructure (GPS, Wi-Fi)	Peer-to-peer communication (DOOR-SLAM), collaborative mapping (C-SLAM)	Lajoie et al. (2020, 2022)	Maintains coordination without central servers; resilient swarm operation
Navigation and Mapping	GPS-denied or signal-limited	Landmark-based localization	Sapkota & Madria (2024),	Robots navigate and

	environments	(LanBLoc), Visual SLAM (VSLAM)	Lu et al. (2022)	map autonomously, ensuring continuous functionality
Autonomy and Human-Swarm Interaction	Managing complex swarms without overloading operators	Dynamic hybrid control models (centralized + decentralized), human-in-the-loop frameworks, decentralized reinforcement learning	Hunt et al. (2023), Kelly et al. (2024), Li et al. (2025), Calzolari et al. (2024)	Enhances real-time decision-making, adaptability, safety, and efficiency of swarms

Note. Data adapted from Lajoie et al. (2020, 2022), Lu et al. (2022), Sapkota & Madria (2024), Hunt et al. (2023), Kelly et al. (2024), Li et al. (2025), Calzolari et al. (2024).

6. Future directions and opportunities

6.1 Adaptive Autonomy and Resilient Communication

Considering the need for autonomous and efficient robots in search and rescue contexts, improvements in decision-making and reliable communication must be further developed. With such an objective, the implementation of Machine Learning strategies presents potential benefits to decision-making, as the system could adjust its actions based on the data collected from the environment (Gielis et al., 2022). This approach would allow for minimal human intervention, enabling aerial-ground swarms to operate more efficiently while minimizing risk to human responders. Moreover, Khatib et al. (2006) propose a coordination strategy enhanced by machine learning-based detection, which improves data integrity and system robustness. This strategy, if used appropriately in search and rescue contexts, could enable faster victim detection and more effective collaboration.

As discussed in Section 5, communication barriers are one of the main obstacles during search and rescue missions, having the capacity to hinder an entire operation. Therefore, it is necessary to develop more resilient communication networks to guarantee mission success in these scenarios (Sterbenz et al., 2010). For example, Mauthe et al. (2016) present deployable backup networks that integrate heterogeneous communication technologies. This approach could maintain communication between robots and responders even when normal systems break down, ensuring that all critical information is delivered. Moreover, Gorbil & Gelenbe (2013) propose Oppcomms (opportunistic communications), an approach that exchanges messages at a close range by exploiting human mobility, without the use of any infrastructure. This system, similarly to the one presented by Mauthe et al., could also maintain reliable and resilient communication despite any environmental or man-made barriers.

These two research thrusts (smarter autonomy and resilient networking) are deeply interconnected: reliable communication is necessary for distributing learned behaviors and coordinating decisions, while intelligent autonomy can help manage network resources (Mauthe et al., 2016) (Gorbil & Gelenbe, 2013). Future progress in these areas should be evaluated against standardized metrics, such as communication latency under interference, decision-making speed in novel scenarios, and the rate of successful task completion without human intervention.

6.2 *Multidisciplinary Collaboration and Policy Frameworks*

The future success of aerial-ground swarm systems in search and rescue missions will certainly depend on collaboration among multiple groups, such as researchers, manufacturers, ethicists, and policymakers (Alqudsi & Makaraci, 2024). These systems, entrusted with life-saving responsibilities, require high dependability, ethical grounding, and real-world applicability. Hence, collaboration between numerous disciplines is needed to ensure safety and reliability in disaster scenarios. Expanding on this, the aerial-ground swarm system must be functional, performing as expected; safe, not putting people's lives at risk during an operation; and ethical, adhering to a set of moral principles that dictate its decision-making (Waykar, 2021).

Moreover, the use of aerial-ground swarm systems should also be discussed at a government level. Therefore, establishing robust policy frameworks is crucial for their effective and ethical use (Winfield et al., 2025). Concerning this, government agencies must develop clear guidelines and regulations to manage accountability in deployments. For example, an article by Pepple (2025) discusses the need for policy and regulation to ensure the humanitarian principles involved with the deployments of such robots.

Furthermore, the development of federal policy frameworks for unmanned vehicles emphasizes the importance of safety and transparency in this system (Watts et al., 2012), especially in emergency response contexts. Expanding on this, it underscores that the path to deployment is not purely technical; successful integration requires parallel progress in technology development, ethical guideline creation, and regulatory framework establishment (Pepple, 2025). The most robust technical system will fail to save lives if policy barriers prevent its timely deployment or if public trust is lacking due to ethical concerns.

7. Conclusion

In this paper, we reviewed the operational advantages of heterogeneous aerial-ground swarms for urban search-and-rescue, stemming from their complementary strengths (UAV overhead mapping + UGV close-range sensing), sensor fusion, and decentralized coordination. These capabilities are promising, but they do not eliminate the hard lessons from field deployments. Fragile communications, sensor degradation in rubble, limited endurance, and gaps in real-time autonomy in complex, dynamic environments still constrain real-world deployment, limiting operational reliability and safety.

Given these gaps, we recommend a focused engineering agenda: prioritize resilient networking, such as opportunistic relays and resistance to degradation; implement robust multimodal perception and SLAM resilient to dust, smoke, darkness, and occlusion; and design autonomous models that are context-aware and confidence-sensitive to enable robust decision-making on when to act autonomously and when to request human oversight. All of this must be validated in realistic field trials, not only in simulations.

Finally, technical advances must go hand in hand with policy and practice. We need interdisciplinary standards; ethical and accountability frameworks; and regular discussions to align development with operational needs and societal values, involving emergency managers, researchers, ethicists, manufacturers, and policymakers. If we coordinate research, policy, and real-world testing now, these swarms can move from promising prototypes to trusted, life-saving tools.

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This paper reviews heterogeneous aerial–ground swarm robotics for urban search-and-rescue (SAR). The manuscript provides a clear introduction and useful historical context. It explains core swarm principles, describes UAV/UGV roles and common sensors, and discusses persistent challenges and future directions. The paper's tone is constructive and the literature coverage is broad, with many recent citations. Overall, the paper is promising but would benefit from a few revisions.

Paper Strengths

The paper demonstrates strong motivation and clear framing of why UAV–UGV swarms are important for urban SAR. It provides useful grounding in real-world deployments (e.g., WTC, ICARUS, Surfside), which helps readers connect theory to practice. The engagement with literature is broad, and includes sensing, SLAM, communication, autonomy, and ethics, with many up-to-date citations.

Comments to the Author

The paper is well written and generally easy to follow. However, much of Sections 2–5 primarily summarize individual works. The review would be more valuable with greater synthesis, highlighting connections, trade-offs, and emerging patterns across studies. Right now, the paper has no figures or tables. Including these would significantly strengthen the clarity of the paper. For example, a table comparing field deployments (platforms, environments, and outcomes) or a schematic of UAV–UGV swarm architectures would add strong pedagogical value.

In addition, extracting quantitative results from cited deployments would be helpful. A short subsection on evaluation metrics and benchmark proposals for future trials could offer practical guidance for both researchers and practitioners. Where possible, highlight areas of and indicate which claims are well-supported versus speculative.

Recommendation

Accept with minor revisions. The manuscript is well written and broadly informed, but it requires the addition of comparative synthesis, figures/tables, and clearer benchmarks to make it worthy of publication.

Thank you for your insightful feedback. Your guidance has been invaluable in strengthening the analytical depth and clarity of my paper, making the connections between ideas clearer, the overall structure more logical, and the final review much more impactful and easy to follow. The specific changes I made are listed below:

1. "However, much of Sections 2–5 primarily summarize individual works. The review would be more valuable with greater synthesis, highlighting connections, trade-offs, and emerging patterns across studies."

I addressed this by shifting the focus from summarizing individual studies to synthesizing broader trends. The revisions introduce a stronger analytical narrative that connects concepts across sections, such as explicitly linking the failures of early deployments to the rationale for modern swarm systems. New comparative tables, such as Tables 1, 2 and 5, were added to highlight performance trade-offs and collective research outcomes, while thematic analysis, such as the field's shift toward infrastructure-independent systems, now clearly illustrates emerging patterns across the cited works.

2. “Right now, the paper has no figures or tables. Including these would significantly strengthen the clarity of the paper. For example, a table comparing field deployments (platforms, environments, and outcomes) or a schematic of UAV–UGV swarm architectures would add strong pedagogical value. “

I addressed this by incorporating 5 tables and 7 figures to enhance the paper's clarity and pedagogical value. Specifically, I added tables that synthesize key information, such as a comparison of core swarm principles and their operational roles, a summary of challenges in early deployments, and an overview of collaborative UAV-UGV approaches. I also included schematics illustrating UAV-UGV collaborative functions and control architectures, providing clear visual reinforcement of the concepts discussed

3. “In addition, extracting quantitative results from cited deployments would be helpful. A short subsection on evaluation metrics and benchmark proposals for future trials could offer practical guidance for both researchers and practitioners. Where possible, highlight areas of and indicate which claims are well-supported versus speculative.”

I addressed this by integrating quantitative data, such as the performance metrics in Table 3, directly into relevant sections to maintain narrative flow rather than creating a separate subsection. Furthermore, I explicitly indicated the nature of the evidence supporting various claims by specifying whether findings were derived from field-tested deployments (e.g., ICARUS, WTC), simulations, or real-world scenarios, and noted where projected benefits remain speculative and require further validation.

In addition to these changes, I refined the paper's academic tone and removed the original section 2.3, because it didn’t fit well in the review’s scope. Other structural improvements included streamlining the introduction and conclusion and strengthening the narrative flow between sections to enhance overall coherence.

This paper provides a comprehensive review of heterogeneous aerial–ground swarm robotics for urban disaster response. It summarizes the foundational characteristics and advantages of swarm robotics, discusses current challenges, and outlines future research directions. Despite the importance of the topic, there exists many points that need to be improved, such as insufficient illustration and confused logicality. I would recommend this manuscript to be accepted for publication after major revision.

1. Scope in Section 2: The authors summarize general principles and benefits of swarm robotics (applicable to both homogeneous and heterogeneous systems), but do not clearly introduce the specific principles and advantages of aerial–ground swarm robotics. Please align this section more closely with the manuscript's stated focus.
2. Irrelevant Content (Section 2.3): The discussion of swarm robotics in agriculture is not directly relevant to the theme of urban disaster response. I recommend deleting this subsection.
3. Collaboration Methods (Section 4.2): The authors describe only one method of UAV–UGV collaboration (UAVs guiding UGV navigation). This section should either summarize additional collaboration strategies from the literature (e.g., UAVs acting as communication relays, UGVs supporting UAV landings, cooperative mapping, etc.) or revise the section title to more accurately reflect the limited scope.
4. In Section 5, the authors discuss the current challenges faced by aerial–ground swarm robotics. Please also summarizes the research efforts and attempts that have been made to address these issues.
5. Lack of Figures: No figures are provided in this review, which makes it difficult to follow. Please add illustrative figures to support the text, for example:

   a. Section 2.4: A schematic summarizing types of urban disasters where aerial–ground swarms could be applied.
   b. Section 3: Images or diagrams of robots used in cited case studies.
   c. Section 4.1: Examples of UAVs and UGVs typically deployed in disaster contexts.
   d. Section 4.2: A diagram illustrating how UAVs and UGVs coordinate within a swarm system.
   e. Section 4.3: Examples of sensor payloads for victim detection and mapping.
   f. Section 4.4: Images of aerial–ground swarm robots used in case examples

6. The manuscript occasionally uses informal expressions (e.g., “way better efficiency,” “huge potential change”). A more professional academic expression is recommended.

Decision

Accept with major revisions

Thank you for your insightful feedback. Your guidance has been invaluable in strengthening this review, making the connections between ideas clearer, the overall structure more logical, and the final analysis more impactful. The specific changes I made are listed below:

1. “Scope in Section 2: The authors summarize general principles and benefits of swarm robotics (applicable to both homogeneous and heterogeneous systems), but do not clearly introduce the specific principles and advantages of aerial–ground swarm robotics. Please align this section more closely with the manuscript’s stated focus.”

I have retained the general overview of swarm robotics to provide a necessary foundational understanding for readers, ensuring that core principles are firmly established before their application to the more complex aerial-ground context. To directly align this section with the paper's specific focus, I have added a new introductory paragraph that explicitly frames these general concepts as a foundation and states that their detailed application to heterogeneous aerial-ground systems will be developed in Section 4, thereby creating a clearer and more logical pathway for the reader.

2. “Irrelevant Content (Section 2.3): The discussion of swarm robotics in agriculture is not directly relevant to the theme of urban disaster response. I recommend deleting this subsection.”

I agree that the content on other applications was outside of the paper's scope. I have therefore deleted Section 2.3 to maintain the focus on urban disaster response.

3. “Collaboration Methods (Section 4.2): The authors describe only one method of UAV–UGV collaboration (UAVs guiding UGV navigation). This section should either summarize additional collaboration strategies from the literature (e.g., UAVs acting as communication relays, UGVs supporting UAV landings, cooperative mapping, etc.) or revise the section title to more accurately reflect the limited scope.”

I have expanded on Section 4.2 to include a broader range of collaboration strategies, such as UAVs acting as communication relays, UGVs serving as landing platforms, and cooperative mapping/localization techniques, supported by a new Table 4 that summarizes these approaches. This revision provides a more comprehensive overview of aerial-ground collaboration methods as found in the literature.

4. “In Section 5, the authors discuss the current challenges faced by aerial–ground swarm robotics. Please also summarize the research efforts and attempts that have been made to address these issues.”

I have expanded Section 5 to include a synthesis of research efforts addressing these challenges. This includes adding a concluding paragraph that identifies the field's evolutionary shift toward self-reliant systems, supported by the new Table 5 summarizing specific approaches and Figure 7 illustrating control architectures, providing a comprehensive overview of current solutions.

5. “Lack of Figures: No figures are provided in this review, which makes it difficult to follow. Please add illustrative figures to support the text, for example:

  a. **Section 2.4: A schematic summarizing types of urban disasters where aerial–ground swarms could be applied.**
  b. **Section 3: Images or diagrams of robots used in cited case studies.**
  c. **Section 4.1: Examples of UAVs and UGVs typically deployed in disaster contexts.**

d. **Section 4.2: A diagram illustrating how UAVs and UGVs coordinate within a swarm system.**
e. **Section 4.3: Examples of sensor payloads for victim detection and mapping.**
f. **Section 4.4: Images of aerial–ground swarm robots used in case examples"**

I have added 7 figures and 5 tables throughout the paper to significantly improve its pedagogical value and visual clarity. These include Figure 1 (survival rates), Figure 2 (urban disaster contexts), Figure 3 (early robot deployments), Figures 4-5 (UAV-UGV coordination), Figure 6 (sensor systems), Figure 7 (control architectures), and Tables 1-5 that synthesize principles, case studies, performance metrics, collaboration methods, and research solutions. Together, they directly address most of the examples you mentioned and make the technical content much easier to follow.

6. "The manuscript occasionally uses informal expressions (e.g., "way better efficiency," "huge potential change"). A more professional academic expression is recommended."

I did my best to refine the language across the entire manuscript, replacing all informal expressions with more precise and professional academic terminology to ensure a consistent and appropriate tone.

In addition to the specific changes discussed, I have enhanced the manuscript's analytical depth by shifting from summarizing individual studies to synthesizing broader research trends. This includes adding comparative tables to highlight performance trade-offs and implementing a stronger thematic analysis that clearly illustrates emerging patterns, such as the field's decisive shift toward infrastructure-independent systems, throughout the paper.

The authors have addressed the most comments in the previous review. The overall structure and clarity of the paper have improved significantly, and it now reads much more clearly.

Strengths:

In Section 2, the authors added a new introductory paragraph that clearly defines the scope of this section and connects the general principles of swarm robotics with the aerial–ground systems which were discussed in Section 4. The deletion of the unrelated agricultural application section (previously Section 2.3) also makes the discussion more focused and consistent with the theme of urban disaster response. These adjustments make the early part of the paper easier to follow and better aligned with the main topic.

Section 4.2 has been substantially improved. The authors have expanded the discussion of UAV–UGV collaboration methods by including several additional strategies, such as communication relay, UGV as a landing platform, cooperative mapping/sensor fusion, and cooperative localization/ranging. A new summary table was added, which helps readers quickly understand and compare different collaboration modes. This addition enhances the technical depth of the review and provides a clearer picture of how aerial and ground robots can complement each other.

The discussion of challenges and possible solutions has also been improved. The authors now include examples of research efforts that attempt to overcome limitations in perception, communication, and coordination in complex rubble environments. This makes the discussion more balanced and forward-looking.

The writing style is more professional, with informal phrases replaced by precise academic wording. The addition of seven figures and five tables significantly improves readability and gives the review a stronger visual and educational component.

Overall, the manuscript has been greatly improved. It presents a clear, comprehensive, and well-organized overview of heterogeneous aerial–ground swarm robotics for disaster response. The revisions have addressed all key concerns and improved both structure and depth.

Suggestions:

1. Among the collaboration strategies you reviewed, which one do you think is most effective in actual disaster situations? Adding a short explanation or example would help readers better understand practical advantages and challenges.
2. Use one standard term, for example: “aerial–ground”. Do not alternate between “air–ground” and “aerial–ground”.
3. Please add a scale bar or measurement indicator in Figure 6 so readers can better understand the size or spatial relationship of the depicted elements.

Final decision:

I recommend the paper for acceptance after a minor revision.