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Autonomous Multi-Robot Coordination Systems for Disaster Response and Search-and-Rescue Operations †

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Abstract

Natural disasters such as earthquakes, floods, and industrial accidents often create hazardous environments that limit human access and slow rescue operations. Autonomous multi-robot coordination systems have emerged as an effective solution for improving the efficiency and safety of disaster response missions. These systems involve teams of heterogeneous robots—including unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and sensor robots—that collaborate to search for victims, map disaster zones, and support emergency teams. Multi-robot coordination enables faster exploration of large and complex environments while reducing operational risks to human rescuers. Recent advances in artificial intelligence, multi-agent systems, and swarm robotics have enabled robots to share information, allocate tasks dynamically, and adapt to unpredictable environments. Research indicates that coordinated robotic systems can significantly enhance situational awareness and operational efficiency during search-and-rescue missions by performing mapping, surveillance, and victim detection simultaneously. This paper presents a technical framework for autonomous multi-robot coordination systems designed to support disaster response and search-and-rescue operations.

Keywords: autonomous multi-robot; natural disaster; artificial intelligence; process innovation

1. Introduction

Disaster response operations require rapid assessment of hazardous environments where human rescuers may face severe risks. Earthquakes, floods, and building collapses often create unstable environments that limit access to affected areas. Autonomous robotic systems have emerged as powerful tools for supporting emergency responders by providing remote sensing, mapping, and victim detection capabilities.

Traditional search-and-rescue operations rely heavily on human responders and trained animals. While effective, these approaches can be slow and dangerous in large-scale disasters. Robotic technologies offer a complementary solution by enabling machines to enter hazardous environments and perform tasks such as structural inspection, debris exploration, and environmental monitoring.

Multi-robot systems provide significant advantages compared with single-robot system. Teams of robots can explore disaster zones simultaneously, improving search efficiency

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and reducing mission time. These systems typically employ distributed coordination strategies where robots share environmental information and cooperate to achieve mission objectives [1,2].

Recent advances in artificial intelligence and multi-agent systems have further improved robotic coordination capabilities, Figure 1. Robots equipped with sensors such as cameras, LiDAR, and thermal imaging devices can detect survivors and transmit real-time data to rescue teams. These technologies enhance situational awareness and allow emergency responders to prioritize rescue operations more effectively [3].

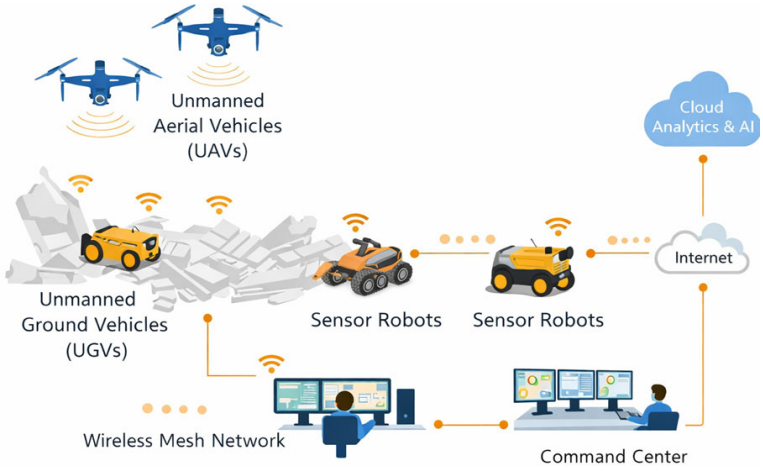


Figure 1. Multi-Robot Disaster Response System Architecture.

2. Literature Review

Research on multi-robot systems has expanded significantly in recent years due to their potential applications in disaster response and environmental monitoring (Table 1). Multi-robot coordination refers to the ability of multiple autonomous robots to collaborate while performing complex tasks such as exploration, mapping, and victim detection.

Table 1. Summary of Previous Multi-Robot Search-and-Rescue Studies.

Study	Robot Type	Coordination Method	Application Scenario	Key Findings
Queralta et al. (2020) [1]	UAVs and UGVs	Distributed multi-agent coordination	Urban disaster search-and-rescue	Demonstrated collaborative perception and mapping capabilities for coordinated rescue missions.
Brambilla et al. (2013) [2]	Swarm robots	Swarm intelligence and decentralized control	Large-area exploration	Showed that swarm robotics enables scalable and fault-tolerant exploration in complex environments.
Murphy (2014) [3]	Ground robots and aerial robots	Human–robot collaboration	Disaster response operations	Highlighted the effectiveness of robots in hazardous environments for victim detection and environmental monitoring.
Bakhshipour et al. (2017) [4]	Swarm robots	Artificial intelligence-based coordination	Search-and-rescue missions	Demonstrated improved search efficiency through swarm intelligence algorithms.
Korsah et al. (2013) [5]	Heterogeneous robot teams	Multi-robot task allocation (MRTA)	Cooperative robotic missions	Proposed taxonomy and algorithms for efficient task allocation among robotic agents.
Nguyen et al. (2020) [6]	Multi-agent robotic systems	Deep reinforcement learning	Autonomous coordination tasks	Demonstrated that machine learning can optimize coordination strategies among robotic agents.

Swarm robotics is a widely studied approach in which large numbers of simple robots cooperate using decentralized coordination rules. Inspired by biological systems such as ant colonies and bee swarms, swarm robots can collectively explore large areas while maintaining system robustness even if individual robots fail [4].

Another important research area is multi-robot task allocation (MRTA). Task allocation algorithms assign tasks to individual robots based on their capabilities, energy levels, and spatial positions. Effective task allocation improves system efficiency and reduces redundant exploration during search missions [5].

Machine learning has also been integrated into multi-robot systems to enhance coordination and decision-making. Multi-agent reinforcement learning algorithms allow robots to learn optimal collaboration strategies through interaction with their environment. These algorithms have been successfully applied in wildfire monitoring and disaster response scenarios [6].

Despite these advancements, challenges remain in communication reliability, scalability of coordination algorithms, and real-time data processing in dynamic disaster environments.

3. Methodology

This research proposes an Autonomous Multi-Robot Coordination Framework (AMRCF) for disaster response and search-and-rescue missions (Figure 2). The framework integrates heterogeneous robotic agents, distributed communication networks, and artificial intelligence algorithms for cooperative exploration and victim detection.

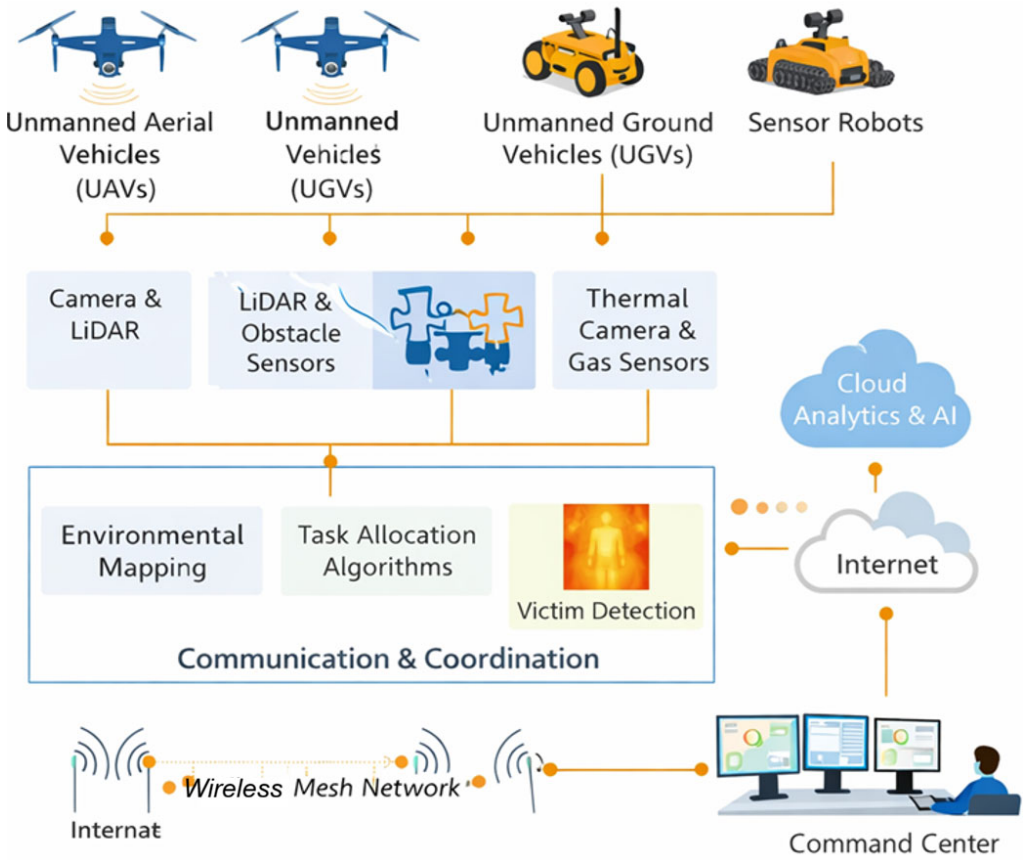


Figure 2. Proposed Autonomous Multi-Robot Coordination Framework.

3.1. Robotic Platforms

The proposed system employs three types of robotic agents (Table 2):

- Unmanned Aerial Vehicles (UAVs) for aerial reconnaissance and environmental mapping
- Unmanned Ground Vehicles (UGVs) for navigation through collapsed structures and debris fields
- Sensor robots equipped with thermal cameras and gas sensors for victim detection

Table 2. Robot Platforms and Sensor Configuration.

Robot Platform	Sensor Type	Measured Data/ Capability	Primary Function in Search-and-Rescue
Unmanned Aerial Vehicle (UAV)	RGB Camera	Aerial images and video streams	Rapid aerial surveillance and disaster area mapping
Unmanned Aerial Vehicle (UAV)	LiDAR Sensor	3D terrain and obstacle detection	Environmental mapping and obstacle avoidance
Unmanned Ground Vehicle (UGV)	LiDAR Scanner	Distance measurement and obstacle detection	Navigation through debris and collapsed structures
Unmanned Ground Vehicle (UGV)	Ultrasonic Sensors	Proximity detection	Collision avoidance and safe navigation
Sensor Robot	Thermal Camera	Heat signatures from humans	Victim detection in low-visibility environments
Sensor Robot	Gas Sensors	Toxic gas concentration levels	Hazard detection and environmental monitoring
Sensor Robot	Microphone/Acoustic Sensor	Sound detection	Identification of trapped victims through sound signals
Ground Robot/Sensor Robot	GPS Module	Location and navigation data	Position tracking and coordination among robots

Each robot is equipped with onboard processing units, navigation systems, and wireless communication modules.

3.2. Communication Architecture

Robots communicate through a wireless mesh network that supports real-time data exchange. The communication network enables robots to share environmental maps, sensor data, and mission updates with other agents.

3.3. Coordination Algorithm

The coordination system uses a distributed multi-agent architecture. Each robot operates as an autonomous agent capable of performing tasks such as:

1. Cooperative exploration using SLAM algorithms
2. Dynamic task allocation using MRTA algorithms
3. Victim detection using deep learning-based image recognition

3.4. Decision Support System

Data collected by the robotic agents are transmitted to a central command platform where rescue teams can visualize disaster environments through real-time maps and sensor readings. The platform provides decision-support tools for prioritizing rescue operations.

4. Results

Simulation experiments were conducted to evaluate the performance of the proposed autonomous multi-robot coordination framework. The simulation environment represented

a disaster-affected urban region containing collapsed buildings and blocked transportation routes. The robotic team consisted of five UAVs and three UGVs equipped with cameras, LiDAR sensors, and thermal imaging devices.

The experimental results demonstrate that coordinated multi-robot systems significantly improve search efficiency compared with single-robot systems, Figure 3. The robotic team was able to explore the disaster environment approximately 3.1 times faster than a single robot operating independently. Parallel exploration allowed robots to cover large areas simultaneously while sharing mapping information through the communication network.

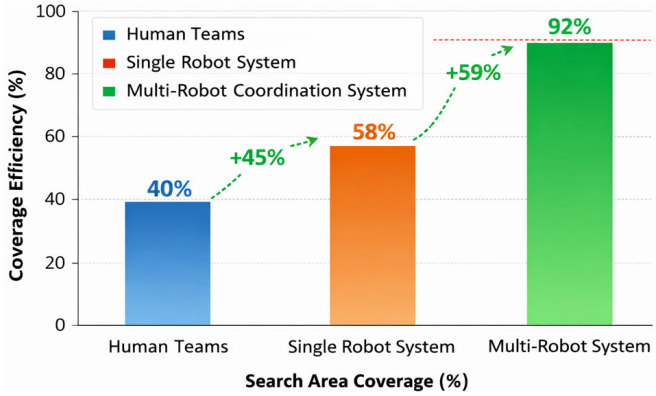


Figure 3. Search Coverage Efficiency Comparison.

Victim detection performance was evaluated using thermal imaging and computer vision algorithms, Figure 4. The system achieved a victim detection accuracy of 92.4%, enabling reliable identification of potential survivors in complex environments. UAVs provided aerial imagery that helped ground robots navigate through debris and locate accessible routes.

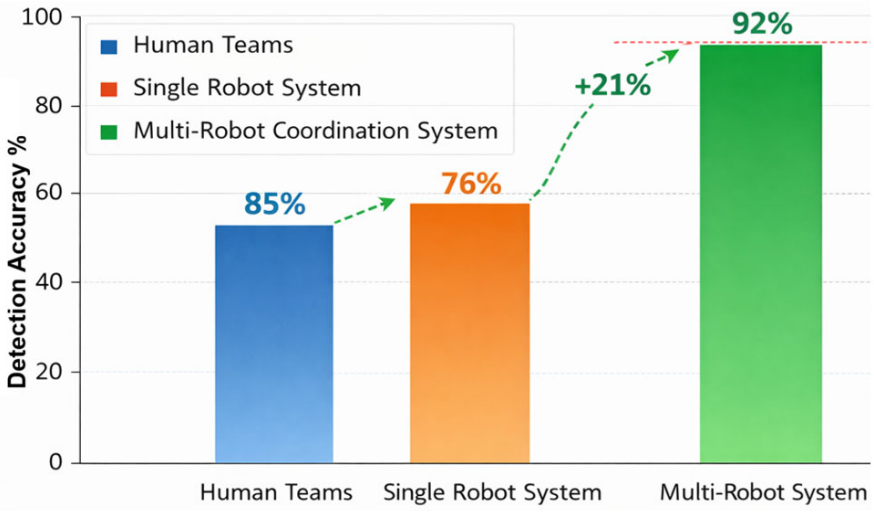


Figure 4. Victim Detection Accuracy Comparison.

Another important result was the improvement in situational awareness for emergency responders, Table 3. Multi-robot SLAM algorithms enabled robots to merge individual maps into a unified disaster environment model. This map was transmitted to the command center, allowing rescue teams to monitor search progress and allocate resources more effectively.

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Table 3. Performance Comparison of Search-and-Rescue Systems.

System Type	Area Coverage Rate	Victim Detection Accuracy	Response Time	Operational Risk to Rescuers	Typical Application Scenario
Human Rescue Teams	Moderate	High (≈85%)	Slow	High	Manual search in disaster zones such as collapsed buildings or earthquake sites
Single Robot System	Low to Moderate	Moderate (≈70–80%)	Moderate	Low	Small-scale inspection tasks and limited area exploration
Multi-Robot Coordination System	High	Very High (≈90–92%)	Fast	Very Low	Large-scale disaster search-and-rescue missions with coordinated aerial and ground robots

5. Challenges and Limitations

Despite the advantages of autonomous multi-robot coordination systems for disaster response, several challenges limit their large-scale deployment in real-world search-and-rescue operations, Table 4. One major limitation is the reliability of wireless communication networks in disaster environments, where damaged infrastructure, debris, or electromagnetic interference may disrupt robot-to-robot communication. Limited battery capacity of mobile robots also restricts mission duration and operational coverage. In complex disaster environments, robots may encounter obstacles such as collapsed structures, uneven terrain, and poor visibility, which can affect navigation accuracy and sensor performance. Additionally, coordinating large numbers of robots requires scalable algorithms capable of handling dynamic environments and unpredictable mission conditions. Data processing and decision-making must also occur in real time, which demands significant computational resources. Finally, the high cost of robotic platforms and maintenance may limit adoption by emergency response organizations.

Table 4. Challenges and Limitations of Multi-Robot Search-and-Rescue Systems.

Challenge Category	Description of Limitation	Impact on SAR Operations	Possible Mitigation Strategies
Communication Reliability	Wireless communication may be disrupted in disaster environments due to debris, damaged infrastructure, or signal interference.	Loss of coordination between robots and delayed data transmission to command centers.	Deploy mesh networking, redundant communication channels, and satellite links.
Limited Battery Life	Mobile robots and UAVs have limited battery capacity, restricting mission duration and operational coverage.	Short mission times may reduce search effectiveness in large disaster areas.	Use energy-efficient algorithms, battery swapping stations, and solar-assisted charging systems.
Navigation in Complex Terrain	Collapsed buildings, debris fields, and uneven terrain can challenge robot mobility and navigation accuracy.	Robots may become trapped or unable to reach certain areas.	Implement advanced SLAM algorithms, terrain-adaptive locomotion, and obstacle avoidance systems.
Scalability of Coordination Algorithms	Coordinating large numbers of robots increases computational complexity and communication overhead.	Reduced efficiency and delays in task allocation and decision making.	Develop scalable multi-agent coordination algorithms and distributed control architectures.

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Table 4. *Cont.*

Challenge Category	Description of Limitation	Impact on SAR Operations	Possible Mitigation Strategies
Sensor Limitations	Sensors such as cameras, LiDAR, and thermal sensors may be affected by smoke, dust, or poor lighting conditions.	Reduced accuracy in victim detection and environmental mapping.	Combine multi-modal sensor fusion techniques and AI-based data filtering.
Deployment and Operational Cost	Robotic platforms, sensors, and maintenance require substantial financial investment.	Limited adoption by emergency agencies with constrained budgets.	Promote modular robot designs and government funding for disaster response technologies.

6. Conclusions

Autonomous multi-robot coordination systems provide significant advantages for disaster response and search-and-rescue operations. By integrating heterogeneous robotic platforms, distributed communication networks, and artificial intelligence algorithms, robotic teams can explore hazardous environments efficiently while reducing risks to human responders. The proposed coordination framework demonstrates substantial improvements in search efficiency, victim detection accuracy, and situational awareness. Multi-robot systems enable parallel exploration of disaster environments, allowing rescue teams to identify survivors more rapidly. Future research should focus on improving communication reliability, scalability of coordination algorithms, and integration with next-generation wireless technologies such as 5G and 6G networks. Advances in machine learning, edge computing, and swarm intelligence are expected to further enhance the autonomy and adaptability of robotic systems. These developments will enable intelligent robotic teams capable of supporting large-scale disaster response operations and improving emergency management capabilities worldwide.

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