

REVIEW

Autonomous Multi-Robot Systems for Real-Time Environmental Monitoring and Disaster Response

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ABSTRACT

Autonomous multi-robot systems (MRS) are revolutionizing environmental monitoring and disaster response by enabling real-time data collection, enhanced situational awareness, and efficient task execution in hazardous environments. They are made up of autonomous and collaborative groups of robots that are fitted with high-tech sensors, machine learning algorithms, and communication technologies that enable them to handle a host of tasks, including environmental surveillance and search and rescue missions. The MRS has major strengths compared to the conventional approaches, which are increased response rates, operation in hazardous or even inaccessible locations, and scalability when dealing with high-volume operations. This review examines the core technologies of MRS, which are sensor integration, autonomous navigation, and coordination algorithms, and how they are used in environmental monitoring and managing disasters. Such issues as environmental variability, power constraints, reliability of communication, scalability, and ethical issues are also analyzed. Nevertheless, the problems do not deter the further development of AI, energy systems, and communication standards, which support the functionality of MRS and allow more efficient, adaptable, and effective systems. The next generation of autonomous MRS has huge potential of enhancing disaster resilience, environmental conservation, and management of resources. MRS can be instrumental in reducing the impact of natural disasters, tracking ecosystems, and protecting human life by working around the current constraints.

Keywords: Autonomous Robots; Multi-Robot Systems; Environmental Monitoring; Disaster Response; Coordination Algorithms

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1. Introduction

Environmental surveillance and disaster management have been the major issues of concern in recent decades owing to the rising frequency and intensity of natural disasters, global warming, and ecological degradation^[1,2]. The quick gathering and processing of data in dynamic and risky settings is a common aspect of responding to such challenges, which is highly challenging for human responders. The existence of the need for efficient and scalable as well as real-time solutions has led to the investigation of autonomous multi-robot systems (MRS) as a transformative solution to the problems. Independent MRS can be used to increase the levels of environmental monitoring, disaster response, and eventually save lives and resources by acting in inaccessible, unsafe, or excessively large environments^[3].

The conventional environmental surveillance systems, like stationary sensors or satellite images, are usually incapable of delivering localized real-time data in disaster-affected regions. In the same manner, the traditional disaster response mechanisms are usually slow and restricted to human factors, including the availability of the disaster areas, communication issues, and manual coordination requirements. Autonomous MRS, however, is advantageous in the sense that it can operate autonomously, in an extended environment, and around the clock, providing real-time data collection, situational awareness, and decision-making in critical situations. Autonomous MRS can collaborate to gather and analyze data, detect hazards, and deliver timely information by integrating robotics, artificial intelligence (AI), and advanced sensor technologies, which are critical in decision-making in environmental monitoring and managing disasters^[4,5].

The recent increase in the number of natural disasters (wildfires, hurricanes, earthquakes, floods, volcanic eruptions) has seen the need to better prepare, respond faster, and utilize resources in an optimized way^[2]. The United Nations Office for Disaster Risk Reduction (UNDRR) reports that natural disasters are increasingly becoming destructive and impact millions of people in different parts of the world and cost billions of dollars in damage to economies. The threat of such calamities is also intensified by environmental degradation through deforestation, pollu-

tion, and the extinction of wildlife. Conventional response strategies that frequently comprise human teams operating in hazardous or remote areas are extremely problematic in regard to speed, safety, and scalability.

Moreover, the environmental monitoring, which is needed in order to identify the early warning signs of natural disasters and evaluate the long-term changes occurring in the ecosystems, necessitates the continuous, universal, and quality data collection in large geographical locations. The human-driven techniques are also restricted by the fact that they require physical presence in hazardous areas, time, and the expense of collecting, processing, and analyzing the data. Here is where self-controlling MRS comes into being because they can be able to operate in remote or dangerous areas without the intervention of a human being. These systems can monitor large-scale locations on a continuous basis, gather numerous types of environmental data (e.g., the quality of air, water levels, radiation), and detect possible threats. During disaster response, MRS can aid human groups through rapid surveying of the disaster-impacted area, finding survivors, and evaluating the damage with the reduction of risks to human lives^[6,7].

The possibility of the multi-autonomous robots working together in one system creates prospects of greater cooperation, whereby the various robots can specialize in certain tasks. As an example, aerial robots (drones) could give a bird-eye view of the disaster-inflicted areas, whereas terrestrial robots (ground-based units) could explore pothole areas and conduct close-up inspections and search and rescue missions. Moreover, the fact that these robots are capable of communicating and exchanging data on a real-time basis brings a certain degree of coordination that enhances efficiency, provides redundancy of tasks, and makes it possible to respond to the changing environment swiftly^[8].

The present review is dedicated to the existing autonomous multi-robot systems to monitor the environment and provide disaster response in real-time^[9]. By offering an overview of the important technologies, uses, and issues surrounding the same, the objective is to give an in-depth insight into the manner in which MRS is transforming these areas. Another important aspect of robotics, AI, sensor integration, and communication technologies that have been mentioned in the review is that these systems are be-

coming more and more viable to be used in practice and on a large scale.

We will discuss the main concepts and underlying technologies that will make autonomous MRS possible, which are sensor integration, machine learning algorithms, strategies of coordination and cooperation, and communication protocols. Moreover, the application to various applications (environmental monitoring of natural resources (air, water, and soil), hazard detection (wildfires, floods, earthquakes), and disaster response activities, including search and rescue, damage assessment, and infrastructure monitoring) will be reviewed. Actual examples of real-life implementation will present available knowledge on the effectiveness and the limitations of MRS in these areas, and show which implementations were successful and which areas still need development^[10-12].

Another area of critical interest of this review will also be the obstacles that impede the change in the widespread adoption and implementation of autonomous MRS in disaster response and environmental monitoring. They are technical problems like navigation in dynamic and unpredictable conditions, power restriction, and communication difficulties, and non-technical ones, like ethics, safety, and compatibility with the existing disaster management systems. Finally, the review will focus on future perspectives of the field, looking at the new trends of AI, machine learning, and sensor technologies, and speculating on the possibility of incorporating autonomous MRS into the global approach to disaster management and environmental protection^[13,14].

Overall, this review aims to present an in-depth discussion of the ways autonomous multi-robot systems are reshaping the field of real-time monitoring of the environment and disaster response, both the present state of the art and the future perspectives of the technologies. It is through this discussion that we seek to emphasize the opportunities, challenges, and innovations that are going to drive the future of autonomous robotics in the following critical areas.

2. Fundamentals of Autonomous Multi-Robot Systems

The framework of autonomous multi-robot systems

is quickly becoming one of the perspectives that can help to mitigate the challenges of real-time environmental monitoring and disaster response. Such systems entail the synchronized operation of several robots, which can be used to handle activities without necessarily being under human influence. Decentralized coordination, collective intelligence, and the capacity to work under difficult conditions make MRS a powerful tool in use in environmental surveillance, as well as disaster management applications. In this part, we discuss the most important features, enabling technologies, and special applications of autonomous MRS.

2.1. Definition and Key Characteristics

As a system that is made up of and contains two or more robots collaborating to reach a shared goal without involving a human operator, an autonomous multi-robot system is characterized^[12,15]. The system always has sensors, actuators, and computing capabilities fitted on each robot so that it can manage to navigate and carry out activities in the real world. The overriding feature that makes MRS unique compared to the single robot systems is the fact that the robots are able to work together, communicate, and coordinate their action in a manner that improves the overall system performance. **Figure 1** gives an example of an autonomous MRS reference architecture that describes how local autonomy, inter-robot communication, and shared representations help in coordinated operation in the presence of uncertainty.

The robots in an MRS may work in a decentralized fashion, that is, every robot may make particular decisions relying on the local information and exchange data and information with other robots across the network^[16]. The benefits of this decentralized model are that it is more scalable, flexible, and resilient. The ability to distribute tasks among multiple robots allows the system to respond to dynamic and unpredictable environments, and this is of great importance, especially in disasters where the situation changes at a very fast rate.

Another aspect that is essential to any MRS is the communication and coordination strategy, which allows the robots to collaborate with each other. The robots should be capable of providing information regarding their environment, status, and progress, and can have real-time updates

and distribution of the tasks in case of need. The coordination algorithms should be resilient to possible failures or violent conflicts between the robots so that the entire system is operable and efficient to achieve its goals^[17,18].

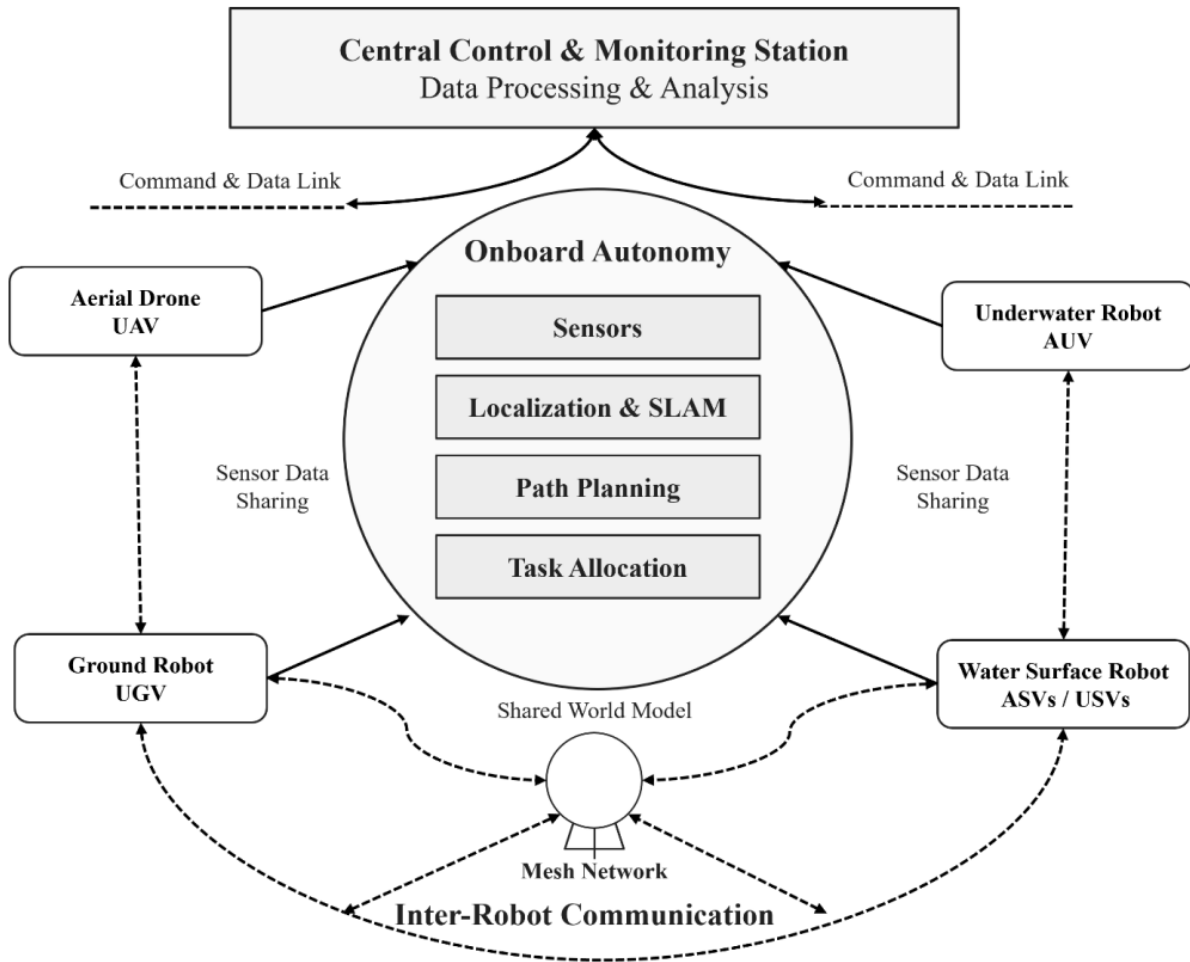


Figure 1. Reference architecture of an autonomous multi-robot system: robot platforms, sensing, onboard autonomy, inter-robot communication, and shared world models supporting cooperative decision-making.

2.2. Key Technologies Supporting MRS

Autonomous multi-robot systems rely on the collaboration of various technologies that are vital in facilitating the functionality of these systems in the real-world setting^[19]. The hardware is a central part of these systems, and it encompasses devices of different robots, each of which is specialized in a task and environment. As an example, aerial robots (drones) are more suitable in terms of giving a wide area coverage and scouting the environment, whereas terrestrial robots have a higher likelihood of negotiating tricky situations, and are more appropriate in operations like search and rescue.

A MRS is usually made up of robots that have many

sensors that give the relevant information that allows it to move and perform tasks efficiently. Such sensors can consist of cameras, LIDAR, GPS, accelerometers, as well as environmental sensors (temperature, humidity, gas detectors, etc.). The information provided by these sensors should be analyzed in real-time to enable decision-making and communication between robots. This is where more sophisticated algorithms are vital, which are powered by machine learning and artificial intelligence, allowing the robots to learn through their environment, adapt to new circumstances, and make their own decisions^[20,21].

The process of localization and mapping is highly important to MRS because robots need to be aware of their location in relation to one another and to their sur-

roundings^[22,23]. Such methods as Simultaneous Localization and Mapping (SLAM) permit robots to develop maps of unfamiliar space and, at the same time, maintain their position. This can be particularly useful in unsteady environments, like the one encountered in a disaster, where the terrain layout can shift quickly as a result of the disaster.

Another essential element of MRS is communication technology, as it can guarantee that the robots are capable of exchanging information with each other. Traditional communication infrastructure can also be inaccessible or unreliable in most cases of disaster response.

Consequently, MRS will have to rely on ad-hoc communication networks that will enable the robots to communicate in real-time. This may include direct communication between the robots or via relay systems, which increase the distances over which the communication can be done. The strength of these communication systems is needed to bring about effective coordination of the robots, even when there is a GPS-denied or grossly disrupted environment^[24]. As it was highlighted in **Table 1**, autonomous MRS capabilities are the direct result of the close integration between platform modalities, sensing suites, onboard intelligence, and networking infrastructure.

Table 1. Core technologies enabling an autonomous multi-robot system for real-time environmental monitoring and disaster response.

Technology	Description	Examples
Robotic Platforms	Types of robots used in MRS (aerial, terrestrial, aquatic)	Drones, ground robots, underwater robots (AUVs)
Sensors	Sensors used for environmental sensing and navigation	LIDAR, cameras, thermal sensors, GPS, humidity sensors
Algorithms	Algorithms for localization, mapping, coordination, and task allocation	SLAM, path planning, reinforcement learning
Communication Systems	Systems that enable data exchange between robots and with human operators	Wi-Fi, mesh networks, robot-to-robot communication

2.3. MRS for Environmental Sensing and Disaster Response

Most alluring uses of the autonomous MRS include the sphere of environmental monitoring. The possibility of using several robots that are able to gather information from various sensors permits monitoring large geographies continuously and in real time. To take an example, environmental surveillance can be performed with the help of robots monitoring air and water quality, its pollution, or dangerous substances in the environment. Autonomous robots can be used to carry out persistent surveillance in remote or unsafe areas that do not pose a problem to human intervention^[8,25].

The benefits of MRS are even more evident during disaster response. In case of a disaster, it can be saved by the capability to quickly send robots to examine the situation, which will save lives and considerably shorten the response time. Independent MRS can be deployed to disaster areas to provide search and rescue services, damage assessment, survivors, and even containers. The system is flexible in that it enables the robots to be given certain

tasks depending on the dynamic nature of the situation, e.g., in case the situation is rescue operations or an infrastructure assessment, once the situation changes^[26,27].

Using the example of an earthquake aftermath, it is possible to send robots to examine the building, identify trapped people, and report to human responders about the important findings. Equally, in the flood-prone regions, the robots with specialized sensors can be used to keep an eye on the water levels, identify flood threats, and issue early alerts. The fact that MRS can work itself in such sophisticated and dangerous conditions reduces the risk to human life to a minimum and promotes the efficiency of disaster response operations as a whole^[28].

Besides, the interaction of several robots enables assigning tasks, which is why it is possible to reach a large territory or several crucial points at the same time. This cooperative action is especially useful in cases when time is of the essence, like in search and rescue operations or in detecting hazards in the environment. Cooperating robots have an opportunity to adjust their behavior dynamically, responding to the variations of the situation in the field more effectively and rapidly^[29,30].

2.4. Challenges and Future Directions for MRS

Although autonomous multi-robot systems have great potential in enhancing environmental monitoring and disaster response, there are still multiple obstacles in the context of scalability, strength, and compatibility with currently existing systems. Indicatively, coordination and task distribution among large populations of robots in complicated settings necessitate complicated algorithms. The robots should be capable of interacting with one another and making sure that they do not disrupt the work of the other robots. Additionally, such systems should be capable of operating in conditions that have unreliable or no communication facilities, as is frequently experienced in disaster areas ^[31,32].

MRS research in the future is probably going to be concerned with these issues, not to mention how to better control the autonomy and intelligence of the robots. Machine learning, AI, and sensor fusion will allow robots to comprehend their surroundings and react to them better. Also, the evolution of stronger communication systems, including the improved energy control systems, will improve the scalability and sustainability of MRS in long-term operations in remote and dangerous locations ^[33,34].

The ability of autonomous multi-robot systems to transform the way environmental conditions are monitored and the reaction to disasters increases as the latter continue to evolve. With the concept of integrating these systems with other technologies like IoT, big data analytics, and cloud computing, the future of MRS appears bright, as it can fulfill unprecedented opportunities to make real-time decisions and effective disaster management.

3. Applications in Environmental Monitoring

In the context of environmental applications, it is important to distinguish between monitoring and surveillance, as the terms represent different operational objectives. Environmental monitoring typically refers to systematic, long-term data collection aimed at identifying trends, patterns, and changes in ecological or atmospheric conditions over time. In contrast, environmental surveillance is

generally more targeted and short-term, focusing on the detection of specific events, anomalies, or hazards, such as pollutant leaks, wildfire outbreaks, or illegal activities. Autonomous multi-robot systems can support both paradigms by enabling persistent monitoring as well as rapid-response surveillance, depending on mission requirements. Environmental monitoring is an important element in solving global problems like climate change, pollution, and the management of natural resources ^[35]. Monitoring systems should be effective enough to gather data in real time and on a large scale, particularly in remote or dangerous places where human presence is hard or unsafe. Multi-robot systems, also known as autonomous multi-robot systems, have become potent devices that could be used to survey various environmental indices within expansive and dynamic topographies. MRS provides capabilities to respond to environmental threats promptly by deploying several autonomous robots with a variety of sensors that could help in continuous monitoring of the environmental conditions and collect useful data. In this part, we discuss the uses of MRS in environmental monitoring with particular attention to the major areas to which the systems have the highest effect.

3.1. Environmental Sensing with Autonomous MRS

Among the largest benefits of autonomous multi-robot systems in the sphere of environmental monitoring, one may single out the possibility of gathering an extensive range of data from various sources and offering constant coverage of vast territories. Such systems can be used to track such parameters as air quality, water pollution, soil contamination, and dangerous materials. As an illustration, it is possible to deploy autonomous drones to examine air quality in different altitudes and obtain information about the level of pollution, greenhouse gas emissions, and particulate matter. They are also able to measure the temperature, humidity, and atmospheric pressure, which are necessary in the monitoring of climate change and weather patterns ^[10,36]. Because monitoring objectives differ by medium and hazard, **Table 2** maps key environmental parameters to sensor requirements, robot modalities, and operational capabilities.

Table 2. Environmental monitoring targets and corresponding multi-robot sensing requirements, platform choices, and operational capabilities.

Environmental Parameter	Sensors Required	Robotic Platform	Capabilities
Air Quality	Gas sensors, particulate matter sensors, and CO ₂ sensors	Aerial drones, ground robots	Continuous air sampling, high mobility for wide-area coverage
Water Quality	pH sensors, turbidity sensors, salinity sensors	Underwater robots, surface robots	Real-time water monitoring, pollutant detection in water bodies
Soil Moisture	Soil humidity sensors, temperature sensors	Ground robots	Soil sampling, in-depth data collection in agricultural fields
Radiation Detection	Radiation detectors, gamma sensors	Ground robots, drones	Detection of radioactive substances in disaster zones

On the same note, the earth-based robots are applicable in checking the parameters of the environment on the ground. With sensors to monitor soil moisture, temperature, and chemical composition, such robots will be able to collect data in the agricultural fields, forests, and wetlands [37]. The data is imperative in determining the health of the ecosystems, deforestation, and the effects of climate change on the biodiversity and the ecosystems.

Autonomous underwater vehicles (AUVs) and surface robots may be used to survey the water quality of oceans, lakes, rivers, and reservoirs [38]. These robots are capable of gathering information about the parameters of pH, salinity, dissolved oxygen, turbidity, and the presence of pollutants like metals or organic pollutants. Having the capability to collect this data on a large scale and in remote locations where a person might have restricted or unsafe access boosts the real-time monitoring of the environment.

With the incorporation of multiple sensors into a multi-robot system, sensor fusion is possible, where information from different sources is integrated to give more accurate and comprehensive information about the surrounding environment. Indicatively, aerial robots can be useful in supplementing humidity measurements of ground-based robots to give a more accurate depiction of microclimates or local weather conditions. Sensor fusion allows a holistic approach to monitoring the environment, where several robots will be used to gather and interpret the data at various angles and from different sources [39].

3.2. Autonomous Systems for Hazard Detection and Prevention

Besides general environmental surveillance, auto-

nous MRS are of great importance in identifying and mitigating environmental risks [40]. Natural disasters, including wildfires, floods, and landslides, are some of the disasters that can be anticipated or at the initial stage when the appropriate monitoring mechanisms are in place. With the proper sensors, autonomous robots will be able to monitor the early indicators of such dangers and communicate important data to decision-makers before it becomes a more serious occasion.

As an illustration, aerial drones with thermal imaging cameras and sensors can be used to detect wildfires by detecting an abnormal rise in temperatures or smoke levels. These drones are able to cover a wide space within a short time as they can detect the possible places where the wildfires can be before they run out of control. In the same vein, terrestrial robots will be able to measure soil moisture and temperature levels to determine the probability of forest fires or landslides in mountain areas or forests. Robots can be used in flood-prone regions to check river levels and rain levels to give early warning to prevent the effects of the flooding. Areas that may experience flooding can utilize autonomous systems that monitor the water levels all the time and note even minor changes, which can be a signal of a flood [41-43].

In addition to natural disasters, autonomous MRS can also monitor and solve other types of environmental hazards, including industrial pollution, oil spills, and radiation leakage. Chemical sensors built on robots can also make patrols of industrial areas, the waterways, and coastal areas, where the robots will detect the presence of harmful chemicals or radioactive wastes in the environment. These systems will be able to quickly determine the source of the spill/leak, the extent of the contaminant

spread, and real-time data that can be used to implement more efficient containment and response actions in case of a leak or spill ^[44].

Autonomous MRS allows timely intervention and prior solutions to prevent most of the harm that may be occasioned by environmental hazards by offering real-time data and analysis. This active hazard identification strategy is essential in safeguarding the lives and systems of the environment against the negative impact of natural and artificial disasters.

3.3. Case Studies in Environmental Monitoring

Several case studies are used to explain how autonomous multi-robot systems can be successfully deployed to monitor the environment in the real world. An example of this is the application of drones in monitoring the quality of the air and pollution in cities. Air pollution has become a big problem in most of the cities across the world, as such pollutants as nitrogen dioxide, sulfur dioxide, and particulate matter have become a serious health hazard. Drones with air quality sensors have been adopted in such settings to measure the level of pollution at different heights and different localities to have a clear picture of the situation and assist the local authorities in determining the most polluted localities. Following the fact that the drones could fly over the traffic and city obstacles, it would be a perfect platform to gather real-time data in the regions where the stationary air quality monitoring installations might be insufficient or unavailable ^[45,46].

The other effective application of MRS in environmental monitoring is that it is applicable in coastal regions to monitor marine pollution and detect oil spills ^[44]. The autonomous underwater vehicles have been used to survey bigger areas of the coastline, and the data gathered on the quality of water and the detection of contaminants like oil, heavy metals, and plastics. These robots can maneuver through difficult seaside features and can navigate to areas where human divers cannot. In other instances, AUVs have been employed along with the surface drones to form a multi-layered system of monitoring, which is capable of detecting surface and subsurface pollution.

Likewise, autonomous ground robots have been applied in monitoring deforestation, surveying forested

regions, and collecting data about the density of trees, soil health, and biodiversity. Such robots are applicable in many areas that are hard and unsafe to occupy. MRS can assist in monitoring the level of illegal logging, forest health, and evaluating the impacts of climate change on forest ecosystems by gathering data on the status of forests ^[47].

These case studies reveal how useful and practical autonomous multi-robot systems can be in environmental monitoring. The fact that they can collect data in real-time, cover a considerable area, and work in environmentally unfriendly or unreachable areas has found its way to be of invaluable worth in solving urgent environmental concerns.

3.4. Future Directions in Environmental Monitoring with MRS

The ability of autonomous multi-robot systems in the sphere of environmental monitoring is bound to grow as these systems keep developing. Incorporating more sophisticated sensors, better communication networks, and more sophisticated AI algorithms into MRS will help it gather even more accurate and detailed data ^[48]. An example of this is the creation of smaller robots that have improved senses of the environment that enable a more detailed collection of environmental information, including tracking microclimates or the health of a given species of plants.

Furthermore, MRS, together with other emerging technologies, including the Internet of Things (IoT), big data analytics, and cloud computing, may transform environmental monitoring and offer real-time and high-resolution data that can be distributed through large networks ^[49]. This would facilitate better cooperation between robots, researchers, and decision-makers and make us better respond to environmental challenges and disasters.

It is likely that in the future, the use of autonomous MRS in environmental monitoring will be even more deeply entrenched in the movement to combat the global environmental problems ^[50]. These systems will be important in improving sustainability practices and reducing the impact of environmental degradation and climate change by enhancing the efficiency, scalability, and accuracy of collecting data.

4. Disaster Response and Management Using Autonomous MRS

The use of autonomous multi-robot systems in disaster management has received a lot of interest because they can work in dangerous conditions and provide real-time information and support critical tasks, such as search and rescue, damage analysis, and recovery [9]. Several factors that especially affect human responders include the unpredictability of disasters (both natural, such as earthquakes, floods, and wildfires, and human-made, such as chemical spills or industrial accidents), which creates difficulties in responding to human-generated disasters. Under these circumstances, MRS can provide the opportunity to not just increase situational awareness but also perform the tasks that might otherwise be too hazardous or time-consuming for human teams. The section addresses the uses of MRS in disaster response, in which it brings its contributions at different levels of disaster management, such as in detecting the disaster and recovery.

4.1. Role of Autonomous MRS in Disaster Scenarios

The disasters can come at any time and with minimal or no warning, and therefore have limited time to act [51]. Under such high-pressure scenarios, time is of the essence, and the capacity to evaluate the damage promptly, find survivors, and allocate resources can significantly change lives and ensure that no more damage is caused. There are a number of benefits of autonomous MRS in disaster response missions. To begin with, they are able to be deployed quickly and cover a wide area much faster than human teams. Through autonomous work, robots are able

to keep a constant check on the situation and gather data, and while a good communication infrastructure does not present itself, it will give real-time situational awareness to the decision-makers. To clarify platform trade-offs for time-critical operations, **Table 3** compares aerial, ground, underwater, and swarm-oriented approaches in terms of strengths and operational constraints.

Autonomous MRS are specifically useful in disaster response because the area is either too hazardous or inaccessible to human beings. An example is the case of an earthquake, where the damaged structures may be unstable, and it is not safe to have rescue personnel enter buildings. Robots, especially aerial drones and ground robots, can work in the collapsed buildings, in tight spaces, and find survivors by observing heat signals or cameras and sensors [52]. These systems may be deployed into buildings, tunnels, or dangerous locations where the presence of human beings may be a life threat.

Moreover, during emergencies, such as wildfires or chemical spills, the fact that MRS can be used without the interference of humans in the toxic or high-temperature areas makes responding to the situation quicker and safer. Special autonomous robots with installed sensors can identify dangerous substances, monitor the extent of the tragedy, and pass important information to the human responders [53]. Being capable of doing work on-the-fly and working independently, they assist in minimizing the time delay in the response procedure, which can considerably decrease the consequences of the disaster in the long term. Disaster operations are naturally staged; **Figure 2** depicts a representative MRS mission workflow from rapid deployment and reconnaissance to survivor localization, assessment, and handoff to human responders.

Table 3. Comparison of robotic platforms for disaster response: operational roles, strengths, and limitations across aerial, terrestrial, aquatic, and swarm deployments.

Robotic Platform	Type of Operation	Strengths	Weaknesses
Aerial Drones	Search and rescue, damage assessment, aerial surveillance	High mobility, wide coverage, quick deployment	Limited battery life, adverse weather conditions
Ground Robots	Structural inspection, survivor search, hazardous material detection	Ability to navigate rough terrain, carry payloads	Slower than aerial platforms, limited range in some environments
Underwater Robots	Coastal, marine, or flood zone monitoring	Effective in aquatic environments, underwater navigation	Limited by water depth, communication challenges in deep water
Swarm Robotics	Large-area exploration, autonomous mapping	Scalable, fault-tolerant, adaptable	Requires complex coordination and communication overhead

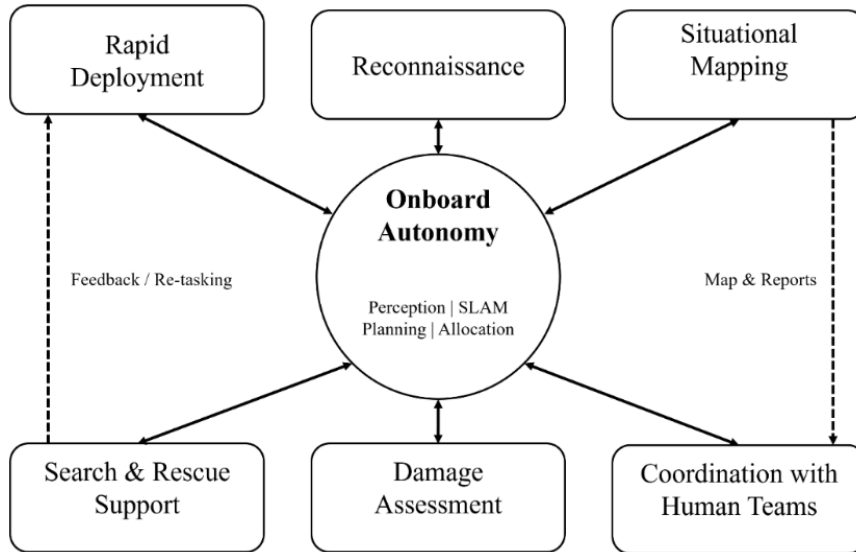


Figure 2. Workflow of an MRS-enabled disaster response mission: deployment, reconnaissance, situational mapping, search and rescue support, damage assessment, and coordination with human teams.

4.2. Coordination, Task Allocation, and Communication in Crisis Situations

Coordination of different teams in disaster areas, dealing with varied and different activities, is important to make sure that resources are utilized efficiently and effectively. By definition, autonomous MRS are meant to be cohesive, i.e., they are to be used as a team, and robots exchange information and modify their activities depend-

ing on the changing conditions. The process of coordination and allocation of tasks in an MRS is implemented with the use of complex algorithms that allow the robots to subdivide tasks according to their abilities, environmental factors, and priorities on the fly^[54]. Given the heterogeneity of tasks in disaster zones, **Figure 3** illustrates how different robot modalities are assigned complementary roles under a shared coordination and task-allocation layer.

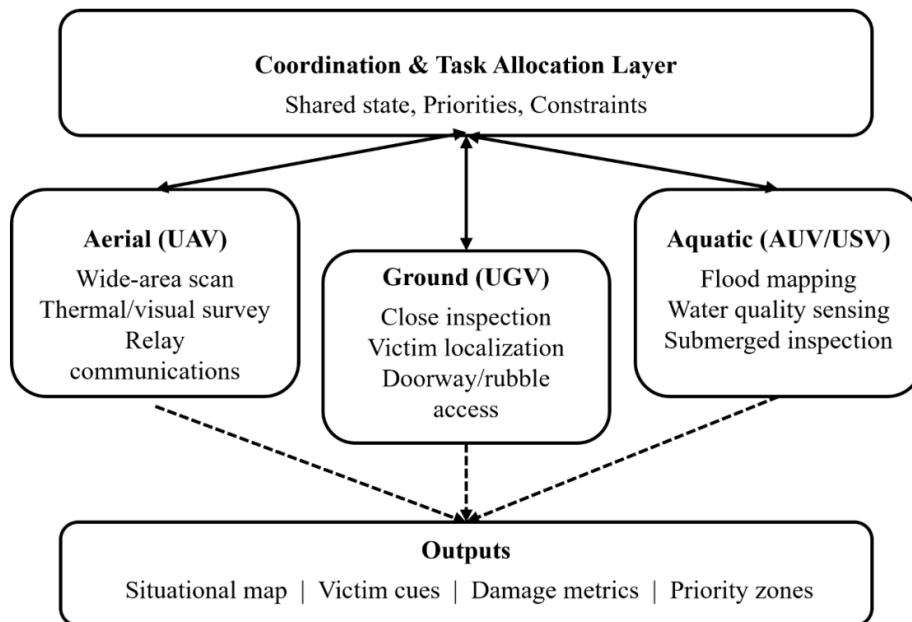


Figure 3. Role partitioning in heterogeneous MRS for disaster response: aerial reconnaissance, ground-level inspection and access, and aquatic monitoring coordinated through task allocation and shared state.

As an example, in the case of a search and rescue operation after an earthquake, a swarm of drones might be employed to cover vast regions and locate possible places of people, and ground robots might go inside the buildings to find their victims [52]. The system may be set in a way that the drones coordinate with the ground robots, and hence the coverage area will be as much as possible, and nothing of importance will be missed. After the position of the survivors is tracked down, ground robots can be sent to deliver medical supplies or communication gadgets.

Disaster response entails communication as an important facet, especially in cases where the regular communication channels are ineffective or impaired [34]. The use of autonomous MRS implies that ad-hoc communication systems like robot-robot communication should be used to ensure connectivity and exchange information in real-time. Where conventional networks are not available, the robots are able to form their own mesh networks to pass data and coordinate their actions. This decentralized means of communication makes sure that the robots have a chance to work even in the place where the communication infrastructure is limited and disrupted.

This flexibility guarantees the changeability and adaptability of the system to the dynamics of the situation, which is made possible by the possibility to dynamically allocate the tasks given the available information and the

capabilities of each robot. To provide an example, in case one robot fails or there is a communication breakdown, then the system can quickly delegate responsibilities to other robots, so that the mission can proceed without significant loss. Such flexibility is essential whenever it comes to cases of disasters, where the ground conditions keep evolving, and the demands of the response teams can change at an extremely high pace [55].

4.3. Case Studies in Disaster Response

It has been observed in several case studies that autonomous MRS proves very effective in disaster response activities. The application of aerial drones in the aftermath of the Nepal earthquake of 2015 might be discussed as one of the most striking instances. During this disaster, drones were used to survey the affected regions quickly and determine the damage. The drones took high-quality images of fallen structures and streets, which aided the rescue efforts to prioritize their work. Besides, the drones had thermal imaging cameras, which can identify possible survivors under the rubble to offer vital information to human rescue groups [56]. Operational experience remains the strongest test of autonomy under uncertainty; **Table 4** summarizes representative real-world deployments and the contributions enabled by multi-robot cooperation.

Table 4. Representative real-world disaster deployments using robotic or multi-robot systems: scenarios, platforms, contributions, and operational outcomes.

Case Study	Disaster Type	Robotic Platforms Used	Key Contributions	Outcome
Nepal Earthquake (2015)	Earthquake	Aerial drones, ground robots	Aerial drones for damage assessment, ground robots for survivor search	Accelerated rescue efforts, improved situational awareness
Hurricane Katrina (2005)	Flooding	Ground robots, aerial drones	Robots for flood monitoring, structural assessments	Improved damage assessment, remote navigation in flooded areas
Fukushima Daiichi (2011)	Nuclear Disaster	Ground robots, underwater robots	Radiation detection, infrastructure inspection	Key data on reactor condition ensured safety for human workers
California Wildfires (2020)	Wildfires	Aerial drones	Fire detection, real-time surveillance of fire spread	Provided early warning, reduced human risk in dangerous areas

On the same note, autonomous robots have been employed in flood-prone areas to survey the area of flooding, gauge the water levels, and identify potential dangers like submerged structures or landslides. The usage of autonomous robots to map the flooded areas and gather detailed information about the water flow was done in 2017, fol-

lowing the catastrophic flooding in Houston, Texas. Such robots worked in places where humans had no access to the site or the site was hazardous, as it was deep in the water and could cause further floods. The robots helped in making faster decisions and mobilizing emergency resources more efficiently by giving real-time information

about water levels and damage caused by floods^[57].

The other use of MRS in disaster response is the application of ground robots in post-disaster recovery^[27]. Following the Fukushima Daiichi nuclear power Plant disaster of 2011, autonomous robots were deployed to survey and determine the destruction of the nuclear power plant. The robots had sensors of radiation, cameras, and other equipment to survey those sites that were far too dangerous to be ventured by human beings, since the radiation levels were huge. These robots gave vital information about the state of the reactors and also contributed towards guiding the recovery efforts.

As these case studies demonstrate, autonomous MRS can be effective during disasters, as they can be utilized to collect information, search for victims, and estimate the extent of the destruction in real-time. These systems save lives by minimizing the human intervention that is required in risky areas and improving the general efficiency of the disaster management processes.

4.4. Challenges and Future Directions in Disaster Response

Although autonomous MRS have a high potential in the field of disaster responses, a number of barriers exist to the implementation and adoption of their use. The fact that effective and sound communication systems are needed is one of the main issues. Communication infrastructure is frequently impaired in the disaster zones, and robots have to use ad-hoc networks to communicate and coordinate. It is essential to make sure these systems are hardy to the environmental factors that could affect their work performance by being hindered, including interference, losing signals, and physical barriers^[58].

The other difficulty is the fact that robots must be able to work independently in highly dynamic and unpredictable areas. Disasters can lead to such swift alterations in the circumstances, like an aftershock after an earthquake or rising or falling floods. This capability to conform to these changes and make real-time decisions relying on sensor data is one of the key aspects of current research in MRS. Future developments of machine learning and AI, sensor fusion will allow robots to navigate such environments better and make better decisions^[39,59].

Regardless of these issues, the future of autonomous

MRS in disaster response is bright. The effectiveness of such systems will be further improved through continued studies on better coordination algorithms, a higher level of communication technologies, and better sensor capabilities. The use of robots in the disaster management process will become increasingly important as they become more autonomous and able to cope with complex tasks, providing additional opportunities to make disaster management processes more efficient, safe, and quicker.

5. Challenges and Limitations

Although autonomous multi-robot systems have significant benefits in real-time-environmental monitoring and disaster response, there is no easy way out in the implementation and application of this technology into the real-life environment. These issues are both technical, operational, and ethical, and these problems need to be resolved to make sure that MRS will be able to operate in dynamic and unpredictable settings^[48]. This part discusses the key obstacles and drawbacks that prevent the wide use of MRS at the moment, such as the problems with environmental factors, scaling, reliability, power consumption, communications, and ethical issues.

5.1. Environmental and Operational Challenges

The autonomous robots are frequently used in extremely dynamic and unpredictable areas, particularly during a disaster, or to carry out environmental surveillance in inaccessible areas. Unpredictability of conditions and terrain is one of the greatest problems MRS has to endure in such environments^[60]. In an example, when carrying out search and rescue operations within the disaster areas, the robots might be faced with the challenge of debris, unstable buildings, or even harsh weather. The robots must also be provided with the required sensors and algorithms to work and travel safely in these environments, such as detecting and avoiding obstacles, maintaining stability on uneven surfaces, or adapting to immediate environmental changes like aftershocks or flooding.

Besides physical barriers, the environmental conditions, on their own, are also a significant challenge. An example is that in locations with low visible objects, like

dense forests, smoke-filled places, or underwater, the sensors and communication systems should be strong enough to be used under such circumstances. The sensor performance and the performance of the robots can be influenced by environmental factors like temperature, humidity, or electromagnetic interference because they can deteriorate sensor performance as well. What is still a focus of research and development is to ensure that robots are capable of functioning in extreme conditions without disruption or loss of communication or data integrity ^[61,62].

Moreover, another reason that can cause the unavailability of accurate real-time data is the variation of the environment. As an illustration, during instances of disaster, the environment can be altered within a short period of time as a result of rubble movement, structural collapse, or weather alteration. The robots should be capable of adapting to these dynamic conditions and respond to real-time decisions using constantly changing inputs. This demands constant revision of localization, mapping, and decision-making algorithms, and the capability to remain in situational awareness even when the environment is changing ^[63].

5.2. Scalability and Robustness

Scalability is a matter of panic as MRS is used in more complex and large-scale applications ^[64]. The capability to send large groups of robots to reconnoiter an enormous region can be a vital requirement in environmental monitoring or disaster response. Nevertheless, the issue of organizing large numbers of robots on large and varied surfaces is challenging in terms of logistics and technological aspects. Among them is the fact that effective coordination algorithms are required that would dynamically distribute the tasks, prevent robots' interference with each other, and maximize area coverage, eliminating overlaps and gaps.

In addition, the strength of such systems should be ensured, especially in cases of many robots ^[65]. Failure of a single robot or a technical problem should not lead to the failure of the complete system. This involves coming up with fault-tolerant systems that can restore to normalcy once hardware or software failures occur. There should be redundancy measures, whereby in case a robot is incapacitated, there should be a backup to carry out the most important jobs. This is especially vital in the framework of

disaster response, when a single failure may ruin the success of the whole mission.

One example is in search and rescue operations, when a single robot is trapped by debris or can no longer communicate with the other robots, the system should be capable of redistributing its tasks to other robots or bringing in other units to keep the situation covered. This degree of fault tolerance and resilience is critical to the effectiveness of large-scale MRS activity in dynamic and frequently hostile settings ^[66].

Scalability is another aspect that provides the possibility to control and handle the massive amounts of data generated by numerous robots ^[49]. The handling of this data, the need to transmit it efficiently, and real-time analysis are more complex when the robots are working on large-scale areas and gathering high-resolution environmental data. An important technical issue will be to ensure that the system can scale not only in hardware (the number of robots) but also in data processing (the amount of data generated).

5.3. Power Management and Autonomy

One of the major constraints of autopilot robots is power control, especially when the robot needs to operate on a prolonged mission or in other cases where charging or battery recharge is impossible ^[67]. Robots need to have adequate sources of energy to carry out their tasks without failure, especially when they are in remote or hazardous locations, such as in disaster zones or in the wild forest.

Present battery technology tends to restrain the working lifespan of robots, especially when they are engaged in work requiring large power consumption, like traversing rugged terrain, using cumbersome sensors, or broadcasting high volumes of information. The fact that the system needs to be charged or replaced with a battery almost as often would delay important processes and decrease the productivity of the whole system. Other robots can be powered with solar panels or other technologies of renewable energy harvesting, but these systems are inadequate to support consistent power over prolonged periods. Moreover, conventional sources of power cannot be applied in such places where underground mines, forests, or flooding occur ^[68].

In order to address these limitations, power management innovations and energy-efficient robotics are needed. To give an example, finding more efficient power sources, including fuel cells, or inventing energy-gathering techniques that will be able to get power out of the environment, may lead to solutions to the problem of increasing the range of robot autonomy. Moreover, it will be important to create robots that can be powered by low-power and profile their energy efficiency by smart algorithms that will help them to be able to work during long hours without the necessity of being recharged all the time^[69].

5.4. Communication Challenges in Complex Environments

One of the most basic features of MRS is effective communication because robots should never stop exchanging data between each other in order to retain their coordination and update their actions in real-time. Communication infrastructure in most disaster and environmental monitoring situations might be damaged, non-existent, or unreliable. It is especially problematic in the disaster zones, where the conventional communication systems might be compromised or overwhelmed, and rescue teams and robots will have to work with little connection^[24].

Under these circumstances, MRS will have to depend on ad-hoc, self-organizing communications networks to communicate. Such networks should be robust enough to use within the setting where the quality or the range of signal reach may be compromised by physical barriers, signal interference, or severe weather conditions. One of the primary problems is to ensure that robots are capable of upholding a trustworthy connection with each other and with human operators, even in distant or GPS-saturated areas, e.g., underground or in places that are densely inhabited by foliage^[61].

In order to solve these problems, more complex communication protocols, including mesh networks or multi-hop communications, are being designed^[34]. Such protocols enable the robots to broadcast messages via intermediate nodes so that long-range communications can be achieved and the connection can be maintained even in adverse conditions. Also, robotics have to be provided with fault-tolerant information systems that should respond

to the changing network environment and guarantee the steady flow of urgent information throughout the working process.

5.5. Ethical and Safety Concerns

The usage of the autonomous MRS in a real-world setting, especially in disaster response, is associated with many ethical and safety issues^[70]. The most urgent problem is the autonomy versus human control. The work of autonomous robots can be a matter of serious consequences in the lives of people because this is the case in such high-stakes situations as search and rescue or hazardous material detection. These systems must hence be configured with fail-safes, redundancy, and controlling measures to ensure that the systems operate within acceptable moral limits and in a manner that best safeguards human beings.

The other ethical issue is that MRS may also be used to take the place of the human job, especially during the management of disasters and environmental monitoring. Although robots are able to increase the performance and safety of human teams, it is feared that the common application of autonomous systems may also result in job displacement in some areas. This brings up the importance of paying close attention to the social implications of implementing MRS, particularly in vulnerable communities or industries where work might be eliminated^[71].

Moreover, autonomous robots in the open areas or at very sensitive areas should have features that prevent privacy invasion and should not violate the rights of people. All data collected by MRS, including surveillance videos, environmental measurements, or personal data, should be handled with care to avoid any abuse and to provide the necessary reports on data protection^[72].

The issue and constraints of the autonomous multi-robot systems in environmental scanning and disaster response are tremendous yet not overwhelming. Although there are still technical challenges, including environmental variability, scalability, power management, and communication challenges, there is a continuous development in robotics, AI, energy systems, and communication technologies that are managing to overcome them. Additionally, ethical and safety issues should be handled to make sure that MRS is implemented in a responsible and

useful way. The fact that these systems will further develop means that their future innovations in the field of disaster management, as well as monitoring the environment, will always increase and will be able to offer new opportunities to enhance efficiency, minimize the threats to human life, and offer real-time solutions to multiple challenging problems the world faces today.

6. Conclusion

The use of autonomous multi-robot systems is fast becoming a breakthrough technology in the areas of environmental surveillance and disaster recovery. These systems use the strength of coordination, decentralization, and real-time data collection to work in harsh conditions and offer invaluable assistance to human responders. Be it utilized during the post-disaster period during the search and rescue mission, or on the long-term environmental monitoring to identify any dangers like wildfire, flood, and pollution, MRS has proven their ability to work effectively and safely in places where the human factor is challenging and risky.

In this review, we have examined the relevant technologies that make MRS possible, including high-quality sensors, machine learning algorithms, and effective communication systems, which have provided robots with the ability to work in teams and do tasks on their own. The combination of the systems to work collectively, be it using an aerial drone or a ground-based robot, or an underwater vehicle, is that various jobs are going to be dealt with concurrently to maximize response time and cover during high-priority activities. Among the attributes that are useful in disaster situations are real-time data gathering and dynamic task deployment, which can be used to alleviate the risks, save lives, and speed up recovery operations, among others.

Yet, as this review has outlined, there are still a few major problems and drawbacks which are yet to be overcome in order to make the most out of autonomous MRS. Some of the main technical barriers include environmental variability, power management, communication reliability, and scalability. Also, ethical and safety issues should be well handled, and so these systems should be

implemented responsibly and in a manner that would put the safety and well-being of human beings and society at heart.

Nevertheless, the future of self-directed MRS in environmental management and disaster management remains bright. The ability of systems to be more resilient, efficient, and adaptable is opening up as a result of ongoing progress in AI, robotics, and communication technologies. The more autonomous, reliable, and coupled with other technologies, including IoT, big data, and cloud computing, MRS will gain further opportunities to grow their abilities and create new possibilities to respond to the challenges of the environment and enhance resilience in disasters. To sum up, it is important to note that autonomous multi-robot systems will become more and more important in contributing to improving global efforts to assess the environment and react to disasters. MRS will become an invaluable asset in protecting human life and the environment by breaking the existing technical barriers and resolving ethical issues that will allow us to have a more responsive, efficient, and sustainable future of disaster management and environmental safety.

A critical frontier for autonomous multi-robot systems in environmental science is the realization of long-term, unsupervised autonomy. Future research must prioritize the development of extreme-endurance robotic platforms capable of operating for extended durations in remote and harsh environments with minimal human intervention. This includes advances in energy-efficient hardware, renewable power integration, and robust system reliability. Equally important is the integration of onboard data processing and edge intelligence to reduce dependence on continuous communication, enabling robots to analyze data and make decisions locally. Furthermore, adaptive mission planning frameworks should be developed to allow robots to dynamically modify their sensing strategies based on observed environmental phenomena, effectively supporting autonomous scientific discovery. For instance, a system could identify an emerging ecological anomaly and autonomously intensify sampling in that region. Such capabilities will be essential for transitioning from reactive deployments to proactive, intelligent environmental stewardship.

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Conflicts of Interest

The authors declare no conflict of interest.

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