Swarm Robotics in Search and Rescue Operations: Challenges, Strategies, and Future Directions

Manaseswaran S
Department of CSE-AIML
Chennai Institute of Technology
Chennai,Tamil Nadu
manaseswarans.aiml2023@citchennai.net

S J Vimal
Department of CSE-AIML
Chennai Institute of Technology
Chennai,Tamil Nadu
sjvimal.aiml2023@citchennai.net

Gowri R
Department of CSE-AIML
Chennai Institute of Technology
Chennai,Tamil Nadu
gowri.r@citchennai.net

Karthikeyan P
Department of CSE
Chennai Institute of Technology
Chennai,Tamil Nadu
karthikeyanp@citchennai.net

Kandavel N
Department of CSE
Chennai Institute of Technology
Chennai,Tamil Nadu
kandaveln@citchennai.net

Saraswathi V
Department of CSE-AIML
Chennai Institute of Technology
Chennai, Tamil Nadu
saraswathiv.cse@citchennai.net

2025 10th International Conference on Smart Structures and Systems (ICSSS) | 979-8-3315-6323-3/25/$31.00 ©2025 IEEE | DOI: 10.1109/ICSSS66939.2025.11346119

Abstract— Swarm robotics has become a radical paradigm of search and rescue (SAR) operations in disaster-prone or risky settings where humans are too risky or impracticable. This review considers the existing strategies, algorithm frameworks, and system level issues behind the implementation of multi-robot swarms to efficiently detect targets and explore the terrain. The synthesis of the discussion incorporates important contributions of behavior-based fuzzy-logic control, distributed particle swarm optimization (DPSO), and the latest methods of optimization and learning like hybrid ant-colony models and multi-agent reinforcement learning. Compaired analysis shows that behaviour-based fuzzy systems offer high levels of robustness to sensor uncertainty but are not scalable whereas DPSO offers the ability to coordinate in a decentralized manner and converge quickly but is sensitive to local-optima and limited modelling of communication. Recent reviews highlight the combination of artificial intelligence, machine learning, and adaptive optimization in order to improve autonomy, energy efficiency and resilience. The critical issues in dynamic-environment perception issue, inter-robot communication latency, energy- aware planning, and real-world deployment under partial observability remain. Based on these discoveries, this paper outlines the hybrid DPSO-fuzzy architectures, graph-neural-network-related coordination and reinforcement-learning-controlled decision policies as the potential new directions in enhancing adaptability and accuracy in complex SAR conditions. The survey concludes by highlighting the need to have integrated systems that integrate distributed intelligence, powerful sensing with secure communications in order to achieve reliable, scalable swarm-robotic systems that can be used in future defence and emergency-response missions.

Keywords— **Swarm Robotics, Search and Rescue (SAR), Multi-Robot Systems, Distributed Particle Swarm Optimization (DPSO), Fuzzy Logic Control, Multi-Agent Reinforcement Learning (MARL), Formation Control, Path Planning, Autonomous Navigation, Disaster Response Robotics.**

I. INTRODUCTION

The emergency situations caused by natural disasters, industrial accidents, as well as defence-related incidents, often result in dangerous conditions where the speed of response and human intervention will be extremely hard.Such situations require autonomous systems that can search unknown environments and find victims and coordinate tasks that are complex and that are likely to vary under uncertainty. Swarm robotics, based upon the behaviour of social insects in nature, provides a potentially promising paradigm of multiple, simple robots cooperating in a local fashion, to realize global goals. Multi-robot systems are more tolerant of faults, have more scalability, and can cover greater areas compared to single-robot systems, and are suitable to time sensitive disaster response robotics.

The recent developments of autonomous navigation and path planning have increased the speed of the implementation of cooperative robot teams in SAR missions. One of them is the distributed particle swarm optimization (DPSO) which has been explored because of its potential to facilitate decentralized decision-making and efficient exploration in changing environments. In like manner, the fuzzy logic control has proven to be very strong in dealing with noisy sensor signals and the uncertainty in the environmental conditions to make the swarm behaviours adaptive. These capabilities are further increased by emerging learning-based algorithms like multi-agent reinforcement learning (MARL) which allows the agent to learn collaborative policies that maximize mission success via experience.

Though these achievements have been made, some still present challenges such as ensuring stable inter-robot communication, reducing energy usage, preventing collisions, and good behaviour in partial observability. In addition, the organization of swarm formations and adaptation of the variety of sensing and control frameworks are research issues. In this paper, the review of the existing strategies, architectures and control models used in swarm-robotic SAR systems are overviewed with a focus on the formation of control, path planning, and adaptive intelligence methods. It juxtaposes traditional optimization-based techniques with new learning-based systems, their advantages and disadvantages and includes the trends of the future including hybrid DPSO-fuzzy systems and coordination with the help of graph-neural-networks. Finally, this paper seeks to bring out the changing role of swarm robotics as one of the enabling factors to the effective, reliable, and intelligent search and rescue activities in complex and uncertain situations..

II. RELATED WORKS

This paper presents a multi-robot swarming architecture for search-and-rescue missions based on dynamic virtual leadership and fuzzy logic used for robots' decision-making. The advantages of exploration and identification of possible victims in experiments carried out in the ARGoS simulator are demonstrated although the overall performance of the system still leaves scope for improvement in scaleability, communication costs, and simulation of sensors. [1]. T This article reviews soft robots designed to be applied in disasters by evaluating materials, locomotion, and sensing capabilities of soft robots. It reviews the advantages of flexibility but also mentions durability and energy limitations associated with it and encourages multidisciplinary laboratory experiments that may help bridge the gap between research and practical applications. [2]. A multi-robot system is developed based on the idea of DPSO. The system uses potential functions for coordination and attraction of victims. The experiments show that it is possible to avoid obstacles and obtain co-operation but in real life, noise, delays and moving victims are difficulty. [3]. The use of military swarms for offensive operations, their functions (manoeuvre, fire-support), the concepts (motherships, expendables), and the practical and ethical challenges of comprehending mission limitations and human-system integration in civilian search and rescue are all covered in this doctrinal analysis.s. [4]. This review investigates aerial system coordination in respect of path planning, task allocation and of formation control, while overcoming communication and privacy issues and addressing AI/ML methods in connection with scalability, ignorance and energy efficiency.[5].

This paper considers formation control and path planning in UAV swarms compared to ground systems, particularly in respect of endurance, collision avoidance and energy which are needed for efficient design of aerial swarm architectures. [6]. In addition to highlighting advancements in formation strategies and comparative data that are useful for modern, learning-based optimization techniques, this review of MMACO optimization techniques highlights hybrid controllers and cluster-based path planning for dynamic environments. [7]. A comprehensive overview of particular SI algorithms (ACO, PSO, ABC, AFS, BFO), including variations and blends as well as applications in the engineering field - false descriptions of the algorithms, taxonomy of SI, pros and cons (PSO simplicity versus ACO versatility), and applications in case study (robotics, scheduling, power systems) of application of the algorithms. Hence this article is well suited for citation when it is required to support a choice of SI algorithm in the case of swarm task allocation, path planning or parametric optimized problems. [8]. This survey looks at coordination and task allocation methods like deep reinforcement learning and offers suggestions for approximating algorithms from simulation to real robotic systems in order to strike a balance between theory and practical concerns like communication limitations. [9]. A significant and basic technical report which establishes SI models (detailed ACO and PSO theory), meta heuristic variants, and a wide range of applications. It is particularly good as a theory reference (mathematical formulation/pheromone update rules, PSO dynamics and variants, it is important to note this because it is important to cite this if one wishes to ground their algorithm designs, or for the parameterization/convergence properties discussion in one's methodology) [10]. The authors review multi-robot search systems with regard to cooperative teamwork, and indicate how intelligent cooperation can greatly improve the robustness and efficiency of such searches. They discuss the methods of communications, task allocation and formation control used by cooperative robots. They identify reinforcement learning, cooperative sensing and adaptive team formations as important areas for future research. The article provides a useful conceptual framework for cooperative robotics in dynamic environments. [11]. The analysis of the living swarms is considered as one of the most effective ways for boosting the coordination of multiple unmanned surface vessels (USVs). The different methods for the coordination of formation control, collision avoidance, and marine rendezvous operations are discussed through the lens of living swarms. The drone analysis looks at the uplifting of the cooperation level among the USVs as the main goal. It also discusses movement in marine swarm behavior along with environmental interference sources, classical algorithms comparison such as PSO and ACO, and provision of more efficient solutions all are the aspects it covers. [12]. This research presents an insight into swarm robotics through the lens of nature's collective behavior. It highlights the main aspects of decentralized control, self-organization, and emergent cooperation. The author of the paper elaborates on the coordination algorithms, the role of machine learning in rescue and monitoring and finally emphasizes the issues of scalability, robustness, and ethical considerations.[13].

We present a machine-learning paradigm designed to predict adverse drug reactions (ADRs) with an emphasis on drug-drug interactions (DDIs) and drug-gene interactions (DGIs). In this instance, it is shown how useful it is to incorporate DGIs into ADR prediction because of the large increases in ADR accuracy shown by these effects. This methodology is said to predict known and possible ADRs with drugs affecting diseases of the skin. Such a system might lead to safer drug usage and a better way of dealing with diseases. [14]. As a novel way of predicting drug drug interactions (DDIs), this study demonstrates that the prediction of drug exposure changes can mechanistically predict DDIs. By leveraging FDA drug labels, the model makes accurate, quantifiable pharmacokinetic change predictions without the need for expensive clinical trials. This innovation will help to save time and support drug usage decisions that are safer [15]. AI and ML in the prediction of adverse effects of drugs at an early stage using SVM, random forests and QSAR etc models make it easier to detect these adverse effects faster and reduce the incidence of adverse effects related to organs and the costs [16]. The use of AI in drug discovery hastens the discovery of targets, virtual screening, the design of molecules using AlphaFold, CNN, GAN and reinforcement learning etc models, thus making drug discovery more efficient and accurate in its early phases of clinical development. [17]. The focus of this article is functionality improvements related to autonomy, control, propulsion, and sensing approaches in UAVs, especially those involving AI-enabled autonomous swarms, LiDAR augmentation, energy systems, and current and potential regulatory and communication limitations that could impact the future abstraction of multi-robot systems.[18]. Behavioral patterns used by penguins inspired a multi robot search and recovery strategy that supplements POA with Random Walks leading to wider exploration, better victim detection rate, and greater efficiency in extreme and communication disadvantaged areas when compared to ACO and PSO.[19]. This paper presents an affordable swarm robotics technology upgrade utilizing generative AI and federated learning on a Raspberry Pi based platform improving on the performance of detection, speed of response and efficiency by 31% compared with the existing swarm robotic systems demonstrating a sophisticated level of swarm intelligence achieved by improved software optimization.[20].

III. Literature Review

The recent improvements in swarm robotics and Search and Rescue (SAR) systems signify advances in the fields of behavioral, optimization-based, and soft-robotic control. [1] presents a fuzzy-controller-based behavioral pattern that allows virtual-leader navigation, cohesion, and avoidance of obstacles to improve victim detection success in uncertain environments. [2] cites soft robotics as a flexible alternative to rigid robots, emphasizing bio-inspired mechanisms of movement and adaptability in collapsed structures while addressing issues in durability and control. Optimization-based coordination as described in [3] employs Distributed Particle Swarm Optimization (DPSO) for decentralized navigation and efficient victim localization. Although mainly defense-oriented, [4] provides essential data on large-scale swarm deployment and coordination of movements that are applicable to SAR formations. Swarms in the field, particularly aerial swarms, have been advanced in [5] with an emphasis on decentralized path planning, AI-enabled control, and communication strategies in UAV-assisted reconnaissance. [6] elaborates on an ant-colony-based routing scheme that produces adaptive communication, ultimately increasing the resilience of dynamic SAR networks. Contemporary modifications in [7] enhance the Max-Min Ant Colony Optimization (MMACO) and hybrid controllers, leading to improvements in robot convergence and efficiency. Major swarm algorithms are outlined in [8]; apart from Ant Colony, Particle Swarm, Artificial Bee Colony, Artificial Fish Swarm, and Bacterial Foraging Algorithms, their advantages as optimization techniques applicable to SAR swarms are highlighted. Decentralized collaboration and task allocation based on machine-learning algorithms are considered in [9] concerning real-world multi-robot systems and their scalability. Finally, [10] provides the theoretical basis for swarm-intelligent models inspired by biological behaviors involving ACO and PSO, forming the backbone of modern decentralized SAR systems. The cumulative understanding of swarm intelligence thus establishes it as an essential foundation for efficient, autonomous, and coordinated rescue systems.

Recent investigation of swarm robotics and multi-robot systems (MRS) has focused on cooperative control, efficient energy usage, and intelligent autonomy through artificial intelligence. In this direction, the work in [11] discusses the innovations in teamwork design for multi-robot search problems based on decentralized coordination, reinforcement learning and practical real-world adoption. Another relevant work is [12] that addresses collaborative swarm intelligence in unmanned surface vessels and which highlights hybrid architectures, and the challenge of including hydrodynamic effects. The review work in [13] covers the theme of decentralized control and emergent behaviours of collective intelligence, scaling and ethical issues. The subject of human-swarm interaction is considered in [14] in which intuitive gesture-based methods of control are developed that increase the effectiveness of the operator in swarm co-ordination activities improves. Another relevant issue is that of energy optimization, covered in [15], which uses a Multi-Objective Ant Colony Optimization algorithm that increases the efficiency of photovoltaic inspection by 22%. The engineering-based contribution in [16] describes how theoretical algorithms can effectively be bridged with proper hardware implementation. The search and rescue problems are handled in [17] where robust methods of task allocation and ad-hoc networking are described. The advances in aerial swarms are covered in [18] which reviews, in particular, UAV autonomy, sensing and control of flight. The bio-inspired Penguin Optimization Algorithm in [19] provides a method of increasing the efficiency of search and victim identification. Finally, the work in [20] works even further toward increases in detection efficacy and reduced latencies in low cost robots using federated learning and generative AI. Altogether these works progress from the theoretical coordination in [11]-[13] to user-oriented interfaces and AI driven autonomous system capabilities in [14]-[20], revealing open issues in scaling, energy management and practical implementation in the real world of intelligent swarm robotic systems.

[1] presents one of the most thorough and practically relevant contributions of swarm robotics to Search and Rescue applications in that it describes a full behaviour-based decentralized control architecture using fuzzy logic. This incorporates a dynamically determined Virtual Leader (VL) mechanism which has been shown to maintain swarm cohesion and allows for coordinated navigation and robus movement in unknown, cluttered and partly observable environments e.g. disaster sites. Its modular fuzzy-behaviour system, i.e. obstacle avoidance, alignment, inter-robot cohesion and dynamic goal seeking, enables considerable swarm adaptation in real time to varying terrains, whilst remaining effective in search of victims. One of the strengths of this work is evident by its clear experimental validation, since the simulation results show conclusively greater area coverage, faster exploration and greater victim detection rates over independent robots. Unlike many general swarm-intelligence, or UAV-swarm papers, [1] concentrates directly on SAR scenarios with a total end to end Framework, whereby biological inspired local rules are united with robust self-organizing decision making. This gives it an advantage in relation to convergence with the real operational requirements of SAR missions considering both the strategic and implementation aspects. Its emphasis of scalability, robustness and fault tolerance, together with the successfully integrated fuzzy controller employed in a swarm behavior context make [1]

the most practically useful and domain specific of all works covered.

[20] makes a future-facing and practically-grounded contribution to the field through the combination of generative AI and federated learning in a cost-effective multi-robot solution. It shows how it is possible to successfully implement advanced intelligence in systems with limited resources, for example Raspberry Pi and MSP430 controllers. The significance of this work is that it has been shown that significant performance improvements can be made, which has been shown to be the case; in particular, improvements have been achieved in the case of object detection which have been seen to improve from an accuracy of 76.4% to 94.3%, and the latency in the case of inference has been improved from 245ms to 85ms. This being achieved by making use of model compression, adaptive aggregation and distributed optimization. There is, however, a difference in this work from previous studies in swarm robotics which have been concentrating on the design of classical biologically inspired algorithms, in that this work has taken a more up-to-date artificial intelligence based architecture which improves perception, co-ordination and scalability without increasing the overheads of communication. Because it consent to combine together lightweight edge inference with federated learning it is regarded as reasonably distinctive among the papers reviewed, being the first instance where the divide between theoretical systems of artificial intelligence and the deployment of these systems in practical situations for multi-robots has been combined together. That it is able to show how a fully functional testbed can work well together in realistic circumstances at a low cost and to show how in particular, great improvements are made in accuracy, efficiency and savings in communication, make it the most significant modern contribution to swarm robotics in that it provides a scalable basis for future SAR, defense, and industrial applications.

Among the examined studies, Paper [20] and Paper [1] represent two significant but different directions in multi-robot systems. Paper [20] represents a practically relevant and forward-looking contribution through use of generative AI and Federated Learning in a multi-robot platform that is inexpensive and shows that advanced intelligence can efficiently operate even on limited hardware such as Raspberry Pi machines and MSP430 controllers. Through model compression, adaptive aggregation and distributed strategies, notable improvements in object-detection ability have been obtained, i.e. from 76.4% to 94.3% in search and from 245 ms to 85 ms for inference latency. Most importantly, the research closes the gap between theoretical AI research and practical implementations of the techniques, allowing perception and coordination to be scaled up without increase in communication. The second work, Paper [1] provides a domain-specific, behaviour-based decentralized architecture for application specifically to Search and Rescue (SAR). Uses fuzzy logic and a dynamically selected Virtual Leader that engenders cohesion, robust navigation and effective determination of location of victims who are in visual clutter and partially observable environments. Work is reinforced by satisfactory experimental validation of results showing: Improved area coverage; Faster exploration; Higher detection rates compared to robot functioning independently. Paper [1] describes work that is superior both in SAR implementation and operational realism of the project. Paper [20] provides however the greatest over-all contribution in that its AI-enhanced techniques provide frameworks that can be applied to several applications (SAR, defence, industrial inspection) and lays a forward-looking foundation for intelligent and resource-efficient multi-robot systems. By uniting federated learning to lightweight edge inference in a fully functioning testbed Paper [20] has made the most scalable, modern and transformative step forward of the works reviewed.

Table I: COMPARITIVE ANALYSIS AMONG PAPER[1] AND PAPER[20]

Feature	Swarm robotics for **Search and Rescue (SAR)**	**AI-enhanced multi-robot systems** using Generative AI and Federated Learning
Primary Focus	Swarm robotics for **Search and Rescue (SAR)**	**AI-enhanced multi-robot systems** using Generative AI and Federated Learning
Core Approach	**Behaviour-based decentralized control** using fuzzy logic	**Federated learning + generative AI** with lightweight edge intelligence
Key Technique	Dynamically selected **Virtual Leader (VL)** mechanism	**Model compression, adaptive aggregation, distributed optimization**
Environment	Unknown, cluttered, partially observable disaster environments	General multi-robot environments (SAR, defense, industrial use cases)
Main Capabilities	Obstacle avoidance, alignment, cohesion, dynamic goal seeking	Improved perception, coordination, and scalable intelligence
Performance Results	Improved **area coverage, faster exploration, higher victim detection rates**	Object detection accuracy improved from **76.4% → 94.3%**; latency reduced from **245 ms → 85 ms**
Communication	Not heavily	Optimized to

Overhead	emphasized	avoid increased communication overhead
Scalability	High, focused on SAR-specific swarm behavior	Very high, applicable across **SAR, defense, and industrial inspection**
Practical Validation	Strong simulation-based experimental validation	Fully functional, low-cost real-world testbed implementation
Main Strength	Highly **domain-specific SAR framework** with realistic operational focus	**Most modern and transformative contribution** due to scalable AI integration
Overall Contribution	Best for **SAR-specific practical deployment**	Most **scalable and future-ready framework** across multiple domains

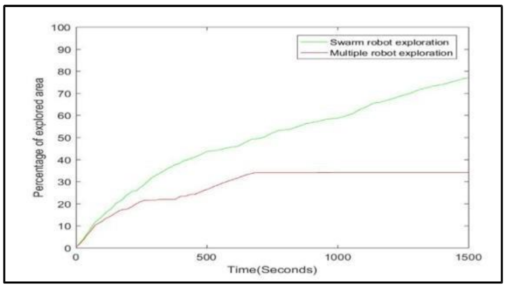

Figure1: Leadership failure experiment coverage over time[1].

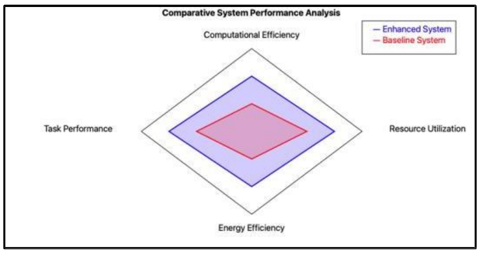

Figure 2: system Performance Comparison[20]

IV. Discussion and Limitation

The holistic assessment found in this review indicates that swarm robotics as a multidisciplinary area, and SAR are evolving rapidly. Collective intelligence, distributed optimization and adaptive learning, all have potential to enhance efficiency of exploration, reliability and overall mission success in unpredictable environments. Distributed Particle Swarm Optimization (DPSO) and fuzzy logic control are still two of the best known algorithmic solutions due to their decentralized nature and ability to function in uncertain knowledge inputs. However, these approaches are still not sufficiently adaptable nor scalable for particular deployment in highly dynamic disaster scenarios characterized by restricted communication. The area of application of multi-agent reinforcement learning (MARL) and graph type strategies offer the best promise for further fruitful research since swarms could learn from their experience and modify strategies accordingly depending on environmental changes.

Despite some progress with advances in algorithms and vehicle capabilities of swarm systems, such systems for operational SAR missions currently have many serious drawbacks. Most important of these is the reality gap and the fact that models which work well in simulation environments do not do so well in real life on LR vehicles because the sensors are noisy and the terrain variable and hardware has limited physical constraints. Ethical problems also arise from limited bandwidth and communications lag time preventing the availability of information and its dissemination in real time when such information is needed for collaborative real time rescue missions especially in cases of collapsed structures or areas out of the range of GPS. On the energy management and power optimization fronts, these have not not, as yet produced appropriate readily gleaned solutions because long excursions by LR vehicles require onr, adequate battery usage management systems plus intelligently and organized recharging systems for the swarm as a whole. Furthermore existing algorithms are, in general, essentially based on conditions of ideally simple sensing and localization with very significant results being manifest from interactions between interfering environmental stimuli and hardware limitations in performance and dynamic obstacles which in reality are not imputed.

In terms of methodological problems, the literature indicates a reliance on traditional optimizations algorithms which have the undesirable property of local minima associated with them and do not tap self-learning abilities. Hybrid methods involving DPSO and fuzzy (or reinforcement learning concepts), have yet to be explored to a greater extent for computational burdens and convergence stability. Another area that is lacking in the existing literature is a look into secure and robust means of robot-to-robot communications. This is particularly so in military/defense related applications, for instance, SAR, where signals are likely to be jamming and other cyber threats. Future work must explore energy aware (or resistant), communication robust, learning self well to swarm architectures which blend theory and practice in application solutions that produce the emergence of systems capable of field deployment. All of these areas of difficulty must be addressed in order to further harness the potential that swarm robotic systems may have for a reliable autonomous tool for next generation disaster relief robotics.

V. CONCLUSION AND FUTURE SCOPE

The increasing relevance of swarm robotics in search and rescue (SAR) missions is evident from this review. This shows that distributed intelligence, adaptable control and cooperative decision making are vital in hazardous and dynamically changing environments. Based upon a stringent analysis of the literature a comparison of the advantages of a behaviour-based fuzzy logic approach, used in environments with a level of sensor uncertainty, as compared to Distributed Particle Swarm Optimisation (DPSO) which leads to scalable and decentralised swarm robotic co-ordination in more than one robot have been provided. The literature also shows that contemporary techniques as Multi-Agent Reinforcement Learning (MARL), suitable variants of Ant Colony Optimisation (ACO) and also techniques based upon Graph Neural Networks (GNN) thus giving solutions to the problems of autonomy and adaptive behaviour through the formation of context dependant communication and behaviour patterns are emerging. Overall, therefore these aspects indicate that swarm robotics is moving from a stage of research concentrated on simulation techniques to an operational intelligent mission critical style as portrayed by SAR commandeering in the actual environment.

While significant strides have been made toward swarm robotic systems for search and rescue (SAR), several areas still need to be addressed before that end will be realized. Areas include low communication bandwidth, limited power sources, poor field sensors, and no general methodologies to coordinate large scale swarms. Future research should be undertaken with particular attention to the combination of hybrid optimization methodologies, including the fast convergence time obtained with the DPSO swarm intelligence algorithms. Fuzzy logic systems also should be included for the reason that the inclusion of fuzzy systems leads to the development of adaptive planning methods such as MARL methodologies. The above methodologies would allow one to combine explorative and exploitative actions in dynamic environments with the promise of robustness to non-linear situations. The implementation of other research areas including energy aware planning, secure communication methodologies, and on-line learning systems are paramount to increase the endurance of missions and systematic resilience to the failure of systems or adversarial interference. Further, an area of considerable promise lies within workable areas of promise afforded by GNN-based message passing architectures which could be adapted to create scalable systems of coordination in cooperating agents which could share information relating to the state of their environment in abstracted form. The final success of swarm robotics in SAR will depend upon the all-integration of advances in algorithm design and sensory systems with validated solutions in practice.

Future considerations will have to be made in bridging the simulation to reality gap with the thorough experimentation of heterogeneous swarms of aerial and ground robots to provide systems which are adaptable to real-world disaster situations. With these methods validated swarm robotic systems will evolve into completely autonomous, energy aware resilient agents that will redefine modern disaster response robotics and defence operations.

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