SWARM ROBOTICS IN THE MILITARY PPERATIONS: CHALLENGES AND OPPORTUNITIES

Miloš Jovanović [1], Jelena Vasiljević [1], Dragan Lazić [2], Igor Medenica [1,3] and Dhinaharan Nagamalai [4]

[1] Faculty of Computer Science, University Union, Serbia
[2] Metrology laboratory Technical Test Center, Belgrade, Serbia
[3] Electric Power Distribution of Serbia, Serbia
[4] Wireilla, Australia

ABSTRACT

This paper delves into the utilization of swarm robotics in military operations, focusing on its challenges, opportunities, and implications for modern warfare. The paper aims to explore the capabilities of swarm robotics, assess its impact on battlefield tactics, and discuss the ethical considerations and future prospects of integrating swarm robotics into military strategies. AI implementation as well as machine learning into the SWARM is a focus. Some SWARM principles found in biology are considered and explained as a possible implementation into the robotic SWARM for possible military implementation.

KEYWORDS

SWARM, robotics, artificial intelligence, machine learning, military

1. INTRODUCTION

SWARM robotics involves multiple robots operating together to perform tasks collaboratively. In military operations, these robots can enhance capabilities such as surveillance, reconnaissance, search and rescue, and combat support as well as direct combat. Utilizing SWARM robotics offers significant advantages but also presents unique challenges.

This is an area of multi-robot systems inspired by the collective behavior of social insects such as ants, bees, and termites. This field focuses on the design, coordination, and control of large numbers of relatively simple robots that interact locally with each other and their environment to achieve a common goal.

The key aspects of Swarm robotics are collective behavior, scalability, robustness, flexibility, local communication and interconnection. Collective behavior is the primary feature of swarm robotics. This is the emergence of complex global behaviors from the interaction of simple individual behaviors. Each robot follows simple rules, and through local interactions, the swarm exhibits sophisticated collective behavior. Regarding the scalability, Swarm robotic systems are inherently scalable. Adding more robots to the system does not require significant changes in the control algorithms. This scalability is advantageous for tasks that require coverage over large areas or redundancy. Swarm robotic systems are robust and flexible. They can adapt to changes in the environment and continue functioning even if some robots fail. This robustness is due to the decentralized nature of the control mechanisms, where there is no single point of failure. Robots in a swarm communicate and interact locally rather than relying on a central controller.

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2. BIOLOGICAL PRINCIPLES

Swarm behavior is well known in biology, especially in some lower rate organisms like ants, bees, hornets etc.

Swarm principles observed in ant colonies have been a significant source of inspiration for swarm robotics. These principles revolve around simple rules followed by individual ants that lead to the emergence of complex and efficient collective behaviors. The key principles of Swarm in ants are: stigmergy, self-organization, task-allocation, scalability and robustness.

Stigmergy is a form of indirect communication where ants leave pheromone trails that influence the behavior of other ants. In swarm robotics, robots use digital pheromones or similar signaling mechanisms to coordinate actions and share information about the environment.

Ants self-organize to accomplish tasks without central control. Each ant follows simple local rules, and through their interactions, a coherent group behavior emerges. Robots in a swarm system operate based on local rules and interactions, allowing the group to adapt and reorganize in response to changes in the environment or task requirements.

In ant colonies, task allocation is dynamic and flexible. Ants switch tasks based on colony needs, availability of resources, and their own experience or condition. Swarm robotic systems use adaptive task allocation algorithms to distribute tasks among robots efficiently, enhancing flexibility and resilience.

The effectiveness of ant colonies is not significantly impacted by the addition or loss of individuals, showcasing high scalability. Swarm robotics aims to achieve similar scalability, where adding more robots to a system should enhance its capabilities without requiring major changes to the control algorithms.

3. OPPORTUNITIES

Regarding the SWORM, there are several opportunities. Here will be mentioned some of the most important. In view of the Enhanced Efficiency and Coverage such as Surveillance and Reconnaissance, SWARM robots can cover large areas quickly and provide real-time data. Precisely due to the characteristic that swarm robotics consists of a large group of individuals, good organization of these individuals, or rather, good organization of the entire swarm system, can cover a very large area, a vast space, or volume. This is particularly significant in military applications. The modern battlefield, as we have witnessed in recent years, is characterized by a highly complex structure that encompasses both a large area and immense redundancy in terms of the geographical terrain, the complexity of the battlefield itself, and the inability to determine potential threats on the battlefield in real-time. With the application of SWARM, this characteristic becomes significantly pronounced. [1-3]

Regarding Search and Rescue, in real combat scenarios, SWARM robots can locate and assist victims more efficiently than individual robots or human teams.

Resilience and Redundancy - Fault Tolerance: If one robot fails, others can compensate, ensuring the mission continues without significant disruption. The resilience of swarm systems to the incapacitation or destruction of individual units is particularly noteworthy. Thanks to their large numbers and efficient organization, swarms are capable of carrying out any operation or task with minimal losses or precisely defined losses.

Distributed Functionality: Tasks can be distributed among multiple robots, reducing the risk of complete mission failure. This characteristic particularly comes to the fore during combat operations. The use of SWAEM in combat operations allows the task on the battlefield to be distributed in such a way that the SWAEM is not focused on a single target, but rather, based on the global objective, it autonomously determines which targets are of higher importance. This enables the optimal deployment of the entire swarm, ensuring that the overall task is accomplished to the greatest extent possible. In combat scenarios, the **decentralized decision-making** capability of swarm robotics is a game-changer. Unlike traditional systems that rely on centralized control, swarms can dynamically assess the battlefield, prioritize targets, and allocate resources efficiently. This not only enhances mission success but also minimizes resource waste and maximizes operational effectiveness. The ability to adapt in real-time to changing conditions makes swarm systems particularly valuable in complex and unpredictable combat environments.

Observing the Cost-Effectiveness, producing smaller, simpler robots can be more cost-effective than manufacturing larger, more complex single units. Comparing the cost of an individual robot in a SWARM to the cost of a complex robotic structure, it is evident that the cost of an individual robot is significantly lower, thanks to the simplicity of the individual unit within the SWARM structure. However, the total cost of the SWARM can significantly exceed the cost of a single complex robotic structure precisely due to the large number of units in the SWARM. Nevertheless, when analyzing the cost-benefit of deploying a SWARM versus a single complex robotic structure, several factors must be considered. The first factor is the cost of the complex robotic structure. The second factor is the total cost of the SWARM system. The third factor is the probability of survival of the single complex robotic structure during the execution of the task. The fourth factor is the estimated loss of individual units in the SWARM structure during the execution of the task.

Scalability: SWARM systems can be easily scaled up by adding more units to the network. This is a significant advantage of SWARM structures. The addition of a new unit to the SWARM is a simple and straightforward operation, similar to increasing the number of individuals in biological structures. Moreover, an individual unit can be assigned to different SWARM structures depending on the defined task at different points in time. Within a precisely defined time interval, the unit is a member of a precisely defined swarm structure with a given task.

Regarding Flexibility and Adaptability as well as Dynamic Reconfiguration: SWARM systems can adapt to changing environments and mission requirements. Another major advantage of SWARM structures is their adaptability and dynamic reconfiguration, which allows the entire system to adjust to dynamic parameters and environmental conditions. Moreover, this characteristic enables the SWARM, during the execution of a task, to define or recognize multiple independent objectives necessary for the completion of the overall mission. Consequently, the SWARM can reconfigure its entire structure so that specific parts of the system are oriented towards specific objectives. The adaptability and dynamic reconfiguration of SWARM systems make them exceptionally well-suited for complex, dynamic, and multi-objective tasks. By autonomously recognizing and prioritizing multiple goals, and reconfiguring themselves to address these goals simultaneously, SWARM systems significantly enhance mission efficiency and success. This capability, inspired by natural systems like insect colonies, positions SWARM robotics as a transformative technology for a wide range of applications.

Autonomous Decision-Making is something that SWARM is unique. Advanced algorithms enable SWARM robots to make decisions autonomously, reducing the need for constant human oversight.

Advanced control algorithms implemented in SWARM systems are primarily based on biological principles. A characteristic of biological systems is that each individual contributes to the collective goal during the execution of a task. The community, that is, the SWARM, must solve the assigned task by assigning roles to individual units depending on the environment and circumstances. Each unit is aware of the main objective, but each unit is given a specific task to contribute to the overall goal. As we have already mentioned, this is a characteristic of biological systems. Each unit possesses a control structure based on artificial intelligence of simple structure. The community as a whole is a collection of units, but it is not merely a collection of simple control algorithms. Rather, it can be considered a complex artificial intelligence control structure. In this case, the control algorithm is distributed across the units, which, as mentioned earlier, are based on principles of simple-structured artificial intelligence for solving simple tasks, while the community as a whole represents a more complex control system.

The biological principles underlying SWARM systems—such as decentralized control, distributed intelligence, and emergent complexity—make them highly efficient, adaptable, and resilient. By combining simple, AI-driven individual units into a collective structure, SWARM systems achieve a level of intelligence and functionality that far exceeds the capabilities of any single unit. This approach not only mirrors nature but also provides a robust framework for solving complex, real-world problems.

In Figure 1., a global control structure of a SWARM system is depicted. This figure illustrates the complexity of the SWARM structure and the sophistication of the control algorithm embedded within the SWARM system.

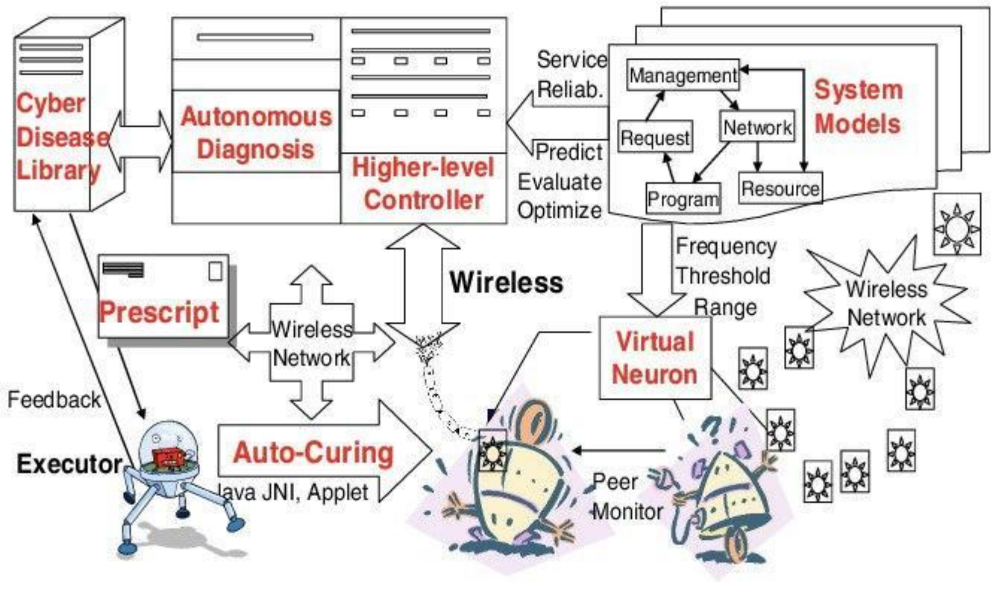

Figure 1. Swarm Robotic System Architecture (SRSA) [4]

The global control structure of a SWARM system, as illustrated in Figure 1, underscores the complexity and sophistication of SWARM robotics. By combining simple, intelligent units with an advanced control algorithm, SWARM systems achieve a level of coordination and adaptability that is unmatched by traditional robotic systems. This makes them ideal for a wide range of applications, from military operations to disaster response and industrial automation.

4. CHALLENGES

4.1. Communication and Coordination

Robust Communication Networks ensuring reliable communication among SWARM units in varied and potentially hostile environments. This task is critical. Coordination algorithms are designed to develop effective algorithms for task allocation, path planning, and collision avoidance. This is very complex.

4.2. Security Concerns

Regarding security problems there are several security issues. Some of them are especially noted.

- Cybersecurity - SWARM systems are vulnerable to hacking, jamming, and other cyber threats.
- Counter-SWARM Measures - Adversaries may develop techniques to disrupt or neutralize SWARM operations.
- Technical Limitation - Battery Life and Power Management: Ensuring sufficient power for prolonged operations is a significant challenge.
- Sensor Limitations: The performance of SWARM robots is heavily dependent on the quality and reliability of their sensors.
- Ethical and Legal Issues – Autonomous Lethal Decision-Makin. The use of autonomous systems in lethal operations raises ethical questions.
- Compliance with International Law: Ensuring that SWARM operations comply with the laws of war and international regulations is essential.
- Environmental Constraints - Terrain Challenges. SWARM robots must navigate diverse and often difficult terrains.
- Weather Conditions: Adverse weather can affect the performance of SWARM systems.

5. CONCLUSION

SWARM robotics presents a transformative opportunity for military operations, offering enhanced efficiency, resilience, and flexibility. However, realizing these benefits requires overcoming significant technical, security, and ethical challenges. As technology advances, addressing these challenges will be crucial to the successful integration of SWARM [5-10] robotics into military operations.

By investing in research and development, fostering international cooperation, and addressing ethical concerns, the military can harness the full potential of SWARM robotics to achieve superior operational capabilities.

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AUTHORS

Mr. Milos D Jovanovic received Phd in robotics at School of electrical engineering, Belgrade, Serbia. He is a leading researcher at the Technical Test Center, Ministry of Defense, Serbia. He is an assistant professor at the School of Computing, Union University, Belgrade. His major research interest is humanoid robotics, wireless sensor networks in robotics and metrology in robotics.

Jelena Vasiljevic is Associate Professor of Intelligent System at the School of Computing, Union University in Belgrade, where she works as an Associate Professor for PhD, Master and Primary Studies as: Professor of Analysis and Making Genetic sequences – PhD studies; Professor of Bioinformatics, Robotics (one year), Neural Networks (two years), Fuzzy Logic and Knowledge Based Systems – Master Studies; Professor of Intelligent Systems (Artificial Intelligence), Neural networks, Genetic Algorithms, Robotics – Primary Studies (one year).

Mr. Dragan M Lazic PhD candidate, received his master's degree in the field of automation at the Faculty of Electrical Engineering in Belgrade, Serbia. He is the head of the metrology sector at the Technical Test Center. His main interests are wireless sensors, calibration of inertial sensors, vibration sensors and metrology.

Igor devotes himself to a scientific and engineering career working on large projects. He led and participated in over 30 projects within the Ministry of Trade, Tourism and Telecommunications, Electric Power Supply of Serbia, Electric Power Industry of Serbia and Electric Power Distribution of Serbia, and The School of Computing.

Possesses extensive experience in the digitalization of information systems, cyber security, and the creation of innovations in the field of smart houses. Areas of expertise are mobile, web, and hardware engineering and development.