SWARM DRONE OPERATIONS IN HOSTILE EM ENVIRONMENT

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Whatever question arose, a swarm of these drones, without having finished their buzzing on a previous theme, flew over to the new one and, by their hum, drowned and obscured the voices of those who were disputing honestly.

— Leo Tolstoy, *War and Peace*

INTRODUCTION

A swarm is a group of interactive individual identities that collectively operate to achieve a common objective. The concept of swarms comprises the futuristic autonomous air weapon systems having great military potential for the execution of innovative daring missions. The inter and intra communication within the intelligent Unmanned Aerial Vehicles (UAVs) swarm system which is intricately complex, is prone to Electro-Magnetic (EM) signals interference. As the technology evolves and matures, the risks associated with drone swarms' operations need to be addressed *ab-initio* at both the conceptual and design stages.

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UAV swarm communication and their control options demand reliable and secure communication links between the airborne entities and the ground/air control stations that are part of the system environment. This is also essential to exchange large amounts of data to enable coordination, movements and actions to ensure mission success in a benign or hostile EM environment.[1]

The recent Ukraine conflict has again brought out the intricacy of managing air operations in a hostile Electro-Magnetic Spectrum (EMS). The freedom of movement and action in an Electro-Magnetic Environment (EME) rather than just the radio frequencies spectrum is the military canvas of operation. The swarms' success, therefore, depends on crafting the most effective, efficient use and exploitation of the EME. The EME conflict includes Electro-Magnetic Operations (EMOs), which shape the EME for executing operations. This is the new form of conflict, labelled as 'hybrid' or 'new generation', with EW as a key capability under which airborne swarms are expected to undertake missions.[2]

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The swarm's efficacy in a mission's success depends on reliable and secure communication between its individual elements and the proper performance of the various systems Artificial Intelligence (AI) modules. Thus, these entities in the swarm are vulnerable to spoofing, jamming and cyber-offensive actions. Effective counter-measures against swarms will be brought to bear to degrade their performance if not to completely neutralise them. The characteristic independence of swarms to quickly respond

1. Marcin Frackiewiczin, "What are the Expected Communication and Control Options for a Drone's Swarm?" *TS2 Spaceon*, February 21, 2023, https://ts2.space/en/what-are-the-expected-communication-and-control-options-for-a-drones-swarm/. Accessed on July 15, 2023.
2. Commander Ignacio Nieto, SP N, "The Electromagnetic Environment and the Global Commons: Are We Ready to Take the Fight to the Spectrum?" Spanish Joint Command, Published January 2020 in Journal Edition 29, *Journal of the JAPCC* (Joint Air and Space Power Conference), https://www.japcc.org/articles/the-electromagnetic-environment-and-the-global-commons/. Accessed on July 15, 2023.

instinctively, will probably be fought with a counter-swarm weapon (larger and/or more advanced swarm).[3]

In this article, the various aspects of swarms are deliberated upon to help military commanders in planning swarm operations in a hostile EM environment. Also, certain aspects of communication which need to be considered in the design and formulation of qualitative requirements for drone swarms have been reflected upon. Swarms comprise an evolving technology and military commanders need to remain abreast of this to efficiently employ the swarms in a hostile military environment and during their guidance of the technologists developing the military drone swarms.

There is a need for developing a drone swarm operational concept of war-fighting in both benign and, more importantly, hostile EME, towards which, testing drone swarm attack technologies for war-fighting needs serious research and out of the box strategic thinking.

SWARM COMMUNICATION

In a contested EM order of battle setting, a swarm calls for precise and secure data exchange to execute the mission and, thus, interactions through a suitably structured network comprise a design challenge for UAV swarms.[4] There is a need for developing a drone swarm operational concept of war-fighting in both benign and, more importantly, hostile EME, towards which, testing drone swarm attack technologies for war-fighting needs serious research and out of the box strategic thinking.

The usual communication and control for drone swarms is through Radio Frequency (RF) communication. Another choice is optical communication which uses light to send and receive data. A third preference is the commercial

3. Alessandro Gagaridis, "Warfare Evolved: Drone Swarms Backgrounders", *Geopolitical Monitor*, June 10, 2022, https://www.geopoliticalmonitor.com/warfare-evolved-drone-swarms/. Accessed on July 15, 2023.
4. BH Wang, DB Wang, and ZA Ali, "A Cauchy Mutant Pigeon-Inspired Optimization–based Multi-Unmanned Aerial Vehicle Path Planning Method", *Measurement and Control*, 2020, https://www.researchgate.net/publication/338557447_A_Cauchy_mutant_pigeon-inspired_optimization-based_multi-unmanned_aerial_vehicle_path_planning_method. Accessed on July 15, 2023.

and dependable cellular communication. Finally, the alternative of combining the various methods for specific tasks or switching between options is possible. This, along with satellite communication, offers the greater flexibility and reliability required in air operations.[5] The swarm control systems communication must be able to securely manage many individual entities from the control station. Adequate bandwidth is essential for enormous data inter-exchanges for the effective operation of the swarm, that includes safety, obstacle avoidance and all-weather operational capability. In the future, air operations' autonomous flight of swarms will transform the way they are employed.

Swarms may operate as transmitter, relay and receiver nodes due to their inherent mobility. In a hostile EM setting, swarms need multi-channel access to network securely and, hence, require omnidirectional antennae which results in reduced spectrum efficiency. Energy conservation in individual entities of the swarm due to limited battery capacity needs serious consideration in the communication design. Large UAVs employ traditional anti-jamming techniques like frequency hopping and spread spectrum to maintain reliable control communication links with the ground station. These are not suitable for the high-speed data communication required in swarms.[6]

Joint communication-motion-antenna programming in UAV swarms to combat jamming has been researched in the literature. However, it is difficult to fully comprehend and model the consequences of a complicated EM environment on the swarm communication system. Similarly, it is a challenge to develop the joint communication-motion-antenna programming in swarms. In order to address this challenge, the reinforcement learning AI approach has been implemented, wherein the complete complex environment is not modelled. Only, all possible actions taken by the entities are evaluated, and using unsupervised AI techniques, the optimum control actions are generated.

5. Frackiewiczin, n. 1.
6. Jinlin Peng, Zixuan Zhang, Qinhao Wu, and Bo Zhang, "Anti-Jamming Communications in UAV Swarms: A Reinforcement Learning Approach," Special Section on Advanced Communications and Networking Techniques for Wireless Connected Intelligent Robot Swarms, *IEEE Access*, vol 7, January 2019, https://ieeexplore.ieee.org/document/8928502?denied. Accessed on July 29, 2023.

A Multi-Dimensional Anti-Jamming Reinforcement Learning (MDAJRL) algorithm has been proposed in the Institute of Electrical and Electronics Engineers (IEEE) paper,[7] which effectively solves the complications of the environment, and its effectiveness has been verified by simulations.

Satellite communication is used in security, defence, or long distance operations, away from the control centre. However, in civil and private applications, the choice is now increasingly cellular communication. Indoor communication of the entities is largely through Bluetooth and other Point-to-Point (P2P) protocols which are considered efficient. In military swarms which are multi-layered networks, the communications comprise a complicated process and will entirely depend on the intended mission.[8]

Artificial intelligence, secure navigation strategies and cryptography are integral to military UAV communication techniques which ensure efficient, reliable, and low-latency communications between various nodes of the UAV network. Energy efficiency in UAVs is a challenge during secure communication and in onboard computing. Maintaining reliable communication during network jamming or interference can be a serious issue in swarm elements to conserve energy for mission success.[9] In the civil domain, UAV clusters, including swarms, are being increasingly considered for establishing emergency communication infrastructure and disaster surveillance. The process of individual and swarm routing, seamless handover and energy efficiency is an area of contemporary research.

SWARM ARCHITECTURE

Swarm architecture is based on communication, mission doctrine, control, etc. The approaches include bottom-up modelling approaches and top-down approaches for designing swarm systems. The mission doctrine is all

7. Ibid.
8. Abhishek Sharma, Pankhuri Vanjani, Nikhil Paliwal, Chathuranga M. Wijerathna Basnayaka, Dushantha Nalin K. Jayakody, Hwang-Cheng Wang, and P. Muthu Chidambaranathan, "Communication and Networking Technologies for UAVs: A Survey", *The Journal of Network and Computer Applications*, vol 168, October 15, 2020, https://doi.org/10.1016/j.jnca.2020.102739. Accessed on July 29, 2023.
9. Ibid.

important in the design of the airborne military swarm system architecture.[10] A Mission-Based Architecture for Swarm Composability (MASC) has been presented in the research paper by K Giles and K Giammarco.[11] This framework focusses on the phases, tactics, plays and algorithms. According to this architecture, the mission explains the entire task, the phases evaluate specific periods, the tactics are the individuals' usage in a particular order for task performance, the play describes the swarm behaviour, and the algorithms are the procedures. The architecture can perform the thinking task, execution task, reaction task and intra-swarm socialisation task efficiently. Moreover, the Internet of Things (IoT) supports swarm architectures and facilitates interactions as well.[12]

The swarm continuously changes its position to adapt to the new environment, therefore, detecting and tracking the swarm's position, status and the external environment transformations in the period of a swarm's operation are quite challenging. The Dynamic Data-Driven Application System (DDDAS) is one of the solutions, which assists in the environment and the mission's adaptation.[13] The wireless ad-hoc networks are capable in providing efficient communications. The intra-connection of UAV swarms is independent but the interconnection is dependent on the base station. Three forms of networks which include the Flying Ad-hoc Network (FANET), Mobile Ad-hoc Network (MANET), and Vehicle Ad-hoc Network (VANET), are in use. UAVs also can act as aerial base stations in a swarm to support the infrastructure of the communication.[14] The airborne station improves

10. K Giles, and K Giammarco, "Mission-Based Architecture for Swarm Composability (MASC)", *Procedia Computer Science*, 2017, https://pdf.sciencedirectassets.com/280203/. Accessed on July 29, 2023.
11. Ibid.
12. Ibid.
13. M Silic, and K Mohseni, "Field Deployment of a Plume Monitoring UAV Flock", IEEE Robotics and Automation Letters, 2019, 4(2), 769-775, https://ieeexplore.ieee.org/ielaam/7083369/8581687/8613865-aam.pdf. Accessed on July 29, 2023.
14. S Al-Emadi, and A Al-Mohannadi, "Towards Enhancement of Network Communication Architectures and Routing Protocols for FANETs: A Survey", In the 2020 3rd International Conference on Advanced Communication Technologies and Networking (CommNet). IEEE, 2020, pp. 1-10, https://www.researchgate.net/publication/343761099_Towards_Enhancement_of_Network_Communication_Architectures_and_Routing_Protocols_for_FANETs_A_Survey. Accessed on August 5, 2023.

transmission efficiency and reduces response delays which are critical for cooperation, control, and path planning.

Swarming exists in organic populations but it is also motivated by a military tactic wherein multiple combat units from several axes orchestrate a coordinated and structured attack on an objective. However, today, swarming has innovatively changed the traditional concepts of command and control where a single person commands and controls several UAVs at a time.[15] The swarm makes decisions collectively and executes its mission using relatively simple instructions facilitated by AI technology and edge computing. Features like follow the leader, path planning, sensing, and avoidance have already been developed in the Veronte Autopilot which is a miniaturised avionics system for the advanced control of autonomous vehicles ensuring task success. Advanced features of swarming now include self-healing and adaptive formation flying.[16] Enriching the competence of artificial swarm intelligence, increase in the autonomy among the swarm agents and commodification to reduce the cost are the areas of research worldwide.

SWARM INTELLIGENCE (SI)

A swarm has a collective brain of all the individual elements brains which is way ahead and smarter. Swarm intelligence is now a promising area of artificial intelligence based on biological structures or processes and is a hot topic of research across the globe. SI is due to the robust interconnections of the real system having many feedback loops. All the individual agents in the swarm follow well-defined rules within themselves and the environment as well. However, for this strategy, a large number of individual entities must be present in the swarm. How large, will decide the swarm's capability and capacity to complete the desired tasks. It emulates the behaviour of

15. Muhammad Mubashir Iqbal, Zain Anwar Ali, Rehan Khan and Muhammad Shafiq, from the edited volume, *Aeronautics*, edited by Zain Anwar Ali and Dragan Cvetković, Chapter, "Motion Planning of UAV Swarm: Recent Challenges and Approaches", submitted June 21, 2022. Reviewed July 4, 2022, Published August 6, 2022, https://www.intechopen.com/chapters/82985. Accessed on August 5, 2023.
16. Ibid.

ants in which the advancing ants gather the intelligence while the rear ants exploit that data.[17]

Swarm intelligence-based optimisation techniques depend on communication among individual elements during the search. Where the search is in a hostile EM environment, it will adversely impact the search performance.

The main characteristics of SI include distribution, stigmergy, cooperation, self-organisation, emergence, and imitating natural behaviour. Stigmergy is an important phenomenon with which the swarm agents interact indirectly with the environment which allows them the awareness of their surroundings and removes the individual interactions of the members. Imitating natural swarm behaviour is the key aspect of swarm intelligence. In swarm path planning, for example, initially, positive pheromones are used to mark the entry to the shorter paths, and later, swarm intelligence marks the no-entry by a negative pheromone for the disagreeable routes for the others.[18]

Swarm intelligence-based optimisation techniques depend on communication among individual elements during the search. Where the search is in a hostile EM environment, it will adversely impact the search performance. During search-and-rescue missions of drone swarms behind enemy lines, the individual swarm agents are in a hostile environment that can result in the loss of some of the agents.[19] This will reduce the number of agents as well as the quantum of information for which the swarm will

17. NV Karadimas, N Doukas, M Kolokathi, and G Defteraiou, "Routing Optimization Heuristics Algorithms for Urban Solid Waste Transportation Management," WSEAS Transactions on Computers 2008; 7(12): 2022-2031, https://www.researchgate.net/publication/228714142_Routing_Optimization_Heuristics_Algorithms_for_Urban_Solid_Waste_Transportation_Management. Accessed on August 5, 2023.
18. M Schranz, GA Di Caro, T Schmickl, W Elmenreich, F Arvin, A Şekercioğlu, et al., "Swarm Intelligence and Cyber-Physical Systems: Concepts, Challenges and Future Trends," *Swarm and Evolutionary Computation*, https://pure.manchester.ac.uk/ws/portalfiles/portal/175341536/1_s2.0_S2210650220304156_main.pdf. Accessed on August 5, 2023.
19. Vipul Mann, Abhishek Sivaram, Laya Das, and Venkat Venkata Subramanian, "Robust and Efficient Swarm Communication Topologies for Hostile Environments", *Swarm and Evolutionary Computation*, vol 62, April 2021, https://www.researchgate.net/publication/343825607_Robust_and_Efficient_Swarm_Communication_Topologies_for_Hostile_Environments. Accessed on August 5, 2023.

dynamically adapt to the new environment for search. This typically will have a negative effect on the swarm's performance.

The vital feature of swarm intelligence is the adaptability of the individual members in the system which can be assigned any sub-task which the SI perceives to be of higher priority.

SI in the military perspective implies that the operator does not strictly control every agent within a swarm. Instead, he dispatches the swarm to the designated area and then the swarm intelligence takes over to accomplish the mission. The vital feature of swarm intelligence is the adaptability of the individual members in the system which can be assigned any sub-task which the SI perceives to be of higher priority. Mission-critical operations can be executed by the member which has the ability at that point of time and is not constrained by any hierarchy within the swarm.[20]

A recent development in military drone swarm simulation is the emergent swarm. Manned military systems' intelligent models, coalesced with swarm intelligence that models unmanned systems is the new cognitive architecture of the emergent swarm.[21] The emergent swarm has been designed to model all aspects of multi-domain operations. It is intended to explore the decentralised control of unmanned systems to understand the manned-unmanned war-fighter integration. This will aid in refining the current air battle tactical doctrine. The military training simulation software of emergent swarms enhances commanders' interactions between manned and unmanned systems, and between human intelligence and artificial intelligence.[22]

The individual members in a swarm do not communicate directly with each other: they do so through environmental alterations which serve as external memory. The combined stigmergy behaviour of all the swarm members is the simulation of the desired task. The individual agents pick their actions by harmonising between a perception-reaction model and

20. Sentient Digital, Inc. "Military Drone Swarm Intelligence Explained", https://sdi.ai/blog/military-drone-swarm-intelligence-explained/#:~:text=Swarm%20intelligence%20is%20the%20principle,to%20any%20of%20the%20individuals. Accessed on August 5, 2023.
21. Ibid.
22. Ibid.

any random model. They respond to this perception-reaction model while observing and modifying the local environmental properties in a continuous loop.[23] Proto-Swarm, Swarm, Star-Logo, and Growing Point are some programming languages used for swarm intelligence execution.

SWARM FLIGHT CONTROL

The anti-collision, search and tracking issues in the swarm formations imply control of all the individual UAVs during the planned path. The centralised and distributed platforms are the two major control platforms used in automation control of swarms. The centralised platform ensures higher quality control outputs but limited scalability, whereas the decentralised platform gives greater scalability and is less complex to implement. A multi-layer distributed control framework provides excellent connectivity of the UAV swarm nodes and simplifies the application designs.[24] In order to maintain safe combat flying formation of large-scale swarms', development of low-cost sensors is necessary. To reduce the response of swarm retaliation under threat environments, dynamic sensing and potent safe flight protocols are critical. Intra-swarm communication standardisation by upgrading the frequency bands, cooperative counter-measures and signal distortion monitoring are now central to meet the next-generation networks in swarm operations.[25]

The UAV swarm path planning is quite challenging and is classified into dynamic path planning, 3D path planning, area coverage path planning and optimal path planning. Dynamic path planning is indispensable for the task execution of a swarm, while 3D path planning is under threats and

23. M Shafiq, ZA Ali, A Israr, EH Alkhammash, and M Hadjouni. "A Multi-Colony Social Learning Approach for the Self-Organization of a Swarm of UAVs", *Drones*, 2022, https://www.researchgate.net/publication/360160779_A_Multi_Colony_Social_Learning_Approach_for_the_Self-Organization_of_a_Swarm_of_UAVs. Accessed on August 12, 2023.
24. J Wu, Y Yuanzhe, J Ma, W Jinsong, G Han, J Shi, et al., "Autonomous Cooperative Flocking for Heterogeneous Unmanned Aerial Vehicle Group", IEEE Transactions on Vehicular Technology, 2021, 70(12), 12477-12490, https://www.semanticscholar.org/paper/Autonomous-Cooperative-Flocking-for-Heterogeneous-Wu-Yu/3ef4583a6a3e6c72890cffce32c554ce7599f851. Accessed on August 12, 2023.
25. Iqbal, et al., n. 15.

emergencies and is hugely complicated. For optimal path planning, battery capacity and energy consumption need attention.[26]

The ability to self-organise is essential for swarm collaboration. During self-organising swarm flights, the risk of collision is likely, and all the members of a swarm must know each other's position using a multi-hop connection and implementation of the collision avoidance protocol for safe flights. Also, use of the Global Positioning System (GPS) and in the case of non-existence of GPS, the location can be predicted using the Euclidean principle with three known locations. A few such safe flight protocols such as the goose swarm algorithms, Reynolds rule, and pigeon flock algorithm are available in the research literature.[27]

Lightweight, low-cost payloads and platforms are essential for swarms. High capacity performance batteries are indispensable for uninterrupted missions. The capacity of the battery also can be increased by improving the agents' load carrying capacity. However, this will require more energy consumption and, hence, a technological trade-off in mission accomplishment.[28]

SWARM OPERATIONS IN HOSTILE ENVIRONMENT

With advanced jamming technologies now available to the military commanders, the effectiveness of drone swarms can be degraded if not completely compromised. Resilient networks have now been designed that overcome communications and GPS systems jamming. The US Defence Advanced Research Projects Agency (DARPA), after tests on one of its networks, announced that the drone systems "efficiently shared information,

26. L Collins, P Ghassemi, ET Esfahani, D Doermann, K Dantu, and S Chowdhury, "Scalable Coverage Path Planning of Multi-Robot Teams for Monitoring Non-Convex Areas", IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2021, pp. 7393-7399, https://www.researchgate.net/publication/350485425_Scalable_Coverage_Path_Planning_of_Multi-Robot_Teams_for_Monitoring_Non-Convex_Areas. Accessed on August 12, 2023.
27. ZA Ali, H Zhangang, and D Zhengru, "Path Planning of Multiple UAVs using MMACO and DE Algorithm in Dynamic Environment", *Measurement and Control*, 2020, 53(5), 1-11, https://www.researchgate.net/publication/341681827_Path_planning_of_multiple_UAVs_using_MMACO_and_DE_algorithm_in_dynamic_environment. Accessed on August 12, 2023.
28. Iqbal, et al., n. 15.

cooperatively planned and allocated mission objectives, made coordinated tactical decisions, and collaboratively reacted to a dynamic, high-threat environment with minimal communication."[29] The tests highlighted the drone's ability to collaborate, navigate, attack, etc., all through short bursts of communications in spite of jamming technology.

The swarm SI is stacked into five modules: mission decision-making, planning layer, control and communication and application modules. In the decision-making module, detailed mission plans are visualised as executable tasks with ascribed priorities. The planning layer develops these details in determining the flight path of a swarm. In the control module, the swarm's mission is tactically directed in the swarm formation. The communication module manages the data exchange in a planned manner for ensuring the data fusion. The application module delineates the situation in which the swarm has to operate.[30] All swarm individual members talk to each other, through one node which has a radio link to communicate with the Ground Control Station (GCS). This inter-intra model of swarm operation is widely used in military reconnaissance swarms.

Operations of drone swarms in a hostile environment require dynamic re-planning of the mission. This includes changes to the planned flight route as well as the new mission payload work plan and modifying configuration parameters for each sensor of the swarm for efficient mission execution. On detection of a threat, this may be executed by the swarm algorithms, automatically or by intervention by the operator in a semi-automatic manner. The planning layer, as discussed above, will have changed the flight path and the application layer will have looked at the environment to implement

29. Daniel Pereira, "In the AI-driven Conflict in Ukraine, is 'the Swarm' the Systems Design Architecture of the Future?", *OODA Loop, Security and Resiliency*, April 27, 2023, https://www.oodaloop.com/archive/2023/04/27/in-the-ai-driven-conflict-in-ukraine-is-the-swarm-the-systems-design-architecture-of-the-future/. Accessed on August 12, 2023.
30. Barbara Siemiatkowska and Wojciech Stecz, "A Framework for Planning and Execution of Drone Swarm Missions in a Hostile Environment", *MDPI Journal*, Special Issue Special Applications of Microsensors. Published June 17, 2022, https://www.mdpi.com/1424-8220/21/12/4150. Accessed on August 12, 2023.

the threat avoidance or mitigation. The results of these algorithms are then used to re-plan the mission.[31]

The intelligent wireless communication network system based on environment awareness is the anti-jamming technology for UAV swarm communication. It senses the EM environment and uses AI technology to map the environment according to the knowledge base of radiation sources. By dynamically modifying transmission power, carrier frequency and modulation schemes without modifying the hardware, it can adjust to the stochastic deviations of the communication signals and not disturb the continuity of the radio link. This is called cognitive communication and the process can be executed at the beginning of transmission or in the process of transmission, resulting in uninterrupted communication to the swarm.[32] The swarm can obtain the order of battle of the EM generating forces and wisely sense the EM real-time situation to finally execute the counter-measures based on the prior knowledge base of radiation sources.

Swarms, inter-linked and in constant intra-communication, share their sensors' information and take collective AI decisions to achieve their overall mission objective. Each swarm member is a mere component dynamically tasked to perform a specific function. All combined comprise a 'hive mind' that self-coordinates the actions of its elements. The sensor specific elements will have designated tasks of detection and tracking, EW tasks, attacker's role or be the information sharing mode. This large-scale coordination results in a faster response and its combined resilience to the swarm's mission execution capability. The swarm, acting as a multi-domain task force, acts proactively in the battlespace and executes complex non-linear and counter-intuitive manoeuvres.[33]

31. Ibid.
32. Wu Jian, Liu Rang and Zhao Sen, "The Cognitive Communication Based Anti-Jamming Method for UAV Swarm Communication", *Materials Science and Engineering*, May 2020, OP Conference Series, https://www.researchgate.net/publication/341493387_The_Cognitive_Communication_based_Anti-jamming_Method_for_UAV_Swarm_Communication. Accessed on August 20, 2023.
33. Alessandro Gagaridis, "Warfare Evolved: Drone Swarms, Backgrounders", *GeoPolitical Monitor*, June 10, 2022, https://www.geopoliticalmonitor.com/warfare-evolved-drone-swarms/. Accessed on July 15, 2023.

The swarm's effectiveness depends on reliable and resilient intra- and inter-swarm communication. The derived SI is entirely based on efficient functioning of the AI governance modules, thus, making it susceptible to cyber and Electronic Warfare (EW) counter-operations.

This has massive potential to revolutionise the nature of air warfare. Swarms will enhance the tempo of operations without risking the loss of lives like in search and destroy missions, suppression of enemy air defences, attacking mobile air defences, Intelligence, Surveillance, Reconnaissance (ISR), counter-insurgency, over-the-horizon targeting, air combat, and Anti-Access/Area Denial (A2/AD). Synergy with manned platforms is now beginning to emerge like the F-35 fighters equipped with advanced data fusion software to control swarms as force multipliers.[34] Operationally efficient swarms are in niche software and hardware technology domains requiring advanced AI algorithms, high quality sensors and resilient data links. Thus, due to the technical complexity and the high costs of the necessary know-how, effective military air swarms are likely to be the exclusive assets of the high-tech, developed countries.

The swarm's effectiveness depends on reliable and resilient intra- and inter-swarm communication. The derived SI is entirely based on efficient functioning of the AI governance modules, thus, making it susceptible to cyber and Electronic Warfare (EW) counter-operations. As the swarm technology proliferates, effective counter-measures will also be developed and brought on to counter this weapon. The novel counter-swarm weapon will be another (larger and/or more advanced) swarm in an aerial combat of decentralised swarms on the horizon.[35]

INDIAN SWARM INITIATIVES

Swarm drone programmes are being globally pursued by all armed forces: the Icarus project of France, Lightning of Russia, RAPAZ of Spain, Blue

34. Ibid.
35. Ibid.

Bear swarm of the UK, and the N-Raven of the UAE/South Africa; and in India, recently there was a drone swarm on show, hitting targets on India's Army Day.[36] China and the USA are taking leaps in this domain. The DARPA's 'Mosaic Warfare' which is based on low cost entities to overpower adversaries, actually relies on swarming technologies. The Indian Air Force's (IAF's) Mehar Baba Swarm Drone Competitions are encouraging the local industry to play an important role in developing the swarming technologies for operational use in the IAF. India has also embarked on the development of swarm systems with the US under the Defence Technology and Trade Initiative (DTTI). Also, Hindustan Aeronautics Limited (HAL) is engaged with a start-up, "New Space Research Technology", to develop a proposed system called Air Launched Flexible Asset-Swarm (ALFA-S). This will be canister-based and can be launched from an aircraft/helicopter. A prototype is expected to be put up for trials in about two years.[37]

The indigenous "swarm drone attack system" design must be futuristic to cater for the rapidly changing technology and counter-measures. The approach must cater for the size of the swarm for enhanced SI, survivability of the drones in an adverse and hostile environment, and a suitable mix of the various types of air agents to cater for conventional and unconventional threats.

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36. Ritu Sharma, "Indian Air Force 'Bets Big' On Swarm Drone Technology to Overwhelm, Outfox Enemy Defense Systems", *The EurAsian Times*, August 19, 2023, https://www.eurasiantimes.com/the-era-of-swarm-drones-is-here-the-indian-air-force/. Accessed on August 23, 2023.
37. Lieutenant General Dushyant Singh (Retd), "Swarm Drones: New Frontier of Warfare," *SP's Land Forces*, Aero India 2021 Special, https://www.spslandforces.com/story/?id=747&h=Swarm-Drones---New-Frontier-of-Warfare. Accessed on August 20, 2023.

the concept of operations, therefore, a review of the war-fighting doctrine, concepts and capabilities is required alongwith, if considered essential, modification of the force structure. The future battlefield will be aggressive and time sensitive, hence, swarm deployment has to remain abreast of the changing dynamics of warfare and the technologies associated with it.[38]

Swarm technology has great potential in commercial applications—it is just waiting to be harnessed. The use of a cellular mobile framework and, especially, of imminent 5G networks with M2M (Machine-to-Machine) communication capabilities for UAV swarms' communication would greatly increase the swarms' efficiency and commercial utility.[39] 5G communication systems will enhance maximum download speeds of 10 Gbps with network latency as low as 1ms. This is most suited for streaming video from onboard cameras or Light Detection and Ranging (LiDAR) systems.[40]

A case for the use of cellular networks as the communication infrastructure for non-military UAV swarms and developing a test-bed of hardware and software to test UAV swarm architectures needs serious consideration for indigenous swarm design in India. These could also be ported to the military swarms' tasks within the coverage of the cellular network.[41]

OPTIONS TO COUNTER SWARMS

Unlike kinetic machine guns and air defence systems, the use of the Electro-Magnetic (EM) spectrum is more effective against swarms. An air transportable Tactical High-Power Operational Responder (THOR) which is an EM weapon has been developed by the US Air Force Research Laboratory. THOR radiates broad spectrum and wide beam Radio Frequency (RF) energy, capable of degrading numerous drones simultaneously. The

38. Ibid.
39. Mitch Campion, Prakash Ranganathan, and Saleh Faruque, "A Review and Future Directions of UAV Swarm Communication Architectures", Department of Electrical Engineering, University of North Dakota, https://und.edu/research/rias/_files/docs/swarm_ieee.pdf. Accessed on August 20, 2023.
40. Ibid.
41. Ibid.

"Mjolnir", which is a follow-on, has additional drone detection capabilities and extended ranges to enforce RF saturation.[42]

A different option is to combat swarms by lasers. High-powered lasers are a hard kill option by overheating the onboard electronic system. Integrated with tracking radar, lasing systems can be an effective anti-swarm weapon. The use of such defensive lasers is questionable in dense weather conditions or low-visibility areas. Cladding the individual swarm elements with a reflective coating will provides some protection in shielding from lasers.[43]

Jamming is a counter-measure against simple drones, but that effectiveness will decline against drones with sophisticated counter-counter-measures. These typically interfere with the swarm's ability to navigate and maintain station in formation, resulting in collisions or flight into the ground. A simple counter-measure against such an attack is to programme the swarm to return to home mode navigation which is based on its internal stand-alone inertial navigation system.[44]

An additional method to fight invading swarms is to employ defender drones. It is a war of attrition to disrupt the swarm's attack mission to achieve success. Though an effective concept, it cannot defeat an entire swarm without the support of other swarm defence systems.[45]

Swarms were considered to be dispensable after completion of their one-way mission, particularly operating in a hostile environment. However, with increasing complexity of the swarm elements, there is a need to recover them, charge them in the air (akin to air-to-air refuelling) and redeploy them whilst in the air. The GA-ASI (General Atomics Aeronautical Systems Inc.) has successfully tested the SUAS/ALE (Aerial Recovery System for Small Unmanned Aircraft Systems/Air-Launched Effects) incorporated on a MQ-

42. Ryan Bridley and Scott Pastor, "Military Drone Swarms and the Options to Combat Them", *Small Wars Journal*, August 18, 2022, https://smallwarsjournal.com/jrnl/art/military-drone-swarms-and-options-combat-them. Accessed on September 2, 2023.
43. Ibid.
44. Ibid.
45. Ibid.

20 Avenger to recover and redeploy smaller drones mid-flight. SUAS/ALE can also be used in refuelling, recharging, and rearming of airborne drones. GA-ASI Advanced Programmes Vice President Mike Atwood stated after the Dugway trial, "We are excited to see this technology enable long-range kill chains from today's manned and unmanned systems supporting operations in highly contested environments."[46]

CONCLUDING THOUGHTS

Swarm drones are AI-centric and dependent on reliable and secure communications. Academia, particularly the Indian Institutes of Technology (IITs) and National Institutes of Information Technology (NIITs) need to be actively associated in research of the emerging technologies in this area and they need to be funded appropriately by the Government of India over and above, or through, the Innovations for Defence Excellence (iDEX). Creating centres of excellence in AI technology and communications for swarm drones, in both the military and civil domains, with domain specialists from the military and other agencies, is recommended to be seriously considered at a strategic level.

The present initiatives of the IAF and other sister Services to have competitions for the budding start-ups in swarm design and development need to continue and the projects' complexity extended for futuristic missions in a non-benign military environment.

For the air warfare employment of drone swarms, an experts group within the IAF may be formed to develop scenarios of the EW environment wherein swarm employment will be operationally considered, and a communication test-bed established for evaluating the technologies that can be employed for resilient communication. This group needs to be flexible and dynamic, able to respond to emerging hostile EM threats and provide solutions in near real-time for the swarm operational commanders.

46. Rojoef Manuel, "GA-ASI Demonstrates Large Drone Recovering Smaller Ones Mid-flight", *The Defence Post*, October 11, 2023, https://www.thedefensepost.com/2023/10/11/general-atomics-aerial-recovery/?expand_article=1. Accessed on October 13, 2023.

The Swarm Drone Doctrine is suggested to be included in the Aerospace Doctrine of the IAF from which will flow the actions necessary to operationalise the swarms for future air warfare. The swarm drone operational concept of war-fighting in benign and, more importantly, hostile electro-magnetic environments is the immediate requirement. For this, testing swarm drone attack technologies for war-fighting needs serious research and out of the box strategic thinking.