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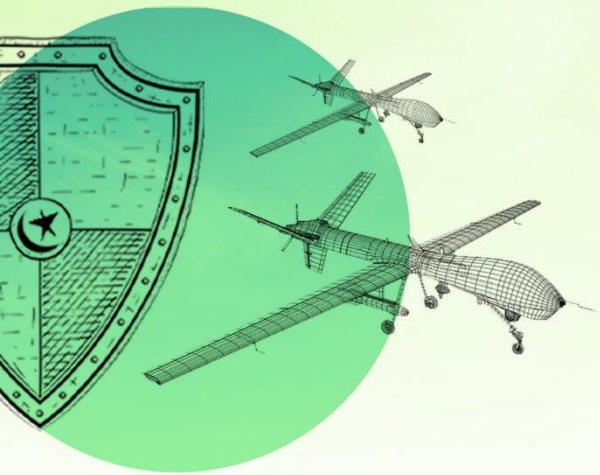

Era of Drone Swarming: Exploring Battlefield Implications

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Working Paper

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Abstract

Novel technologies, with more efficiency, precision, autonomy, speed, data-driven insights, and adaptability, are leading to renewed expectations on the battlefield. One such technology that has stirred considerable excitement in military thinking over recent years is Drone Swarming. Increasing attention is paving the way for its swift adoption by different states with the aim of better performance with reduced costs. This Working Paper examines existing literature on the subject to analyse future utility and impact of drone swarming in warfare. The findings reveal that the technology holds considerable promise for various military purposes, including offence, defence and several additional military roles on the battlefield. While opportunities are captivating military thinkers, they must also be mindful of associated challenges. Presence of effective countermeasures and possibility of even more potent countermeasures in the future, granting appropriate levels of autonomy, and ethical considerations pose concurrent dilemmas. Given rapid proliferation of the technology and its recent advent in South Asia, there is a pressing need for Pakistan to start exploring and seriously investing in this technology to meet future military requirements.

Keywords: Technology, Swarming, Drones, Warfare, Pakistan, India.

Introduction

The increasing complexity of warfare necessitates innovative strategies to ensure the survivability of fighting units. The advent of the information revolution has ushered in what Metz refers to as the era of 'post-modern warfare,' characterised by heightened asymmetry, accelerated operational tempo, involvement of non-traditional combatants, dispersed power dynamics, complexities in the psychological domain, and uncertainties introduced by emerging technologies.[1] These changes pose both challenges and opportunities for militaries worldwide. Those that fail to adapt to the demands of the post-modern warfare era risk finding themselves at a significant disadvantage.[2] Hence, militaries around the world are increasingly committed to enhancing their capabilities by introducing state-of-the-art weaponry and new strategies, complemented by use of existing emerging technologies, such as drone swarming. This approach aims to enhance operational effectiveness and maintain a decisive edge over current and potential adversaries in the face of emerging threats. Among various military technologies, drone swarming has emerged as a transformative asset, raising expectations about its impact on warfare. It embodies the characteristics of Metz's post-modern warfare by introducing innovative combat techniques and strategies. Drone swarms amplify asymmetry by overwhelming larger forces, enable network-centric operations, blur the distinction between combatants and non-combatants, decentralise power through smaller units, and exert a considerable psychological impact.

In their research paper published by RAND, Arquilla and Ronfeldt discussed the evolution of warfare, identifying three distinct phases. The first phase involved melee combat, characterized by man-to-man fighting. This was followed by the development of formation-based combat, where fighters operated cohesively to protect one another. The third phase introduced manoeuvre warfare, with massed formations strategically positioning themselves to gain an advantage over the enemy.[3]

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1 Steven Metz, *Armed Conflict in the 21st Century: The Information Revolution and Post-Modern Warfare,* report (Pennsylvania: Strategic Studies Institute, 2000), 81, https://press.armywarcollege.edu/cgi/viewcontent.cgi?article=1140&context=monographs.

2 Ibid.

3 John Arquilla and David Ronfeldt, *Swarming and the Future of Conflict,* report (Santa Monica: Research and Development Corporation, 2000) 91, https://www.rand.org/pubs/documented_briefings/DB311.html.

Swarming aligns closely with the principles of manoeuvre warfare, given speed, flexibility, focus, and surprise, rather than the traditional attrition warfare approach of destroying enemy strength through overwhelming force. It has emerged as a niche technology in modern warfare due to its reliance on highly specialised and sophisticated manufacturing processes and its relatively narrow usage base.[4] Swarming is also considered disruptive, thanks to its enhanced coordination, flexibility, and a wide range of innovative military and civilian applications.[5]

Recent advancements in the drone field have been driven by key factors such as automation, swarming, and miniaturisation, all of which are interrelated. These developments enable better trade-offs between altitude, range, payload and speed. Miniaturisation, in particular, allows even micro unmanned aerial systems (UAS) to carry high-value, high-performance equipment. These capabilities make drones indispensable for efficient situational awareness and a variety of potential military tasks in the future.[6]

As states around the world rapidly advance their exploration of drone swarming technology, it becomes crucial to evaluate its implications for warfare. This Working Paper aims to shed light on drone swarming technology, analysing its potential impact by examining its advantages and challenges. While the global literature on this technology is expanding, there is a notable scarcity of research specific to South Asia, particularly Pakistan. To address this gap, the paper briefly explores India's pursuit of drone swarming technology and its potential implications for Pakistan, providing a regional context to the discussion. The paper concludes by offering recommendations for Pakistan to prepare for and adapt to the advent of this transformative technology in the region.

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4 Dan Gettinger, "What You Need to Know about Drone Swarms," *Drone Centre*, November 3, 2014, https://dronecenter.bard.edu/what-you-need-to-know-about-drone-swarms/.

5 Caitlin Irvine, "Swarming Technology is Changing Drone Warfare," *Security Distillery*, July 10, 2018, https://thesecuritydistillery.org/all-articles/swarming-technology-is-changing-drone-warfare-part-one-of-three.

6 Michel Busch, "Unmanned Aerial Systems Miniaturization: Chances and Risks of an Irreversible Trend," *Journal of the Joint Air Power Competence Centre* 25 (2018): 75-79, https://www.japcc.org/articles/unmanned-aerial-systems-miniaturization/.

The research adopts a qualitative methodology, utilising secondary data and a deductive approach. Data has been collected from journals, research papers, reports, websites, and opinion articles. Relevant journals were identified through keyword searches using terms such as 'swarming,' 'drone swarming,' and 'impact on warfare' on Scopus and Google Scholar. Of the 50 journals initially selected for abstract review, 35 were shortlisted for detailed analysis. Overlapping ideas and concepts were synthesised into thematic categories to structure the findings.

The research paves the way for new avenues of inquiry, particularly within the India-Pakistan context. It sparks debates on the development, deployment, and evolution of countermeasures in the region, while also encouraging further exploration of how drone swarming technology could influence the regional balance of power. In addition, the study offers valuable insights for future research on doctrines, strategies and warfighting techniques related to drone swarming, providing a deeper understanding of its potential impact on modern warfare.

Swarming and Drone Swarming: An Overview

Swarming is an innovative phenomenon. One of the most frequent definitions of swarming is proposed by RAND, which defines swarming as 'systematic pulsing of force and/or fire by dispersed, interconnected units, so as to strike the adversary from all directions simultaneously.'[7] A definition proposed by Paul Scharre refers to swarming as 'large numbers of dispersed individuals or small groups coordinating together and fighting as a coherent whole.'[8] Another non-military definition refers to 'swarm or fleet of Unmanned Aerial Vehicles (UAVs) is a set of aerial robots i.e., drones that work together to achieve a specific goal.'[9] Hence, at its core, it involves the

7 Arquilla and Ronfeldt, *Swarming and the Future of Conflict*.

8 Paul Scharre, *Robotics on the Battlefield Part II: The Coming Swarm*, report (Washington, D.C.: Center for a New American Security, 2017), 26, https://www.cnas.org/publications/reports/robotics-on-the-battlefield-part-ii-the-coming-swarm.

9 Anam Tahir, Jari Boling, Mohammad Hashem Haghbayan, Hannu Toivonen et al., "Swarms of Unmanned Aerial Vehicles - A Survey," *Journal of Industrial Information Integration* 16, (2019) : 100107- 100113, https://www.sciencedirect.com/science/article/pii/S2452414X18300086#bib0001.

process by which multiple units direct a convergent assault towards a target from multiple axis.[10]

In the context of drone technology, drone swarming entails deployment of multiple unmanned platforms which autonomously alter their behaviour on the basis of communication with each other and share the same objective.[11] Several rotors are associated with each drone in a swarm and each drone has the ability to vertically hover, take-off, and land (VTOL).[12] The drone swarm's success relies on the formation's ability to communicate, coordinate, and act coherently so that the adversary faces an insuppressible number of potential targets that create an overwhelming and omnipresent situation - seemingly, everywhere and nowhere at once. The complex interconnectedness of the drones enables amplified effectiveness relative to their individual capabilities.[13]

Drone swarms can vary in range and size (small, medium and large),[14] typically comprising 10 to 100s of UAS.[15] While a human pilot can direct and influence the behaviour of a drone swarm, he does not control individual drones; drone swarms have the ability to maintain their formation autonomously.[16] In fact, the level of human involvement can vary depending on the mission. It is also possible that one of the tasks could be performed by the drone swarm autonomously, whereas another task may require approval of a human operator.[17] For example robotic swarms could be used for reconnaissance whereas, a human operator could retain the authority to attack/launch strike.[18] The technology is currently in the nascent stage and a human

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10 Sean J. Edwards, *Swarming and the Future of Warfare*, report (Santa Monica: Research and Development Corporation, 2005), 2, https://www.rand.org/pubs/rgs_dissertations/RGSD189.html.

11 Zachary Kallenborn and Philipp C. Bleek, "Swarming Destruction: Drone Swarms and Chemical, Biological, Radiological, and Nuclear Weapons," *The Nonproliferation Review* 25, no.5 (2018) : 523 - 543, https://www.tandfonline.com/doi/abs/10.1080/10736700.2018.1546902.

12 Tahir, Boling, Haghbayan, Toivonen et al., "Swarms of Unmanned Aerial Vehicles - A Survey,"

13 Zachary Kallenborn, "Swarm Talk: Understanding Drone Typology." *Modern War Institute*, October 12, 2021, https://mwi.usma.edu/swarm-talk-understandingdrone-typology/.

14 Ibid.

15 Irving Lachow, "The Upside and Downside of Swarming Drones," *Bulletin of the Atomic Scientists* 73, no.2 (2017): 96 -101, https://www.tandfonline.com/doi/full/10.1080/00963402.2017.1290879.

16 Ibid., 97.

17 Jacob W. Crandall, Nathan Anderson, Chace Ashcraft, John Grosh, et al., "Human-Swarm Interaction as Shared Control: Achieving Flexible Fault-Tolerant Systems," (paper presented at Engineering Psychology and Cognitive Ergonomics: Performance, Emotion and Situation Awareness: 14th International Conference, Vancouver, July 9-14, 2017).

18 Lachow, "The Upside and Downside of Swarming Drones," 97.

is either kept 'in-the-loop', where the operator is able to retain sufficient control in making plans and executing decisions or 'on-the-loop' where the machine has some level of autonomy under human supervision.[19]

The ability of the drone swarms to communicate with each other is one of its most essential characteristics. The physical characteristics - programming and sensors - are usually kept uniform. [20] Given that environmental factors considerably impact the manner in which swarms are guided, sensors are of great significance. While drone swarms can consist of multiple drones with identical sizes and characteristics, they may also feature diverse configurations, incorporating a range of weapons and sensors to form a heterogeneous swarm.[21] Role differentiation is a key feature of heterogeneous swarms, offering distinct advantages. For instance, sensing drones can identify and track potential threats or targets; attack drones can carry and deploy payloads; communication drones can establish seamless links within the swarm and with external command systems; and decoy drones can divert enemy fire or deceive adversaries by emitting fake signatures.[22]

In his study, Kallenborn highlights that swarms are not always costly, pointing to a low-cost, less sophisticated class of drones capable of enabling rudimentary swarm tactics, or 'fake swarms.' Unlike AI-enabled swarms, these rely on basic coordination and synchronisation. He further predicts that in the future, militaries might develop unimaginably large groups of tiny, ultra-cheap, 3D-printed mini-drones, revolutionising swarm warfare. [23] In the years ahead, operationalisation of drone swarming is likely to be influenced by several factors which include degree of autonomy, and the level of their coordination.[24]

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19 Agrawal, Ankit, and Jane Cleland-Huang, "Explaining Autonomous Decisions in Swarms of Human-on-the-loop Small Unmanned Aerial Systems," (paper presented at the AAAI Conference on Human Computation and Crowdsourcing, California, November 12, 2015).

20 Lachow, "The Upside and Downside of Swarming Drones," 97

21 Zachary Kallenborn, "The Era of the Drone Swarm is Coming, and We Need to be Ready for it," *Modern War Institute,* October 25, 2018, https://mwi.usma.edu/era-drone-swarm-coming-need-ready.

22 Milton B. Adams, Janet A. Lepanto, and Mark L. Hanson, "Mixed Initiative Command and Control of Autonomous Air Vehicles," *Journal of Aerospace Computing, Information, and Communication* 2, no. 2 (2005): 125 - 153, https://arc.aiaa.org/doi/abs/10.2514/1.12963?journalCode=jacic.

23 Zachary Kallenborn, "InfoSwarms: Drone Swarms and Information Warfare," *Parameters* 52, no.2 (2022): 87 - 102, https://press.armywarcollege.edu/cgi/viewcontent.cgi?article=3154&context=parameters/.

24 Thomas Hammes, "Defending Europe: How Converging Technology Strengthens Small Powers," *Scandinavian Journal of Military Studies* 2, no. 1(2021) : 20 - 29, https://sjms.nu/articles/10.31374/sjms.24.

Developed and technologically advanced states are rapidly advancing their investments in drone swarming technology, with the United States and China leading the race. The U.S. Department of Defense (DoD) is spearheading efforts through its 'Autonomous Multi-Domain Adaptive Swarms-of-Swarms' (AMASS) project, which aims to deploy massive drone swarms capable of operating across air, ground, and sea domains.[25] Meanwhile, China is pursuing AI-powered, machine-learning-enabled swarm technology.[26] Previously, China had explored data-link technology for swarms, with a potential focus on targeting aircraft carriers. [27]

However, while high expectations surround drone swarming, the technology presents significant advantages alongside notable challenges. The following section of this research paper details the benefits and potential obstacles associated with drone swarming discussed.

Advantages of Drone Swarms

There are a number of potential advantages offered by the swarming technology, which makes them more appealing for future warfare.

Drone swarms provide an effective and relatively economical asset for military operations while significantly reducing risks to human lives. [28] Their design enhances survivability on the battlefield due to several factors. First, their detection is comparatively more challenging than manned aircraft, making it difficult for the adversary to detect and identify them.[29] Secondly, networked nature of multiple drone weapons systems enables them to carry on their task/mission even if detected, given

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25 Tim Mcmillan, "Pentagon Secretly Working To Unleash Massive Swarms Of Autonomous Multi-Domain Drones To Dominate Enemy Defenses," *Debrief,* February 3*,* 2023*,* https://thedebrief.org/pentagon-secretly-working-to-unleash-massive-swarms-of-autonomous-multi-domain-drones-to-dominate-enemy-defenses/.

26 James Johnson, "Artificial Intelligence: A Threat to Strategic Stability," *Strategic Studies Quarterly* 14, no.1 (2020): 16 - 39, https://www.airuniversity.af.edu/Portals/10/SSQ/documents/Volume-14_Issue-1/Johnson.pdf.

27 Elsa B. Kania, *Battlefield Singularity: Artificial Intelligence, Military Revolution, and China's Future Military Power,* report (Washington, DC: Center for a New American Security, 2017), 23, https://www.cnas.org/publications/reports/battlefield-singularity-artificial-intelligence-military-revolution-and-chinas-future-military-power.

28 Irving Lachow, "The Upside and Downside of Swarming Drones,"97.

29 Dushyant Singh, "Swarm Drones - New Frontier of Warfare," *SP's Land Forces*, 2021 ,4 https://www.spslandforces.com/e-magazine/?magid=76&Name=sp_s_land_forces_1-2021&Info=SP%27s%20Land%20Forces%20-%20Aero%20India%202021%20Special&year=2021.

that some drones may still remain un-intercepted even if attacked by enemy forces.[30] This resilience stems from the fact that the constituent units that make up a swarm could disperse, then promptly come together again to attack, re-organise to ensure that the mission continues till the last UAV in air.[31] Hence, confronting a swarm is equivalent to confronting a cloud-like entity that could pose a challenge to the defending side.

a) Employment

Offensive Employment

In an offensive role, drone swarms can serve as a powerful asset against ground-based targets such as infantry vehicles, tanks, and artillery guns from a distance. The sheer strength of the attacking swarm, coupled with their dispersed nature, can overwhelm targets, making it both costly and challenging for the opposing side to mount an effective defence.[32] Remarkably, these swarms can consist of relatively low-cost drones yet still be capable of neutralizing larger and more expensive weapon systems.[33]

One of the most effective applications of swarm drones is in the 'Suppression of Enemy Air Defences' (SEAD) role, a traditionally high-risk mission for manned aircraft. A notable example of drones excelling in this role occurred during the Nagorno-Karabakh conflict, where Azerbaijan employed numerous drones to successfully target Armenian air defence systems.[34] A detail of drones used by Azerbaijan is given in Table 1:

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30 Tadeusz Zielinski, "Factors Determining a Drone Swarm Employment in Military Operations." *Safety & Defense* 7, no. 1 (2021): 59 - 71, https://www.sd-magazine.eu/index.php/sd/article/view/112.

31 Ibid.

32 Paul Scharre, *Robotics on the Battlefield Part II : The Coming Swarm.*

33 Zachary Kallenborn, "Swarm Talk: Understanding Drone Typology."

34 Shaza Arif, "How Drones in Azerbaijan won the War against Armenia," *Khaleej Mag,* January 26, 2021, https://khaleejmag.com/news/how-drones-in-azerbaijan-won-the-war-against-armenia/.

Table 1: Drones used by Azerbaijan

Name	Features
Harop	Designed to destroy the adversary's radar in Suppression of Enemy Air Defence (SEAD) Range: 1000km Can fly upto 6 hours
Bayraktar	Can be armed with light ammunition Range 8km Can fly upto 24 hours
Skystriker	Used for rapid precision strikes Range: 100km Can fly upto 2 hours
TRG-300 Tiger	Provides effective and accurate firepower Range: 120km

Source: Author's own.

The Armenian air defence systems included Krugs (SA-4), Kub (SA-6), Osa (SA-8), Strela-10 (SA-13), and the S-300. Notably, the Strela-10s and Osas had shorter effective ranges than the missiles carried by TB-2 drones. While systems like the Krug, Kub, and S-300 were designed to intercept larger and faster targets, their effectiveness against smaller, slower drones was limited. [35]

Drones, particularly killer drones, often present a more cost-effective alternative to expensive missiles or manned aircraft. However, employing missiles as countermeasures against swarm drones can be economically inefficient, as the cost of intercepting a swarm often outweighs the value of the drones themselves. Swarm drones can also deplete missile stockpiles, leaving batteries vulnerable to follow-up attacks. Despite their advantages, small drones have limited range and lethality - typically a few kilometres - restricting their use in deeper operational contexts.

[35] Eado Hecht, "Drones in the Nagorno-Karabakh War: Analyzing the Data," *Military Strategy Magazine* 7, no.4 (2022): 31-37, https://www.militarystrategymagazine.com/article/drones-in-the-nagorno-karabakh-war-analyzing-the-data/.

Defensive Employment

Swarm drone technology can also be effectively employed in defensive roles. For instance, it can generate automated protective bubbles around critical targets, intercepting incoming swarm attacks and providing an efficient shield. A sizeable swarm of drones could be deployed over enemy territory to disrupt operations by preventing aircraft from taking off, thereby significantly limiting the adversary's operational capabilities. However, the limited range of swarm drones and the presence of defences at enemy airfields constrain the feasibility of such tactics. In specific scenarios, particularly for smaller airfields located within the drones' operational range, successful employment of swarm drones remains a possibility. Similarly, this technique could be adapted to protect key targets or vulnerable points from potential attacks by low-flying enemy helicopters.[36] This technique could form part of an overall defensive operation coupled with appropriate detection and targeting systems. The details regarding the number of drones in the swarm and their placement would depend on various factors and tactical considerations – something beyond the scope of the paper.

Additional Roles

Advancements in drone swarm technology open opportunities for their tactical application across various established Air Power Doctrinal roles, including control of the air, attack, intelligence, surveillance, and reconnaissance (ISR), and air mobility.[37] Swarm drones, equipped with miniaturised electromagnetic jammers or cyber weapons, can serve as platforms for electronic warfare, disrupting targeting sensors and communications, undermining enemy air defences designed to counter them.[38] Currently, drone swarms are being utilised as sensor platforms for area reconnaissance, with ongoing research exploring their potential to locate mobile missile launchers using AI-augmented UAVs.[39]

The potential applications of swarm drones in CBRN (Chemical, Biological, Radiological, and Nuclear) scenarios are also being explored. These drones can access hazardous areas that are unsafe for humans, using onboard sensors to detect

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36 Paul Scharre, "How Swarming Will Change Warfare," *Bulletin of the Atomic Scientists* 74, no.6 (2018) : 385 - 389, https://www.tandfonline.com/doi/abs/10.1080/00963402.2018.1533209.

37 Ministry of Defence, "UK Air Power,", https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1106210/20220923-Doctrine_bitesize_UK_Air_Power.pdf, [Accessed November 4, 2023].

38 James Johnson, "Artificial Intelligence : Drone Swarming and Escalation," Royal United Services Institute Journal 165, no.1 (2020): 26 - 36, https://www.tandfonline.com/doi/abs/10.1080/03071847.2020.1752026?journalCode=rusi20.

39 Axel Burkle, Florian Segor, and Matthias Kollman, "Towards Autonomous Micro UAV Swarms," *Journal of Intelligent & Robotic Systems* 61, no.1 (2011) : 339 - 353, https://link.springer.com/article/10.1007/s10846-010-9492-x.

hazardous substances and map the spread of contamination. Such missions, which pose excessive risks to human operators, are ideally suited for unmanned systems, offering a safer and more efficient alternative. [40]

Swarm drones equipped with emitters[41] could strategically enhance their electronic signature, creating the illusion of a larger force. This capability could serve as a powerful tool for deception, forcing adversaries to divert resources or saturate their defences in response to a perceived, exaggerated threat. Such tactics could be especially effective in contested environments, where misdirection can create opportunities for other assets to exploit vulnerabilities.

Future advancements in drone swarming technology could enable seamless integration with human-piloted aircraft. This partnership would allow pilots to command large swarms for critical roles such as offence, electronic warfare, reconnaissance, and logistics. By augmenting human capabilities with autonomous systems, such collaborations could significantly enhance battlefield effectiveness while reducing the risks and resource strain on human operators. This evolution could mark a shift in the role of pilots, transforming them into commanders of mixed human-machine teams with expanded operational potential.[42]

Swarm drones also have the potential to transform search and rescue operations, particularly in scenarios where time and accessibility are critical. By distributing across smaller segments of an affected area, swarms could drastically reduce response times compared to traditional methods.[43] Moreover, in difficult terrains where human access is constrained, drone swarms equipped with real-time imaging capabilities could provide actionable insights, enabling more precise and timely decision-making. This application underscores the value of swarm technology in high-stakes, life-saving missions.

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40 Kallenborn and Bleek, "Swarming Destruction: Drone Swarms and Chemical, Biological, Radiological, and Nuclear Weapons," 17.

41 Scharre, *Robotics on the Battlefield Part II: The Coming Swarm,* 37.

42 Kelsey Atherton, "The Future of the Air Force is Fighter Pilots Leading Drone Swarms into Battle." *Popular Science*, March 12, 2021, https://www.popsci.com/future-air-force-fighters-leading-drone-swarms.

43 Kathleen Giles,"A Framework for Integrating the Development of Swarm Unmanned Aerial System Doctrine and Design," *NATO Science and Technology* (2016): 1-22.

Scharre highlights the significant potential of drone swarms, even with human involvement, underscoring their ability to react in real-time to dynamic scenarios - a key advantage in modern warfare. He cautions that while coordinating one or two systems is manageable for military leaders, handling the complexity of 60 interconnected systems is exponentially more challenging.[44] Drone swarms, with their superior speed and coordination, can outperform human capabilities in adapting to rapidly changing events on the battlefield. The integration of AI enhances their responsiveness, enabling real-time communication, seamless coordination, and efficient information sharing. By shrinking the Observe, Orient, Decide, Act (OODA) loop, swarms can provide a decisive advantage,[45] expediting decision-making processes and potentially altering the balance of power in future conflicts.

As discussed above, the convergence of enhanced capabilities and reduced costs makes drone swarming a transformative technology. Its unique attributes such as persistence, maneuverability and scalable autonomy, offer unmatched operational flexibility. These advancements position drone swarming as a game-changing asset with the potential to redefine future strategies and applications.[46]

Challenges of Drone Swarms

Despite its potential, drone swarming faces significant challenges that hinder its seamless integration and performance.

a. Countermeasures

One critical issue is vulnerability of the technology to electronic countermeasures such as jamming, ADS, string net herding, spoofing and electromagnetic interference:

44 Scharre, "How Swarming Will Change Warfare," 387.

45 Frans Osinga, *Science, Strategy and War: The Strategic Theory of John Boyd* (New York: Routledge, 2007), 1.

46 Godwin Asaamoning, Paulo Mendes, Denis Rosário and Eduardo Cerqueira, "Drone Swarms as Networked Control Systems by Integration of Networking and Computing," *Sensors* 21, no. 8 (2021) : 2642 - 2663,https://www.mdpi.com/1424-8220/21/8/2642.

Communication Jamming Electronic Attack

Communication jamming is a potent countermeasure against drone swarms, as it disrupts the critical exchange of information required for coordination and synchronisation. Effective communication is essential for swarms to operate cohesively, share data, and execute synchronised actions. Without it, the swarm risks collapsing into disjointed individual units, reducing its effectiveness and leaving drones to operate independently, akin to uncoordinated melee combat.[47] This challenge becomes exponentially complex as the size of the swarm increases, with hundreds or thousands of drones requiring sophisticated algorithms to optimise performance and avoid collisions. While communication jamming does not physically destroy the drones, it significantly weakens their collective capability by impeding cooperative operations.[48] Drone swarms employing implicit communication techniques, such as co-observation, are somewhat more resilient to jamming. However, even these methods can be disrupted by obscurants or other measures that create interference in the communication spectrum.[49] Such disruptions can lead to mission impairment, coordination breakdowns and an increased risk of fratricide - unintentional friendly fire - among drones operating without synchronisation.[50]

Advanced Air Defence Systems

The efficiency of swarm attacks could be limited when they are used in environments where air defence systems are networked together.[51] Moreover, depending on the kind of swarm employed, some may prove more vulnerable to electronic warfare techniques such as jamming and spoofing by air defence systems. The networked nature of the swarms could be used against themselves through cyber-attacks through which the mission of drone swarms would be impaired.[52]

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47 Zachary Kallenborn, "InfoSwarms: Drone Swarms and Information Warfare," Parameters 52, no.2 (2022): 87-102, https://press.armywarcollege.edu/cgi/viewcontent.cgi?article=3154&context=parameters

48 Matthieu J. Guitton, "Fighting the Locusts: Implementing Military Countermeasures against Drones and Drone Swarms," Scandinavian Journal of Military Studies 4, no.1 (2021): 26 - 36, https://sjms.nu/articles/10.31374/sjms.53.

49 Ibid., 35.

50 Evan E. Roderick , New Weapons, New Options: Electronic Attack in MultiDomain Operations, report (Fort Leavenworth :School of Advanced Military Studies, 2021), 36

51 Singh, "Swarm Drones - New Frontier of Warfare,".

52 Michael P. Kreuzer, Drones and the Future of Air Warfare: The Evolution of Remotely Piloted Aircraft (New York: Routledge, 2018), 45.

It is also reported that Advanced High Efficiency and Destruction (AHEAD) ammunition can be used to release cylindrical tungsten sub-projectiles to increase the probability of interception of an adversary's drone swarm.[53] Moreover, anti-air artillery weapons such as Pantsir S-1 can also be employed to target the swarms. These weapons can shoot approximately 750 rounds before they need to reload.[54] It is pertinent to mention here that the Pantsir S-1 has a high fire rate. Hence, in any environment which is increasingly contested, coupled with strong air defence systems or presence of electronic warfare techniques, optimal effectiveness of swarming techniques can be impacted.

Defender Drone Swarms

One effective method to counter attacking drone swarms is the deployment of defender swarms consisting of drones themselves.[55] While uncoordinated defender drones risk missing targets or even engaging friendly drones, their sheer numbers increase the likelihood of successfully neutralising a significant portion of the attacking swarm. [56] However, defender drone swarms may need to be integrated with other countermeasures, such as direct fire, to enhance their effectiveness. Despite potential coordination challenges, this approach can significantly weaken or disrupt an attacking swarm, reducing its overall impact and buying critical time for additional defensive responses.

String Net Herding

The approach of string net herding has also been discussed in the literature as a potential countermeasure to drone swarming. The approach refers to the employment of closed formation - String Net - of the defending entities/formations around the attacking swarm that would ultimately, confine their movement and guide them to some other location.[57] The principle involved in the process uses a network of strings by defenders to coordinate the movements of several agents towards a particular location. Recent research has proposed that using sophisticated algorithms, multi-

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53 Calcara, Gilli, and Ivan Zaccagnini, "Will the Drone Always Get Through? Offensive Myths and Defensive Realities," 802.

54 Army Technology, "Pantsyr S1 Close Range Air Defence System," October 3, 2000, https://www.army-technology.com/projects/pantsyr/ [Accessed 30 May, 2023].

55 Scharre, Robotics on the Battlefield Part II: The Coming Swarm, 42.

56 Ibid.

57 Vishnu Chipade and Dimitra Panagou, "Herding an Adversarial Swarm in an Obstacle Environment," (paper presented in 2019 IEEE 58th Conference on Decision and Control (CDC), Nice, December 11 - 13, 2019).

swarm herding methods can be successfully applied even if the attacking swarms break into several sub-units.[58]

Directed Energy Weapons (DEWs)

Electromagnetic pulses (EMPs) present a challenging countermeasure against drone swarms. When directed at a swarm, an EMP can disrupt or disable the electronics of individual drones,[59] potentially neutralising the entire system. The scale of impact increases with the size and intensity of the EMP implosion, making it a scalable option for swarm defence.

Looking to the future, Directed Energy Weapons (DEWs) such as high-powered microwaves and lasers are being actively explored as effective tools to combat drone swarms. These technologies offer precision and rapid engagement capabilities, making them ideal for neutralising large numbers of drones in a short time. However, the evolving nature of drone swarm technology suggests that the results of such countermeasures may not always align with user expectations, particularly as drones become more resilient and adaptive to emerging threats.[60]

b. Level of Autonomy

In a potential battlefield, drone swarms do not require an operator for their functioning, yet the human operator can supervise the activities of the swarm.[61] In this context, the distribution of autonomy may present a challenge for decision-makers. Giving full autonomy to the swarm can make them more effective in achieving their mission, but with the inherent risk that it may roll out into unforeseen circumstances such as inadvertent escalation and fratricide, particularly in contested environments.[62] On the contrary, refraining from giving absolute autonomy may impact efficiency of the system, while the adversary forces/swarms may have more

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58 Vishnu Chipade, Venkata Sai, Aditya Marella and Dimitra Panagou,"Aerial Swarm Defense by StringNet Herding: Theory and experiments," Frontiers in Robotics and AI 8, no.1 (2021): 640446 - 640466, https://www.frontiersin.org/articles/10.3389/frobt.2021.640446/full#B6.

59 Xia Zhang, Yijie Bai and Kai He, "On Countermeasures against Cooperative Fly of UAV Swarms" Drones 7, no. 3 (2023) :172 - 197, https://www.mdpi.com/2504-446X/7/3/172.

60 Randall W. Mai, "DE Weapons & Microwaves," in Drone Delivery of CBNRECy – DEW Weapons : Emerging Threats of Mini-Weapons of Mass Destruction and Disruption ed. Randall Nichols, Suzanne Sincavage, Hans Mum, Wayne D. Lonstein, (Independently published, 2022), 71.

61 Irving Lachow, "The Upside and Downside of Swarming Drones," 98.

62 James Johnson, "Artificial Intelligence: Drone Swarming and Escalation," *Royal United Services Institute Journal* 165, no.1 (2020): 26 - 36, https://www.tandfonline.com/doi/abs/10.1080/03071847.2020.1752026?journalCode=rusi20.

autonomy, giving them an edge.[63] There is also the risk that machines may take decisions that may harm human beings.[64] The Russia-Ukraine conflict has shown that new technologies are being manifested on the battlefield. Future employment may be much worse and can even result in situations where drone swarms can lead to genocide-like situations.[65] Hence, deciding the level of autonomy to be granted to swarms to ensure mission effectiveness while adhering to safety standards remains a challenge.

c) Ethical and Legal Considerations

The U.S. Department of Defense has made it imperative that fully autonomous swarms follow the rules of engagement and principles of humanitarian law.[66] However, ensuring that swarms would be able to abide by the principles of humanitarian law remains a challenging task since it requires complex human intelligence.[67] The ethical and legal concerns, including using the right amount of force presents serious considerations for policymakers on the employment of increasingly autonomous weapons.[68] The growing buzz around the technology, can boost the risks of proliferation of the technology which could also amplify privacy concerns complicating the situation. Hence, given inherent complexities of autonomous systems, ad hoc ethical considerations on a case-to-case basis is not the solution, rather the considerations should be holistic, systematic, and informed by multiple stakeholders.[69]

d) High Cost

The cost involved in operating drone swarms is usually perceived to be affordable, making it a potent capability, at a lesser price. However, it needs to be kept in mind that economical drone swarms are usually less sophisticated. Enhancing the overall quality of drone swarms would require additional resources.[70] Ongoing research on

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63 Paul Scharre, *Autonomous Weapons and Operational Risk – Ethical Autonomy Project* (Washington, DC: Center for a New American Security, 2016), 35.

64 Oleksii Kostenko, Tyler Jaynes, Dmytro Zhuravlov, Oleksii Dniprov, et.al , "Problems Of Using Autonomous Military AI Against the Background Of Russia's Military Aggression against Ukraine," *Baltic Journal of Legal and Social Sciences* no.4 (2022):131-145, https://philarchive.org/archive/KOSPOU.

65 Ibid.

66 Lachow, "The Upside and Downside of Swarming Drones," 98.

67 Ibid.

68 Andrew William Sanders, *Drone Swarms*, report (Leavenworth : School of Advanced Military Studies, 2018), 11, https://apps.dtic.mil/sti/pdfs/AD1039921.pdf.

69 Daniel Trusilo.; Thomas Burri, "The Ethical Assessment of Autonomous Systems in Practice," *Multidisciplinary Scientific Journal* 4, no.4 (2021): 749-763. https://doi.org/10.3390/j4040051.

70 *Swarm Robotics Technical And Operational Overview of the Next Generation of*

drone swarming suggests that the cost involved in developing these systems, particularly targeting systems is relatively high.[71] This may make individual platforms more expensive, thus increasing the overall cost of a swarm considerably, making them uneconomical.[72] Increasing costs can pose challenges for specific states bound by economic constraints.

Discussion: The South Asian Context

The dynamics of post-modern warfare, as discussed earlier, are becoming increasingly prominent with the proliferation of drone technology. Drone swarming, particularly when integrated with AI-powered techniques, is expected to play a critical role in future conflicts.

In the South Asian context, the growing interest and investments in drone technology by regional powers like India and Pakistan warrant closer examination. The strategic and military implications of drone swarming in this region, marked by long-standing rivalries, evolving doctrines, and contested borders, highlight its potential to reshape conventional and asymmetric warfare. As both nations enhance their technological capabilities, the role of drone swarms in surveillance, offensive operations, and defense strategies will likely grow, adding new dimensions to regional security dynamics.

India has been investing in indigenous drones such as Panchi, Rustom, Lakshya and Nishant etc., while simultaneously acquiring Heron and Searcher II from Israel, among others.[73] India has also reportedly been trying to acquire drone swarms since 2022.[74] In early February 2023, it was reported that India had received its debut heterogeneous swarm Unmanned Aerial Vehicle (UAV) system for military combat,

Autonomous Systems, report (Geneva : The United Nations Institute for Disarmament Research, 2020), https://www.unidir.org/sites/default/files/2020-04/UNIDIR%20Swarm%20Robotics%20-%202020.pdf.

71 Ibid.

72 Andrew Ilachinski, "AI, Robots, and Swarms: Issues, Questions, and Recommended Studies," *Center for Naval Analysis*, January 16, 2017, https://www.cna.org/archive/CNA_Files/pdf/drm-2017-u-014796-final.pdf. [Accessed June 1, 2023].

73 Monika Chansoria, *Drones : A Perspective on India*, report (Washington DC.: Centre for a New American Strategy, 2017), 4, https://drones.cnas.org/reports/a-perspective-on-india/.

74 Suchet Vir Singh, "Army Bolsters Military Capability with Two Sets of Swarm Drones for Surveillance," *Print,* August 26, 2022, https://theprint.in/defence/army-bolsters-military-capability-with-two-sets-of-swarm-drones-for-surveillance-close-recce/1101665/.

acquired by an Indian startup - NewSpace Research & Technologies.[75] It is claimed that the system, comprising 100 drones, has the ability to target approximately 50 kms into enemy territory.[76] Although 50 km may appear to be a limited range, however in the India-Pakistan context, the contiguity and population centres in the border region, 50 km range may provide potential targeting opportunities. The Indian Army described it as a 'niche and disruptive technology' readily capable of identifying targets using AI-driven software.[77] Furthermore, India is also collaborating with the US on drone technology under its Defence Technology and Trade Initiative (DTTI) for joint production of drone swarms and anti-drone systems.[78] These developments indicate India's intent to enhance drone swarm technology in the future. The most probable areas for their deployment include border regions with Pakistan and China, where strategic tensions and operational demands make such technology particularly relevant.

The introduction of drone swarm technology in South Asia carries the risk of triggering unforeseen escalatory dynamics. Given the lower human risk associated with its use, this technology could be deployed more readily along contested border regions, increasing the likelihood of accidents or miscalculations that could exacerbate existing tensions.

For Indian decision-makers, the presence of such advanced technology may instill greater confidence to undertake offensive operations. This risk is further heightened by the significant deterioration in India-Pakistan relations over the past few years, with little prospect for constructive engagement in the near future. In such a volatile environment, the addition of drone swarming technology could have destabilising effects, potentially fueling an arms race driven by the traditional action-reaction cycle.

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75 Snehesh Alex Philip, "Army Gets its First Set of Offensive Swarm Drone System, IAF Next," *Print*, February 13, 2023, https://theprint.in/defence/army-gets-its-first-set-of-offensive-swarm-drone-system-iaf-next/1368508/.

76 Ibid.

77 Manjeet Negi, "Indian Army Enhances its Military Capabilities, Inducts Swarm Drone Systems," *India Today,* August 26, 2022, https://www.indiatoday.in/india/story/indian-army-inducts-swarm-drone-systems-1992907-2022-08-26.

78 Manu Pubby, "India, US to jointly develop UAVs and share IP rights," *Economic Times,* February 11, 2023, https://economictimes.indiatimes.com/news/defence/india-us-to-jointly-develop-uavs-and-share-ip-rights/articleshow/97828791.cms.

Moreover, the complexity and ambiguity surrounding this technology increase the risk of unintended conflicts, particularly along sensitive border areas. Without effective communication and crisis management mechanisms, the operational use of drone swarms could escalate localised incidents into broader confrontations, posing serious security challenges for the region.

Notwithstanding the above discussion, it is important to note that existing literature on the impact of drone swarms in warfare remains divided. While some studies regard drone swarming as a game-changing technology, others view it as a powerful enabler that falls short of delivering a decisive battlefield advantage. This divergence stems from the fact that while drone swarming technology is still evolving, countermeasures to neutralise it are already available and operational. As a result, the widespread enthusiasm surrounding drone swarms may diminish over time. For example, Bayraktar drones, which initially gained significant attention during the early stages of the Russia-Ukraine war and were credited with Azerbaijan's success against Armenian forces, have seen a notable shift in their role. Once celebrated for their offensive capabilities, these drones are now largely relegated to reconnaissance missions.[79] Samuel Bendett, an expert on unmanned and robotic military systems at the Center for Naval Analyses, attributes this shift to the presence of advanced electronic countermeasures and networked air defence systems, which drastically limit the drones' effectiveness.[80] Supporting this, the Royal United Services Institute later reported that Russia was shooting down approximately 10,000 drones per month. This example highlights a broader reality: technologies that appear game-changing in one operational context may lose their impact when faced with robust defences or innovative countermeasures. Thus, the ultimate effectiveness of drone swarms will depend heavily on the specific battlefield environment and the evolution of both offensive and defensive technologies, platforms employed and the techniques used[81] —a reality that holds particularly true for South Asia. While the technology remains in its nascent stages, its deployment could have significant implications. Though it may not bring about a radical transformation, drone swarms could serve as effective force

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79 Alia Shoaib, "Bayraktar TB2 Drones were Hailed as Ukraine's Savior and the Future of Warfare. A year Later, they've Practically Disappeared," *Insider*, May 28, 2023, https://www.businessinsider.com/turkeys-bayraktar-tb2-drones-ineffective-ukraine-war-2023-5.

80 Ibid.

81 Jack Watling and Nick Reynolds, M*eatgrinder: Russian Tactics in the Second Year of Its Invasion of Ukraine,* report (London : Royal United Services Institute, 2023), 18.

multipliers on the battlefield, enhancing situational awareness, precision, and operational efficiency.

Both globally and regionally, militaries are preparing to integrate drone swarm technology into their arsenals, making it crucial for Pakistan to take proactive measures to keep pace with these advancements. Failure to do so could result in a technological lag, operational vulnerabilities, and significant challenges in adopting and utilising such technologies in the future. Addressing these gaps will be essential to maintaining strategic balance and operational readiness in an evolving military landscape.

Recommendations

With the increasing penetration of drone swarming technology on the global landscape, and the increasing adoption of the technology in South Asia, Pakistan must take measures to enhance its capabilities and also ensure readiness against any threat from the Indian side.

a) Developing Drone Swarming Capability

Burraq, Shahpar, Jasoos, Uqab, Mukhbar, Ababeel are some of the indigenous drones already developed by Pakistan. It has acquired Wing Loong II drones from China.[82] It is also acquiring Bayraktar TB2 and Akinci from Turkey.[83] In July 2023, the Pakistani embassy in Beijing hosted a China-Pakistan drone conference focused on the establishment of a robust drone industry.[84] Under the China-Pakistan digital corridor, collaboration between China and Pakistan is likely to grow in this field.

Considering Pakistan's ongoing investment in indigenous drone technology, it needs to have a directed focus towards drone swarming technology. Given that the technology is dual-use, there is need to invest substantial resources in universities, research institutions and startups to foster innovation in the field. Certified courses

82 Rajeswari Pillai Rajagopalan, "The China-Pakistan Partnership Continues to Deepen, "*Diplomat*, July 9, 2021, https://thediplomat.com/2021/07/the-china-pakistan-partnership-continues-to-deepen/.

83 Umar Karim, "Pakistan-Turkey defence cooperation: The Realization of a Shared Strategic Vision," *Arab News*, July 11, 2023, https://www.arabnews.pk/node/2353576.

84 Editorial, "Conference Highlights Viable Drone Industry in Pakistan," *Express Tribune*, July 28, 2023, https://tribune.com.pk/story/2428215/conference-highlights-viable-drone-industry-in-pakistan.

may be introduced on essential elements of the technology, such as swarm communication, coordination and protocols etc. Encouraging universities and research institutions to develop international collaborations could enable knowledge exchange and help familiarise them with best international practices in this field. Likewise, any diplomatic hurdle in such collaboration needs to be addressed on priority basis. Such a collaborative approach could also help avoid potential pitfalls in the development process leading to a more informed approach.

In warfare, combat training and technological proficiency go hand in hand. It has become imperative to have more familiarity with the swarm and counter-swarm equipment. Hence, there is a need to invest in human resource, capable of handling swarming equipment. This entails comprehensive training of drone operators, technicians and personnel regarding swarm drone operations. By prioritising these training programmes, necessary skills and expertise could be acquired vis à vis the technology.

b) Electronic Countermeasures

In order to effectively defend against swarm attacks, it has become imperative to integrate a combination of hard and soft kill countermeasures. To this end, Pakistan can invest resources in advanced radars capable of tracking and identifying multiple drones simultaneously. Furthermore, investing in electronic warfare (EW) capabilities to impair an attacking swarm should also be the immediate priority. While Pakistan already employs a comprehensive multilayered air defence network, including advanced sensors and systems, these need to be optimised and adjusted to counter the specific threats posed by drone swarms effectively. Future measures should focus on incorporating advanced jamming and spoofing capabilities tailored to disrupt the coordination and functionality of drone swarms. Upgrading sensor networks to include a broader range of types—such as passive detection systems, radar-absorbing technologies, and electromagnetic spectrum analysers—will strengthen early detection and response capabilities. By leveraging and optimising its current systems, Pakistan can bridge operational gaps and ensure its air defence remains resilient against emerging threats. Proactively investing in research, development, and the integration of cutting-edge counter-swarm technologies will not only maintain strategic parity but also enhance its preparedness.

c) Simulations

The real offset in warfare may not necessarily be associated with the sole invention of new weaponry, it is also driven by critically testing complex scenarios, enabling improvements in response options. Hence, it is crucial to explore the potential of combining existing and new technologies via simulations and wargaming exercises at a large scale. Resultantly, such exercises could provide a better picture to address contemporary challenges and achieve the strategic objectives in the longer run.

d) Autonomy

The state must prioritise operationally relevant autonomy. The ideal cognitive architecture for this technology should integrate human oversight with machine learning (ML) capabilities. Robotic vehicles must retain a communication link to keep humans 'in the loop.' Alternatively, they could operate 'on the loop,' where the machine functions autonomously under human supervision. Critical decisions, such as the use of force, should always require human authorisation. Moreover, human involvement serves as a safeguard, acting as a firewall against unintended actions. In cases of lost contact with the operator, swarms should be programmed with predefined rules to ensure appropriate behavior and response.

Conclusion

The emergence of drone swarming represents a significant advancement with both global and regional implications. In the coming years, the technique is expected to garner widespread attention as swarms become increasingly capable of coordinating, exchanging large volumes of data, and executing missions in a highly networked and autonomous manner. This evolution positions drone swarming as a potential cornerstone of long-term military capability, offering opportunities to enhance battlefield effectiveness and enable warfighters to achieve their objectives.

While the technology is undoubtedly a transformative addition to modern warfare, it comes with inherent complexities. The challenges of integrating swarms into military operations are compounded by the evolving landscape of countermeasures and adversarial tactics. The ultimate impact of drone swarming will depend on a range of factors, including the sophistication of weaponry, the adversary's countermeasures, and mastery of tactics for its optimal deployment.

For South Asia, where drone swarming is beginning to gain traction, its implications could be profound. Pakistan is currently investing significantly in drone technology to keep pace with ongoing developments in the region and at the global level. The technology provides an opportunity to address some of the military asymmetry which exist with respect to India at an affordable cost. However, as with any technology, the new inductions/systems would have to be codified in relevant doctrines, strategies and procedures for maximum effectiveness. With time it would be able to draft innovative strategies and cost-effective measures with regards to the swarming technology based on the existing threats.

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