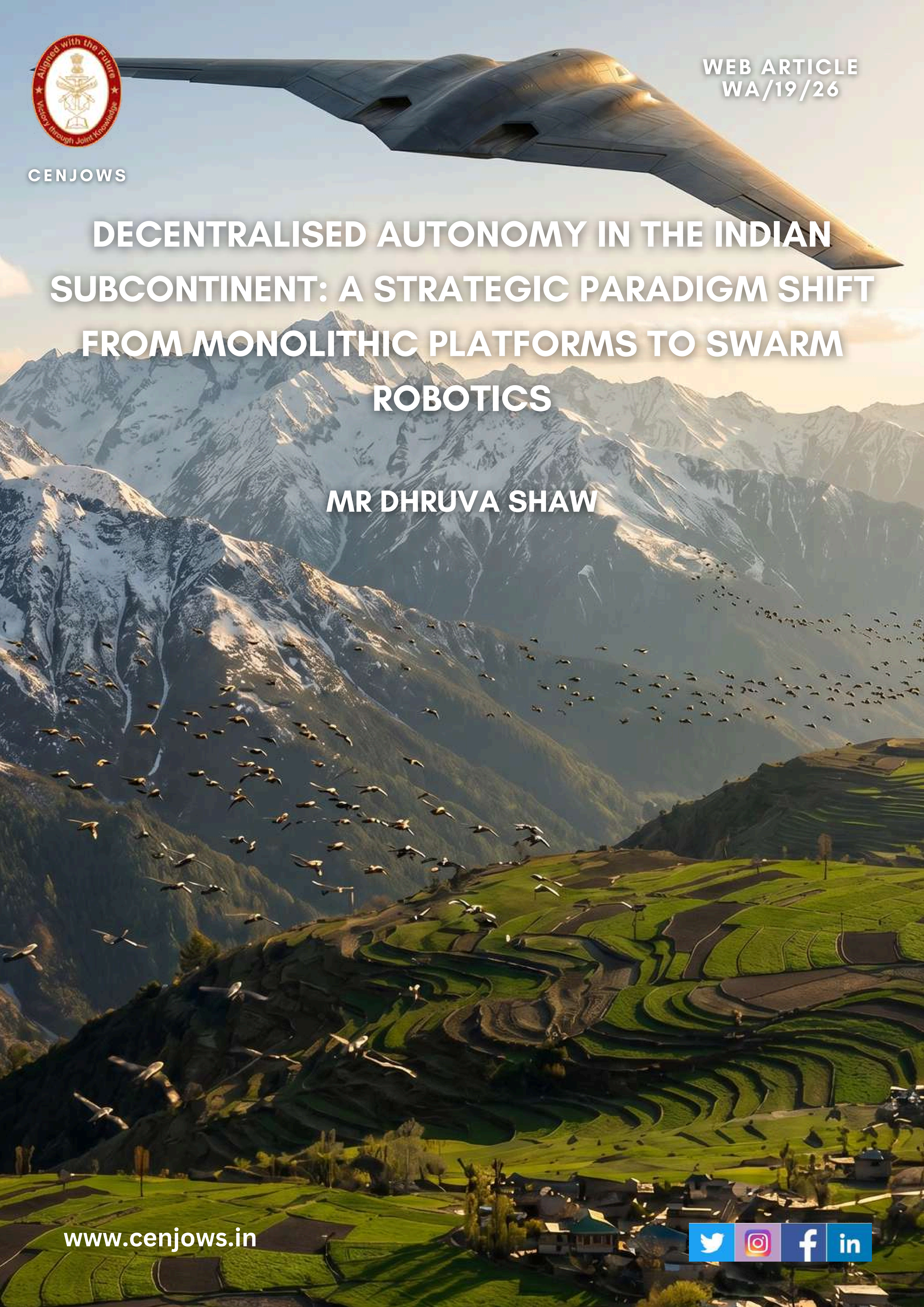

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DECENTRALISED AUTONOMY IN THE INDIAN SUBCONTINENT: A STRATEGIC PARADIGM SHIFT FROM MONOLITHIC PLATFORMS TO SWARM ROBOTICS

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Decentralised Autonomy in the Indian Subcontinent: A Strategic Paradigm Shift from Monolithic Platforms to Swarm Robotics

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Introduction

The strategic trajectory of robotics within the Indian subcontinent stands at a crossroads, characterised by a tension between the legacy of monolithic, high-value platforms and the emergent of decentralised, attritable swarm systems. As of early 2026, the geopolitical and economic realities of the region specifically the lessons learned from the "Operation Sindoor" conflict of May 2025 and the persistent fragmentation of the agricultural sector, have catalysed a re-evaluation of robotic deployment doctrines. This report provides an exhaustive analysis of the ecosystem, feasibility, and strategic recommendations for robotics in India, juxtaposing the traditional "Platform" approach against the "Swarm" paradigm.

Central to this analysis is the case study paper titled *"Robotic Swarm With Independent Selection Of Master-Slave Configurations"* by Dhruva Shaw. This theoretical framework serves as a critical lens through which practical challenges of Indian deployment are examined. The paper’s proposition of a decentralized architecture where individual robots autonomously select leadership roles based on local sensor data offers a potential solution to the vulnerabilities experienced in recent military engagements and the logistical bottlenecks of rural agriculture.

This report argues that while platform robotics exemplified by systems like the MQ-9B Sea Guardian or the DRDO Daksh retain strategic utility for high-end intelligence and disposal tasks, the future of Indian security and food sovereignty lies in the adoption of decentralised swarms. We will dissect the technical specifications, economic drivers, and regulatory landscapes that currently shape this transition, moving beyond surface-level observations to explore the second-order effects of supply chain indigenisation, algorithmic certification, and the doctrinal shift from "man-in-the-loop" to "man-on-the-loop" warfare.

The Platform Paradigm: Legacy, Utility, and Vulnerability

To understand the disruptive potential of the swarm architecture proposed in the case study, one must first rigorously audit the incumbent model: Platform Robotics. In the Indian context, this category encompasses sophisticated, high-capital assets designed to perform complex, multi-mission profiles independently, typically under centralised human control via satellite or high-bandwidth data links.

- **The Strategic Architecture of High-Value Assets**

  India’s defence modernisation in the decade leading up to 2026 has been punctuated by the acquisition and development of Medium-Altitude Long-Endurance (MALE) and High-Altitude Long-Endurance (HALE) platforms. The procurement of 31 MQ-9B Predator drones from the United States, valued at approximately $3.9 billion, represents the zenith of this philosophy.[1] These platforms function as flying data centres, equipped with synthetic aperture radars (SAR), electronic intelligence (ELINT) suites, and precision strike capabilities.

  Similarly, indigenous efforts have focused on the TAPAS-BH-201 (Tactical Airborne Platform for Aerial Surveillance). Developed by the Defence Research and Development Organisation (DRDO), the TAPAS was conceived as a versatile ISR platform capable of operating at altitudes up to 30,000 feet with an endurance of 24 hours. The structural logic of these platforms is one of centralisation: a single, highly capable asset gathers intelligence, processes it, and transmits it to a ground control station (GCS) where human operators make decisions.

  In the ground domain, the DRDO Daksh, a Remotely Operated Vehicle (ROV) for bomb disposal, follows the same paradigm. Costing approximately ₹80 lakh to ₹90 lakh per unit, the Daksh is a robust, tele-operated system designed to handle hazardous objects. Like its aerial counterparts, it relies on a continuous, uncompromised link between the operator and the machine.

- **The "Single Point of Failure" Vulnerability**

  The case study by Shaw identifies a critical flaw in this traditional architecture: the "Single Point of Failure" (SPOF).[2] In a centralised control structure, the entire mission hinges on the functionality of the master unit or the communication link. If the central server malfunctions, or if the specific frequency band used for control is jammed, the platform becomes incapacitated.

This theoretical vulnerability was starkly illustrated during the May 2025 conflict between India – Pakistan, during Operation Sindoor. Analysis of the conflict reveals that centralized platforms, particularly those employed by Pakistan, suffered catastrophic attrition rates when subjected to contested electromagnetic environments. Pakistan deployed Turkish-made Songar quadcopters and other UAVs in centralised attack formations.[3] Indian electronic warfare (EW) units, employing soft-kill tactics, successfully severed the command links of these drones. The Turkish manufacturer Asisguard later admitted that the failure was partly doctrinal, as the drones were not designed for deep-strike missions in GPS-denied environments without autonomous fallback capabilities.[4]

"Operation Sindoor" experience validates the case study's assertion that centralised control becomes inefficient due to "loss of contact and dependency on the single master transmitting frequency".[5] The incapacity of these platforms to self-organize once the link was severed rendered expensive assets useless, turning them into "orange dots" that flashed and faded over Indian skies as they were neutralised by air defence systems.[6]

- **Economic Asymmetry and Non-Attritability**

  The platform approach also imposes severe economic constraints. The unit cost of a TAPAS UAV is estimated between ₹40-45 crore, while imported systems like the MQ-9B cost significantly more.[7] Such high valuations make these platforms "non-attritable" commanders are hesitant to deploy them in high-risk zones where air defence density is high. This creates a paradox where the most capable assets are often withheld from the most critical engagements to preserve capital.

  Furthermore, the manufacturing of these heavy platforms in India faces systemic bottlenecks. The Kaveri engine program, intended to power indigenous UAVs like the Ghatak, has faced long developmental timelines, forcing reliance on imported propulsion systems.[8] The complexity of platform robotics requires a mature aerospace supply chain for hydraulics, precision gears, and thermal management systems, areas where India's MSME sector still faces challenges in consistency and scaling.[9]

The Swarm Paradigm: Theoretical Framework and Case Study Analysis

In contrast to the fragility of centralised platforms, Swarm Robotics offers a paradigm predicated on distributed intelligence, redundancy, and emergent behaviour. The attached paper, *"Robotic Swarm With Independent Selection Of Master-Slave Configurations,"* provides a specific architectural blueprint that aligns with the tactical necessities emerging from the Indian context.

- **Deconstructing the Independent Selection Algorithm**

  The core innovation proposed in Shaw's research is a decentralised decision-making algorithm inspired by biological systems, specifically the behaviour of social insects like bees and the migratory patterns of Siberian birds.[10] Unlike traditional swarms that might still rely on a designated leader, this model empowers *every* robot to assess its own capability and the capabilities of its neighbours to select a "Master" dynamically.

  The algorithm utilises a Lookup Components Priority Table (Table I in the paper) to quantify the operational readiness of each unit. The priority hierarchy is defined as follows:

  - Inertial Measurement Unit (IMU): Highest priority.
  - Ultrasonic Distance Sensor: Second priority.
  - Infrared Sensor: Third priority.
  - GPS (Global Positioning System): Fourth priority.
  - Wheel Encoder: Fifth priority.

  In this logic, a robot possessing a functional IMU and Ultrasonic sensor is deemed more capable of leading likely due to the necessity of stability and obstacle avoidance in immediate navigation than one with only GPS. Robots exchange these "priority values" via local communication channels. The agent with the highest aggregated value (MaxVal) assumes the role of Current Acting Master. Crucially, the system continuously identifies a Next Potential Master (NPM) the robot with the second-highest priority score, ensuring that if the current leader is neutralised, the NPM takes over instantaneously.[11]

- **Bio-Inspiration: Quorum Sensing and Fault Tolerance**

  The mechanism mirrors quorum sensing in bacteria or decision-making in bee swarms, where the collective state is determined by the density of local signals rather than a top-down command. This bio-inspired approach fosters "emergent coordination," allowing the swarm to adapt to dynamic environments without complex pre-programming for every scenario.[12]

The implications for fault tolerance are profound. In the context of the May 2025 conflict, an Indian swarm utilising this architecture would not have succumbed to the EW tactics that disabled the Pakistani Songar drones. If the "Master" drone targeting an enemy radar was jammed, the specific "quorum" logic would detect the silence or data corruption. The NPM, operating perhaps on a different frequency or positioned outside the jamming lobe, would immediately assume command, continuing the mission. This resilience converts the "Single Point of Failure" (SPOF) into a "Graceful Degradation," where the loss of units reduces the swarm's efficiency but does not arrest its function.

- **Relevance of Hardware Prioritisation to Indian Conditions**

  The prioritisation of IMU (Priority 1) over GPS (Priority 4) in the case study is particularly prescient for Indian operational requirements.

  - **GPS-Denied Environments:** The Himalayan border regions, specifically the Line of Actual Control (LAC) and Line of Control (LoC), are notoriously hostile for satellite navigation due to terrain masking (deep valleys blocking line-of-sight) and active GPS spoofing by adversaries.[13] A drone that prioritises GPS for navigation would fail in these zones. By prioritising the IMU, Shaw's algorithm ensures that the robot relies primarily on internal dead-reckoning and stability, making it resilient to external signal denial.

  - **Ultrasonic Limitations:** While the paper prioritises Ultrasonic sensors (Priority 2) for obstacle avoidance, this choice warrants critical examination in the context of the Himalayas. Research indicates that ultrasonic sensors are susceptible to interference from heavy wind, snow, and low air density conditions endemic to high-altitude battlefields.[14] In a practical Indian military deployment, this slot in the priority table would likely need to be substituted with LiDAR or mmWave Radar, which offer greater robustness in fog and snow.[15] However, for the agricultural context in the plains, ultrasonic sensors remain a cost-effective solution for crop height maintenance.

- **Simulation vs. Reality**

  The case study validates this architecture using MATLAB Simulink, simulating three distinct robot configurations.[16] While the simulation proves the logic of role-switching, the transition to physical deployment in India involves overcoming significant hardware integration challenges. The sheer volume of data exchange required for "all-to-all" or "neighbour-to-neighbour" broadcasting of priority tables can saturate the bandwidth of low-cost communication modules (like Zigbee or LoRa) used in swarm robotics.[17] Real-world implementation would require robust

Mobile Ad-Hoc Networks (MANETs) capable of managing high-latency links in mountainous terrain.[18]

Defence Sector Feasibility: The "Air Littoral" and Operation Sindoor

The strategic shift towards swarms is not merely theoretical; it is being written in the doctrine of the Indian armed forces, accelerated by the lessons of 2025.

- **The Emergence of the "Air Littoral"**

  General Upendra Dwivedi, the Indian Chief of Army Staff, has explicitly articulated the concept of the "Air Littoral" the airspace from the ground up to approximately 3,000 meters, as the new decisive domain of warfare.[19] This zone, previously dominated by helicopters and low-flying aircraft, is now saturated with drones, loitering munitions, and quadcopters.

  In this domain, the Indian Army faces a numerical challenge. General Dwivedi noted, "If we advance 500 metres on the front, we may face 10,000 drone equivalents".[20] Traditional air defence systems like the S-400 or Akash missiles are economically inefficient against such threats; using a million-dollar missile to intercept a $500 drone is a losing strategy. This necessitates a "Swarm vs. Swarm" capability deploying dense clusters of defensive drones to intercept hostile swarms kinetically or electronically.

- **Operation Sindoor: A Case Study in Swarm Efficacy**

  The conflict of May 2025 served as a proving ground for India’s burgeoning drone capabilities. Triggered by the Pahalgam terror attack, Operation Sindoor saw the Indian military employ a mix of cruise missiles (BrahMos, SCALP) and, crucially, swarm drone systems.[21]

  - **Indigenous Success:** The operation highlighted the success of the Nagastra-1, a solar-powered loitering munition manufactured by Economic Explosives Limited (EEL) with over 75% indigenous content.[22] These systems, operating in coordination, were able to strike terrorist launch pads and enemy radar installations with precision. Their low acoustic and radar signature allowed them to penetrate airspace that would have been lethal to larger platforms like the Heron or Predator.

  - **The Kill-Web:** The operation demonstrated India's first operational "kill-web," integrating ISR drones, loitering munitions, and ground-based fires into a coherent loop.[23] The decentralised nature of these operations, where decisions to strike could be made by local commanders based on drone feeds without routing through a central command in Delhi, mirrors the "Independent Selection" logic of the case study.

- **Counter-Swarm Capabilities:** India's defence against Pakistan's retaliatory drone swarms was equally instructive. The deployment of the DRDO D-4 anti-drone system and upgraded L-70 guns with air-burst ammunition proved effective.[24] This reinforces the need for swarms to possess "self-healing" properties; if 20% of a swarm is destroyed by flak, the remaining 80% must autonomously reconfigure to complete the mission, a capability inherent in the NPM logic proposed by Shaw.

- **High-Altitude Logistics and Surveillance**

  Beyond combat, the Indian Army faces a unique logistical challenge in the high-altitude areas (HAA) of Ladakh and Siachen. Supplying troops currently relies on costly helicopter sorties or animal transport.

  - **Heavy Lift vs. Swarms:** While the DRDO is developing heavy-lift cargo drones[25], the swarm approach offers an alternative. A swarm of medium-lift drones could distribute a ton of supplies across 20 platforms. If weather conditions take down one drone, 95% of the payload still arrives. A single heavy-lift drone failure results in 100% loss.

  - **Technical Challenges:** Operating swarms in the Himalayas requires overcoming extreme cold (which degrades Lithium-ion battery performance by increasing internal resistance) and rarefied air (reducing propeller lift).[26] The priority table in the case study would need to account for Battery Health as a critical parameter for leadership selection; a drone with a rapidly draining battery due to cold should automatically downgrade itself to "Slave" status or return to base, handing over leadership to a healthier unit.

The Agricultural Context: Economics of Smallholder Swarms

While defence drives the technological edge, agriculture provides the scale required to make robotics manufacturing economically viable in India. The structure of Indian agriculture dominated by small and marginal farmers makes it fundamentally unsuited for the large, monolithic platforms popular in the West.

- **The "Small Farm" Problem and the Swarm Solution**

  In nations like the USA, agriculture is characterised by massive, consolidated landholdings, justifying the investment in large autonomous tractors or single, high-capacity aerial sprayers. In India, 86% of farmers own less than two hectares of land.[27] A large robotic platform is physically incapable of navigating the fragmented, irregular plots and financially out of reach for the individual farmer.

  Swarm robotics offers a modular solution. A "Drone Service Provider" (DSP) can deploy a swarm of 2-3 small drones for a marginal farmer and scale up to a swarm of 50 for a large cooperative or a plantation. This scalability is the economic linchpin of agricultural robotics in India.

- **Locust Control: A Proven Use Case**

  The desert locust invasions of 2020 served as a natural experiment in the utility of drone swarms. The traditional method of tractor-mounted spraying was slow and limited by terrain. The government deployed drones to spray insecticides, but these were largely pilot-controlled operations.[28]

  - **Decentralised Potential:** A decentralised swarm, as proposed in the case study, would revolutionise this. A "scout" drone equipped with high-resolution cameras could identify a locust settlement (using visual recognition) and become the "Master," signalling "Slave" sprayer drones to converge on the specific coordinates. This reaction speed is critical for mobile pests. The sheer area to be covered makes the "independent selection" of roles vital; as drones run out of fluid, they can return to base while others autonomously promote themselves to leaders to continue the tracking.

- **The "Drone-as-a-Service" (DaaS) Model**

  The average annual income of an Indian farmer is approximately ₹77,976 (approx. $1,000)[29] which makes purchasing even a low-cost drone is difficult. The industry has thus pivoted to the Drone-as-a-Service (DaaS) model. Entrepreneurs or Village Level Entrepreneurs (VLEs) own the hardware and sell services (spraying, monitoring) on a per-acre basis.[30]

  - **Case Study Application:** The DaaS model benefits immensely from the heterogeneous swarm architecture implied in the case study. A service provider does not need 10 expensive drones. They need one "Master" drone with expensive compute and sensors (IMU, LiDAR, Multispectral cam) and 9 "Slave" drones that are dumb, cheap, and carry only payload and basic receivers. The Shaw algorithm facilitates this by allowing the high-spec drone to assert leadership and guide the low-spec drones, drastically reducing the Capital Expenditure (CapEx) for the entrepreneur and the service cost for the farmer.

Ecosystem Feasibility: Manufacturing and Indigenisation

The feasibility of adopting swarm robotics at scale is contingent upon India's ability to manufacture the critical components domestically. The "Operation Sindoor" conflict exposed the risks of relying on foreign supply chains, as Chinese-made components could theoretically be compromised or embargoed.

- **The "Make in India" Component Landscape**

  Historically, India has been heavily dependent on imports for drone components, particularly from China.

  - **BLDC Motors:** Brushless DC motors are the workhorses of drone propulsion. Post-2024, startups like Vector Technics and Reflex Drive have begun indigenous manufacturing of these motors, attempting to break the reliance on Chinese rare-earth magnets.[31]

  - **Flight Controllers & Autopilots:** The "brain" of the drone remains a bottleneck, with nearly 90% of flight controllers for small drones being imported.[32] However, indigenous solutions like the Akshayaan autopilot and flight controllers from Aura Semiconductor are entering the market.[33] The decentralised algorithm proposed in the case study requires flight controllers capable of "edge computing" to process the priority table logic locally; standard off-the-shelf controllers may need firmware modifications to support this.

  - **Sensors:** The case study relies on IMU, Ultrasonic, and IR sensors. Simple versions of these are available (e.g., from Robu.in), but military-grade, drift-free IMUs essential for the "Priority 1" slot in the algorithm are still the domain of niche manufacturers like Gladiator Technologies or defence PSUs.[34] Indigenizing high-precision MEMS sensors is critical for the "dead reckoning" capability required in GPS-denied Himalayan zones.

- **Policy Enablers: PLI and Certification**

  The Government of India has recognized the strategic importance of this sector.

  - **PLI Scheme:** The Production Linked Incentive (PLI) scheme for drones, with an outlay of ₹120 crore, has incentivised domestic value addition.[35] In

September 2024, discussions began for a new, larger PLI scheme worth ₹3,000 crore to cover R&D and testing infrastructure.[36] This is vital for funding the development of the complex software architectures required for decentralized swarms.

- **Certification Challenges:** The Quality Council of India (QCI) and DGCA manage drone certification. However, the current framework is platform-centric, certifying individual drone models (Type Certificate). There is currently no robust framework for certifying a *swarm algorithm*. Certifying a non-deterministic, emergent behaviour (where the "Master" changes dynamically) presents a massive regulatory challenge. The Draft Civil Drone Bill 2025 and ongoing BVLOS (Beyond Visual Line of Sight) trials are steps forward, but specific "Swarmworthiness" standards are missing.[37]

Strategic Recommendations

Based on the synthesis of the Shaw case study, the lessons of Operation Sindoor, and the analysis of the Indian ecosystem, this report proposes the following strategic roadmap.

- **For the Ministry of Defence & DRDO**
    - **Shift Procurement to Decentralised Architectures:** The failure of centralised platforms in 2025 necessitates a pivot. Future "Make-II" and iDEX challenges should explicitly request Swarm Operating Systems that utilise logic similar to the Shaw paper’s dynamic, leaderless, and sensor-agnostic.
    - **Development of "Swarm Interoperability Standards" (SIS):** The military employs drones from various manufacturers (NewSpace, ideaForge, Raphe). For a heterogeneous swarm to function (as per the case study where robots exchange priority tables), they must speak a common language. A unified SIS based on an upgraded MAVLink protocol is essential.
    - **Invest in "Air Littoral" Denial:** Developing counter-swarm technologies that disrupt the specific "consensus" signals (quorum sensing) identified in decentralised algorithms. If the enemy uses similar logic, jamming the "priority exchange" frequency could induce chaos in their swarm.

- **For the Ministry of Civil Aviation & DGCA**
    - **Establish "Swarm Class" Certification:** The DGCA must move beyond certifying individual airframes to certifying Collective Behaviours. A "Swarm Safety Case" should demonstrate that the algorithm (like the NPM selection) can safely handle the failure of 10% or 20% of nodes without the swarm becoming a hazard to civil aviation.

    - **BVLOS Corridors for Agriculture:** Accelerate the notification of green zones for BVLOS swarm operations in agricultural belts. The DaaS model for swarms is unviable if a pilot must maintain visual line of sight with every drone in the swarm.

- **For Industry and Academia**
    - **Harden the Algorithm:** Researchers must extend the logic proposed by Shaw to include Trust Metrics. In a battlefield, a compromised drone might broadcast a fake "MaxVal" to hijack the swarm (a Sybil attack). The algorithm needs a "reputation system" to verify that a potential master is reporting honest sensor data.

    - **Focus on High-Altitude Sensor Fusion:** Manufacturers should develop integrated sensor modules (IMU + LiDAR + Thermal) specifically calibrated for Himalayan conditions (cold, snow, wind) to replace the generic Ultrasonic/IR pairing in the priority table for military variants.

Conclusion

The conflict of 2025 and the agrarian realities of India have converged to render the traditional, platform-centric model of robotics insufficient. The future does not belong to the single, gold-plated asset that can do everything, but to the swarm of thousands that can do one thing relentlessly.

The case study, *"Robotic Swarm With Independent Selection Of Master-Slave Configurations,"* provides more than just a technical algorithm; it offers a doctrinal template for this transition. By embedding leadership and decision-making within the swarm itself, India can create robotic systems that are immune to decapitation strikes, adaptable to the fog of war (or the fog of the Himalayas), and economically scalable for the smallholder farmer.

The "Make in India" ecosystem has laid the hardware foundation. The strategic imperative now is to weave these components together with the decentralised logic of the swarm, moving from the vulnerability of the singular platform to the resilience of the collective.

Appendix: Technical Comparison of Sensor Suitability

The following table evaluates the sensors utilised in the case study's priority table against Indian operating environments.

Priority (Paper)	Component	Function	Suitability for Indian Defense (Himalayas)	Suitability for Indian Agriculture	Recommendation
1	**IMU**	Attitude/Accel	**Critical.** Essential for stability in high winds and GPS-denied valleys.	**High.** Necessary for precise flight over crops.	Retain as Priority 1. Indigenise MEMS manufacturing.
2	**Ultrasonic**	Obstacle Avoidance	**Low.** Sound waves scatter in heavy snow/wind. Limited range (<10m).	**Medium.** Good for crop height maintenance, but struggles with dust.	Replace with **mmWave Radar** or **LiDAR** for defense applications.
3	**IR Sensor**	Proximity/Line Following	**Medium.** Good for terminal guidance but susceptible to thermal crossover in varied terrain.	**High.** Multispectral IR is the gold standard for crop health (NDVI).	Enhance to **Thermal IR** for military night ops.
4	**GPS**	Positioning	**Low (Reliability).**	**Critical.** Essential for	Augment with **NavIC**

			High susceptibility to jamming/spoofing at borders.	geofencing landholdings.	receivers and Visual Odometry.
5	**Wheel Encoder**	Ground Distance	**N/A for UAVs.** Relevant only for UGVs (Muntra/Daksh).	**N/A for Drones.** Relevant for autonomous tractors.	Replace with **Optical Flow** sensors for aerial swarms.

DISCLAIMER

The paper is the author's individual scholastic articulation and does not necessarily reflect the views of CENJOWS, the Defence forces, or the Government of India. The author certifies that the article is original in content, unpublished, and it has not been submitted for publication/ web upload elsewhere and that the facts and figures quoted are duly referenced, as needed and are believed to be correct.

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