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KEY DRONES AND COUNTER-UAS TECHNOLOGIES

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KEY DRONES AND COUNTER-UAS TECHNOLOGIES

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Abstract

Rapid advancements in key technologies like artificial intelligence (AI), Radio Frequency (RF) connectivity, Electronic Warfare (EW), advanced sensor systems, navigation and lightweight materials have unlocked array of new combat possibilities for robotics, autonomous or unmanned vehicles particularly unmanned aerial systems (UAS), commonly called drones. In the field of drones, there is a cat and mouse game occurring to outpace each other on two fronts firstly between the manufactures of drones' and Counter-UAS (C-UAS) platforms and secondly between advanced militaries - Russia ably assisted by China and Iran, Ukraine assisted by European Union on other side and US-Israel combination as another front. A famous phrase today is "Drones Wins Battles, but Components Win Wars" whigch highlights the necessity to understand the key technological developments in the field of production of various drones' components.

This monograph has thus focused on key global technological developments in the fields of drones and C-UAS, covering Artificial Intelligence, 3D printing, rotary wing designs for the latest unconventional combat missions, propulsion and power pack including batteries, Electronic Warfare (EW) resilience for communication and Positioning, Navigation and Timing (PNT) methods for drones, and antennas. The monograph has then compiled key recommendations for incorporation by the Indian military.

Key Words

Artificial Intelligence (AI), Electromagnetic (EM), Electronic Warfare (EW), Global Navigation Satellite Systems (GNSS), Ground Control Station (GCS), Command-andControl (C2), Maximum Take-off Weight (MTOW), People's Liberation Army (PLA), Short Take-off and Landing (STOL), Small Drones (sUAS), Size, Weight, and Power (SWaP), Vertical Take-off and Landing (VTOL)

INTRODUCTION

"*The battlefield is a scene of constant chaos. The winner will be the one who controls that chaos, both his own and the enemy's*."

-Napoleon Bonaparte

The intensely contested and equally chaotic battlefields of Ukraine and Gaza are full of multitude of small attrition battles. As attrition maximised human casualties leading to severe manpower shortages, both conflicting sides resorted to technological innovations to minimise their own casualties while causing more attrition to the adversary. Technology is being optimally exploited to minimise chaos on own side while maximising it on the adversary side. The Israelis have gone on to call its two years wars in Gaza as the first war by Robotic Autonomous Systems integrating tens of thousands of drones in the air with thousands of robots and unmanned ground vehicles (UGVs) on ground to replace manpower wherever possible. The Russian and Ukrainian militaries increasingly replaced forward troops in the contested zones with machines like drones and UGVs displaying new innovation daily. While Ukraine's two fully unmanned assaults in December 2024 and July 2025 saw employment of

Unmanned Vehicles (UVs) in an offensive role, Ukrainians claim that few of their UGVs held defences against the Russian onslaught for many days. The Chinese are picking up the lessons to incorporate them in their preparations for the Taiwan conflict and combat readiness along the India-Tibet-Xinjiang border. Apropos, Chinese President Xi Jinping calls technology a core combat capability and talent a strategic resource.

This rapid pace live technology test beds of Ukraine, Gaza and other West Asian/ African battlefields have allowed innovators of numerous countries like China and the US in addition to Russia, Israel and Ukraine, to test their latest innovations. While the rapid prototyping of Iranian Shahed into Geran drones by Russia has been facilitated by massive drone components' production overcapacities of the People's Republic of China (PRC), the battlespace innovations by Israelis and Ukrainians at a rapid pace have drastically reduced production costs. The resultant commercialisation and miniaturisation, particularly in space and the drones' domain has widened the combat employment options and accelerated technological developments. This monograph shall thus analyse key drones and C-UAS technologies in various sections of AI, rotary wing designs, propulsion, EW resilience, etc to highlight key recommendations for the Indian military for pursuing rapid pace technological developments.

ARTIFICIAL INTELLIGENCE (AI)

The year 2025 saw massive investments in AI as a global game-changer technology. The year 2026 and beyond is thus expected to witness an accelerated AI-enabled or Intelligentisation and Autonomisation of drones. The Ukrainian and Iran-Israel-Gaza battlespaces have shown gradually increasing levels of drone autonomy from the earlier fully manual operation (level 0) to the desired full autonomy (level 5). The 5^{th} or the highest level of drones' autonomy allows greater operational flexibility by facilitating drones to independently plan and execute missions, with AI handling all key functions without human intervention, like flight planning, obstacle avoidance, and adapting to changing conditions.[1] The key successful AI use cases are elucidated below, while some of them will be discussed separately under each subject.

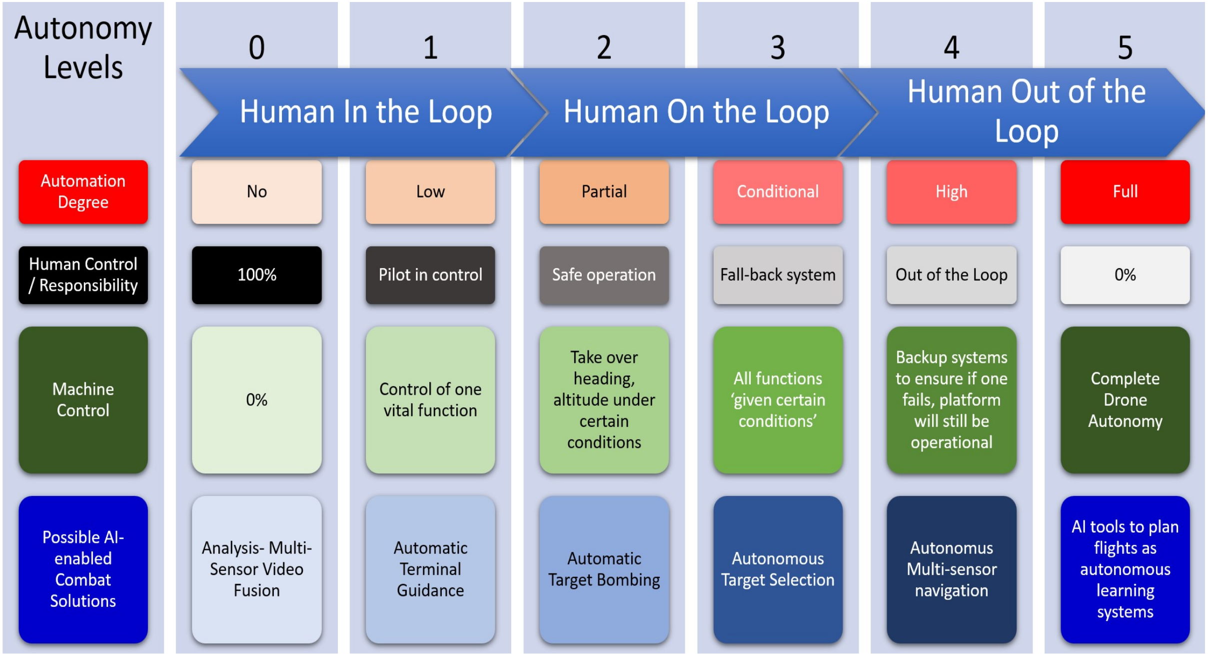


Figure 1: Drones' Autonomy and Intelligentisation Levels

Source: Gonzalo Arana and Javier Romero[2]

Common Machine Learning (ML) and Reinforcement Learning (RL) Algorithms. As highlighted above, ML and RL facilitate drones learn and optimise flight paths based on past experiences. The most commonly used RL and ML algorithms in drones currently are:[3]

- **Convolutional Neural Networks** (CNNs) to facilitate kill chain actions of target detection and identification, and additionally identification of obstacles, people, or landmarks enroute its flight.
- **Support Vector Machines** (SVM) execute classification tasks like detecting anomalies in surveillance footage.
- **K-Nearest Neighbours** (KNN) are primarily used for pattern recognition for tracking adversarial movements and routine deployments.
- **Long Short-Term Memory** (LSTM) and **Recurrent Neural Networks** (RNNs) facilitate predictive analytics and anomaly detection.

Multi-Task Collaborative Scheduling of Heterogeneous UAVs. The Ukrainian battlespace has been all about stacked employment of drones rather than swarms' format. While Russians standardised their drones, the largely decentralised production of drones led to large varieties of non-standard drones with Ukrainian Unmanned

Forces. Even in India, the biggest challenge today is tasking of heterogenous UAVs. Chinese Research and Development (R&D) institute under the Beijing Institute of Technology has now proposed a Flexible Combinatorial Auction Algorithm (FCAA) to coordinate multi-task collaborative scheduling of heterogeneous drones. The Chinese R&D team opines that their algorithm has solved heterogeneous UAV resource scheduling for intelligent logistics in complex environments. The FCAA dynamically adjusts the end user's priorities to recommend the most optimal multi-task scheduling. It has thus empowered adaptation for human–machine collaborative scenarios by adjusting solution valuations based on practical experience. Furthermore, the study claimed that: -

> "*Simulations show that the FCAA achieves a scheduling success rate of over 88% (with a maximum solution benefit proportion of 83.9%) in small-scale multitasking scenarios and a scheduling success rate of 98% (with a maximum solution benefit proportion of 93%) in multi-tasking scenarios, with significantly better time efficiency and solution quality than traditional algorithms*."

India's L&T Precision Engineering and Systems has validated 'Chanakya' in December 2025. It's a decentralised collaborative autonomy framework to manage a heterogeneous swarm of drones. Chanakya has demonstrated capabilities such as Flocking, wherein multiple FW drones took off and synchronised in the air, Mission Autonomy and Video analytics. Overall, L&T's latest development supports AI-enabled collaborative planning, allocation, execution, and monitoring of tasks by heterogeneous drones to achieve a shared mission. [4]

Multi-Target Detection. Ukraine's 'Clarity' AI software has recently inducted with its military. It automatically analyses aerial photographs from reconnaissance drones to quickly detect the location of enemy targets and hand it over to the strike platforms in the least possible time. Thus, a 6-hour job on average is claimed to be completed in 20 minutes, allowing for faster Ukrainian drone operations.[5]

Autopilot. Ukraine's startup Dwarf Engineering has come up with an AI solution Narsil, which can place any drone into an autopilot mode, by making it resistant to communication loss, EW, and GNSS jamming/spoofing. The AI application has reduced drone operators' training time and facilitates the drone pilot to control commands instead of using a joystick constant. Ukraine's Brave1 defence cluster claims that the solution has been integrated into five divisions effectively under combat conditions. [6]

Decision Support. Another Ukrainian startup, Farsight Vision' has supposedly innovated an AI software "Decision Intelligence Platform" which facilitates decisionmaking by field commanders based on 3D models and AI. The software aggregates and intelligently fuses data from drones and sensors to coherently derive accurate analytical conclusions. It detects threats and plans missions in Virtual Reality /Extended Reality. [7]

Israel's AI Modules. Israeli Defence Forces (IDF) have pioneered the use of AI in variety of its drones from tactical to strategic level as illustrated below:

Type	**Key AI Features**
Harop Loitering Munition	Autonomous target recognition and obstacle aversion, Low-noise operation
Heron TP	Target detection and surveillance systems; Triple redundant avionics; Automatic taxi-take-off and Landing (ATOL); Sensor fusion; Big data analysis; Multi-sensor fusion including SIGINT/ELINT and moving target detection radars
Rotem	Sensor fusion, Automatic operation and routing, low visibility and sensitive assault feature
Skylark 3 Hybrid	Advanced surveillance and reconnaissance; Backup feature and error tolerance; Low noise and invisibility capacity; Over the hill intelligence; Convoy and • Strategic infrastructure protection
HERMES 900	Multi-sensor fusion; Analysis
Fire Fly LM	BLOS, dynamic target tracking

Table 1: AI Features in Israeli Drones. Source: Sibel Düz and Muhammed Sefa Koçakoğlu[8]

3D PRINTING OF DRONES

3D printing of drone components has been a technology being used for sufficient time now. However, low-cost 3D printing of complete First Person View (FPV) drone is a significant technological development particularly for low-cost rapid prototyping and miniaturisation. Spanish research has adopted Fused Deposition Modelling (FDM) 3D printing of a crash-resilient and screwless light weight FPV drone (less than 250 grams) made from Polyethylene Terephthalate Glycol (PETG) and carbon fibre composites. Inspired by Japanese joinery, this research has successfully integrated Finite Element Model (FEM), Betaflight firmware 4.5.1, GNSS, telemetry, and real flight performance to boost the structural and functional reliability of micro drones. Autodesk Inventor was used to innovatively design a screwless frame with interlocking and interchangeable arms to overall reduce weight, mitigate stress concentrations, boost operational robustness and facilitate rapid arm replacement on the battlefield.[9]

UNCONVENTIONAL ROTARY-WING UAV DESIGN

With quantum jump in drones R&D by the PRC in 2025, a research paper on unconventional configurations of rotary-wing drones by Mengtang Li from School of Intelligent Systems Engineering, Shenzhen Campus of Sun Yat-Sen University has claimed enhanced performance, versatility, and functionality. The focus of unconventional drone research was to examine key design deviations in mechanical topology, aerodynamic principles, and movement modalities. The proposed advanced designs have supposedly transcended the limitations of conventional drones through innovative designing of rotor arrangements and refining airframe structures, to achieve novel flight mechanisms. The research paper written has categorised these advanced rotary wing drone designs into four distinct groups[10]:

- **Tilted or Tiltable Propeller Design** in drones, mainly quadcopters, aim to enhance UAV manoeuvrability and speed by using propellers with adjustable tilt mechanisms or various tilted angles to generate multidirectional thrust. Tilted propeller designs have fixed propellers oriented in multiple directions and thus excel in static thrust efficiency to improve stability and manoeuvrability. Thus, they encounter limitations in manoeuvring within confined spaces like buildings, etc., due to their fixed orientations. However, tiltable propeller designs, with orientation-adjustable propellers controlled by servo motors, trade mechanical complexity for reconfigurable dynamics, thereby providing enhanced adaptability and task-specific optimisation. Thus, they are hindered by the precision and speed limitations of servo motor dynamics.

- **Expanded Mechanical Structures Design** incorporates additional mechanical components into conventional rotorcraft to introduce new functionalities and expand motion modes.
- **Morphing Multirotor Design** adjusts the overall shape of drones to specific environmental conditions and flight missions.
- **Revolutionary or Groundbreaking Aerodynamic Design Concepts** are distinctive from multirotor designs by fuselage autorotation, minimal actuator configurations, and/or lifting-wing structures.

Tilted Propellers feature a primary rigid framework incorporating multiple propellers strategically fixed in various orientations to direct thrust in multiple directions. They enable diverse functionalities depending on the number of the propellers, their orientation, and their type- unidirectional or bidirectional. They are primarily categorised based on their propeller configurations into the following models[11]:

a) **Forward Advancing (FA) Platforms** have a specific number of propellers and an arrangement that facilitates forward thrust. Tilt-Hex is one example which comprises six unidirectional propellers attached rigidly to its main body, with each propeller oriented in a distinct direction. The Tilt-Hex platform, as elucidated below, has a rigid tool and an articulated arm for precisely executing point contact, sliding manoeuvres, and peg-in-hole tasks. A passive link and gripper system has been incorporated to execute pick-and-place operations and various manipulation tasks.

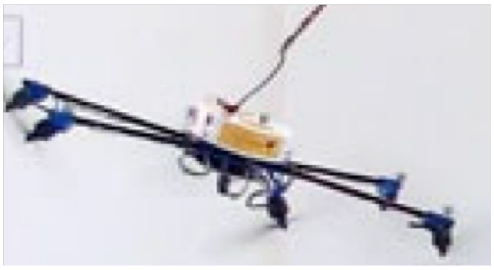


Figure 2: Forward Advancing Tilt-Hex platform with six unidirectional propellers. Source: Mengtang Li[12]

b) **Omnidirectional Agility (OA) Platforms** ensure thrust omnidirectionally for manoeuvrability across multiple axes. AEROX exemplifies this type of platform as elucidated in the figure below. It has eight unidirectional propellers with each one rigidly attached to the main drone body and oriented in a distinct direction. An articulated arm is specifically designed and provided for point contact and sliding manoeuvres. It has been effectively employed for contact inspections in bridges and oil and gas plants.

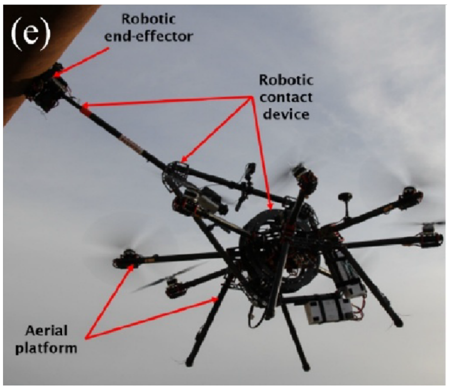


Figure 3: Omnidirectional AEROX platform equipped with an articulated arm tailored

Source: Mengtang Li[13]

c) **Directional Precision (DP) Platforms** employ propellers for highly specialised directional capabilities for specific combat tasks or operations. ODAR, of similar design, has eight bidirectional propellers oriented in diverse directions while rigidly attached to the main body. It uses a simple rigid tool for various tasks like pushing, sliding, and peg-in-hole manoeuvres.

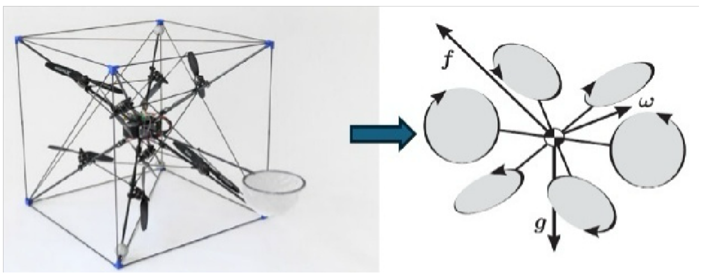


Figure 4: ODAR equipped with a straightforward rigid tool suited for peg-in-hole tasks.

Source: Mengtang Li[14]

Tiltable Propellers platforms have rigid frames alongside mounting of multiple propellers onto movable actuated elements, typically servo motors. The provision of additional actuation lets the propellers pivot independently, and their configuration synchronises motion towards desired directions. Chinese research opines that "*While* *most tiltable propeller platforms primarily function as FA systems, only a few are designed for physical interaction. These limitations stem from the inherent characteristics of the servo motors used to adjust the tilt angle, which often lack precision, exhibit slow dynamics, and suffer from mechanical issues such as backlashes*." [15]

Expanded Mechanical Structure Design provides advantages of structural simplicity and ease of scalability, leveraging existing multirotor control frameworks. These innovations enhance adaption of drones for diverse operational states and improve flight stability. However, they have reliability concerns and inherent challenges of weight and precise balance adjustments, increased energy consumption, and the requirement of more advanced control algorithms. The various possibilities of expanded mechanical structures are elucidated below in the succeeding paragraphs.[16]

a) **Robotic Arms and Grippers** have been innovated since 2011 for employment in helicopters and drones. However, recent technological developments include tendon-actuated gripper for replacing rigid ones for dynamic grasping of unknown objects through advanced control algorithms and soft robotics models; integration of a delta manipulator with 3D printing nozzles on quadrotor sUAS for aerial additive manufacturing; articulated rigid-element morphing mechanism for in-flight shape adjustment and dual-function grasping of diverse objects; mechanically intelligent and passive (MIP) gripper to undertake aerial perching and grasping; and Soft Aerial Gripper (SoAG) wherein a horizontally aligned soft gripper and onboard pneumatic system is basically mounted on an open source aerial robot for safe mid-air catching of micro-robots under aerodynamic disturbances.

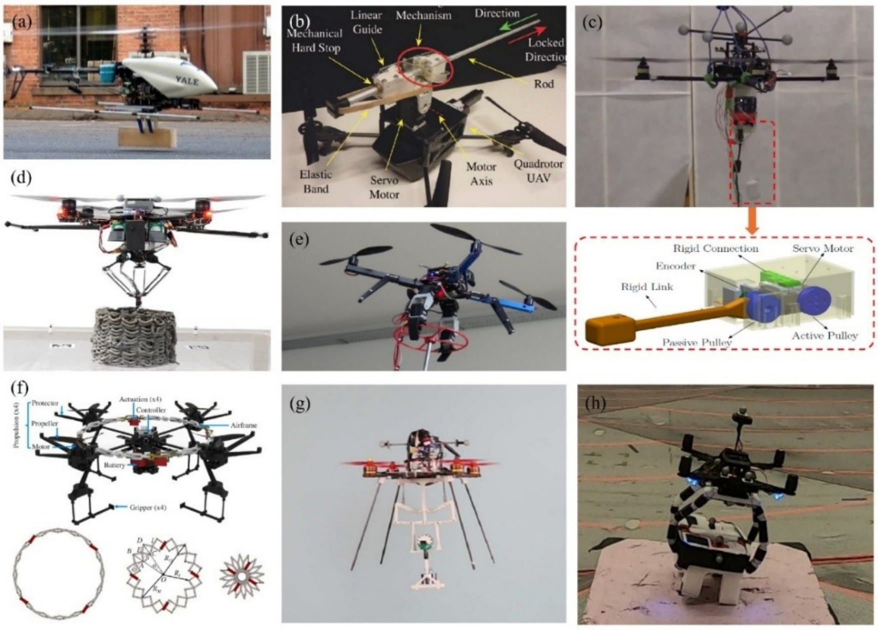


Figure 5: Robotic arms and Grippers. Source: Mengtang Li[17]

b) **Perching Mechanism** incorporate advanced controllers for stable attachment to surfaces or objects, particularly in quadrotor drones, to conserve energy, execute tasks, or conduct surveillance without sustained hovering. They generally integrate bioinspired designs like claw-like grippers, adhesive pads, or compliant structures for better camouflage by adapting irregular shapes thereby maintaining grip under dynamic conditions. Various modern research proposals include the following

- Modular, actuated landing gear framework for sUAS particularly to perch and rest on diverse structures without complex manoeuvring, reduction in power consumption, and enhanced stability for mission continuity;
- Biomimetic robot with passive legs and an underactuated gripper for perching on complex surfaces dynamically.
- Bioinspired drone multi-object perching platform imitating bird feet with elastic toes and gear-driven reconfiguration, achieving 15 times payload capacity and energy reduction by nearly 98.5%.
- Advanced concept of a bat-inspired mechanism incorporating four-link self-locking or ratchet and integrating autonomous target tracking via sensor fusion. The advantages include dependable outdoor perching on unstructured surfaces like branches and 97.1% energy savings.
- Metamorphic bi-stable arms for rapid morphing and perching;

- Passive perching platform incorporating two passive drive modes for landing on flat surfaces and grasping various objects with underactuated fingers. The claimed benefits include lightweight actuator-free operation.
- Possibility of using magnets for perching and unperching on ferromagnetic surfaces.

Figure 6: Examples of Perching Mechanisms. Source: Mengtang Li[18]

c) **Locomotion Mechanism** is the latest technological development for innovating hybrid aerial–ground robots by incorporating wheeled or legged locomotion mechanisms into quadrotor drones. These multimodal systems are made seamlessly adaptable to diverse terrains by fusing the agility of flight for rapid coverage of large areas and navigation over obstacles with the energy efficiency of ground traversal to conserve power during extended missions. They integrate either wheels for planar motion or legged mechanisms for uneven surfaces.

- **Walking Mechanism** or legged structures are more suitable for diverse terrains. One of the best hybrid drones incorporating a walking mechanism is the multimodal robot, LEONARDO. It undertakes complex manoeuvres like slackline walking and obstacle navigation by the coordinated control of thrusters and multi-joint legs, thereby integrating bipedal walking with aerial flight.

- **Wheeling Mechanism** are simpler and include both active and passive types, with the passive variety more prevalent. One ideal hybrid terrestrial/aerial vehicle incorporating a walking mechanism is SytaB which uses two independently passive spherical wheels and a bicopter. It provides energyefficiency, reduces attitude regulation for sensor stability and ensures smooth transitions between terrestrial and aerial modes.

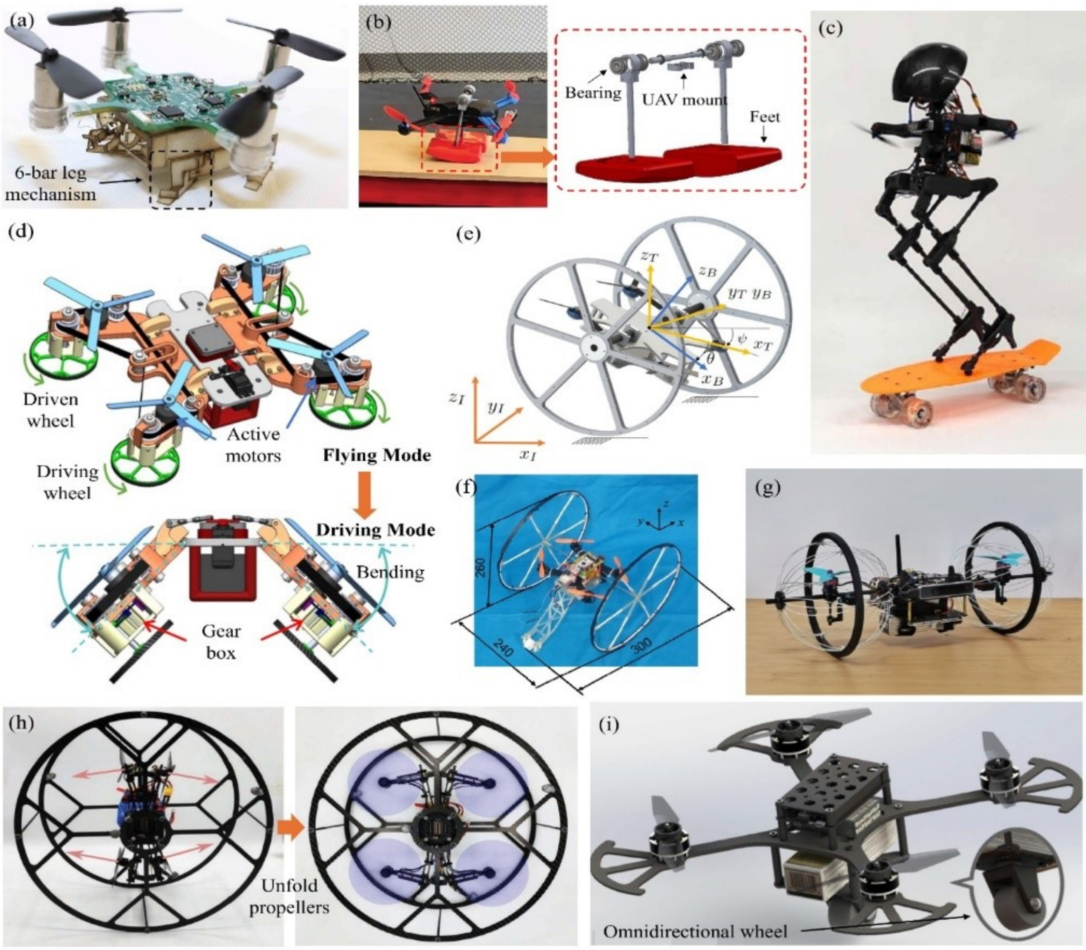


Figure 7: Examples of Locomotion Mechanisms. Source: Mengtang Li[19]

Ukrainian drone companies are appropriately developing “Ambush drones” which hide under the cover of leaves, while being perched in trees and wait for targets.

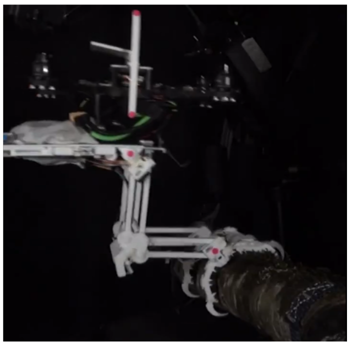


Figure 8: Drone equipped with the bird-inspired grasping mechanism "SNAG" (Stereotyped Nature-inspired Aerial Grasper). Source: Stanford University[20]

Morphing Multirotor Design drones, as per Mengtang Li, integrate "*adaptable components or structures capable of altering their configuration through mechanical, electrical, or other methods*. *These mechanisms include adjustable connectors, movable frames, and rotatable propellers*". As against the tiltable propellers platform, morphing multirotor drones modify their shape to meet unique task requirements. The resultant improved manoeuvrability, dynamic adaptability and enhanced operational performance facilitate adjustments in confined spaces and optimise flight efficiency.[21] Based on recent technological advancements, morphing multirotor drones can be categorised into two types as elucidated below:

a) **Frame-Morphing Multirotor** drone navigates through confined spaces by actively adjusting its frames. They enhance environmental adaptability and are further classified into two types- foldable-frame morphing and rotatable-frame morphing.
    - Foldable-Frame Morphing mechanisms facilitate UAVs to adjust their structure dynamically, thereby making them more adaptable for obstacle navigation, gap traversal, and space-constrained operations. X-Morf is an example of one such drone which actively adjusts the angle between its two frame arms. Two more innovative designs are the SQUID which is launched from a tube and deploys its rotary wings mid-air and the SplitFlyer which is a transformable quadcopter comprising two bicopters that disassemble mid-air. Recent developments include a biomimetic morphing quadrotor. The key challenges of Foldable-frame morphing are compromised structural stability during folding and unfolding processes, resultant increased risk of faults and failures because of intricate

mechanical structures, requirement of advanced control systems, highly accurate sensors and algorithms for precise foldable deformation. [22]

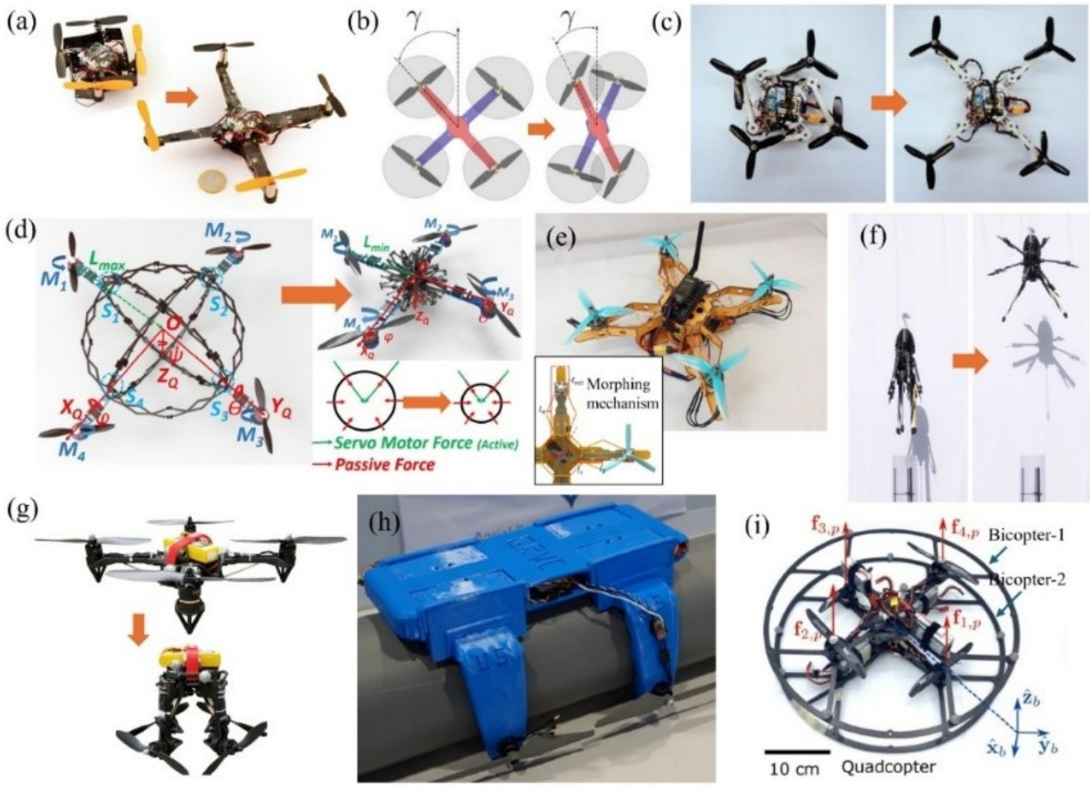


Figure 9: Examples of Foldable-Frame Morphing Designs. Source: Mengtang Li[23]

- Rotatable-frame Morphing drones use structural configurations to meet diverse flight environments and mission requirements by altering their shape and layout through the manipulation of rotating components. One suitable example is the Bi2 Copter robot that connects two bicopter modules for ensuring continuous 360° tilt angle adjustment and efficient thrust utilization to undertake wall flying and spherical coverage. Rotating frames exhibit comparatively lower mechanical complexity than foldable-frame types. Future research is expected to concentrate on reducing the driving structure for arm rotation and enhancing drone control precision. [24]

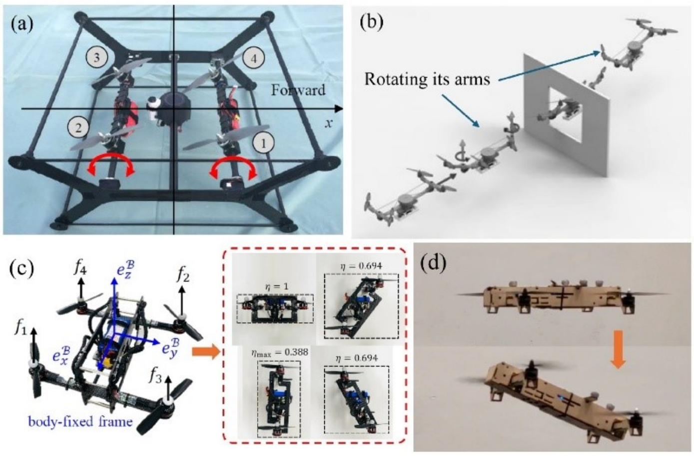


Figure 10: Examples of Rotatable-Frame Morphing Designs. Source: Mengtang Li[25]

b) **Linkage-Morphing Multirotor** incorporates multilink adjustable linkageshaped frame, which alters its form and structure whenever required, to ensure task-specific adaptability. Stable flight control is ensured by maintenance of optimal performance during morphological changes. The precise control systems facilitate navigation across confined spaces or switch flight modes by adjusting linkage angles. HALO, a transformable aerial robot, is an ideal example as it achieves the shape-adaptive aerial grasping of large objects by integrating a closed-loop multilink structure with tilted propellers. HALO's major limitation is the uncontrollable singular configurations. A research team, exPRC, proposed the design of DRAGON an upgraded version of a transformable aerial robot with dual-rotor gimbal modules. This design has supposedly enhanced translational and rotational stability during hover and integrated advanced thrust control strategies like rotor gimbal control. The natural example of an eagle's claw has inspired the innovative design of a biomimetic morphing quadrotor with vertically folding arms and a closed-loop multilink structure. Adaptive sliding mode control and morphology through admittance filtering has facilitated the grasping of unknown objects. [26]

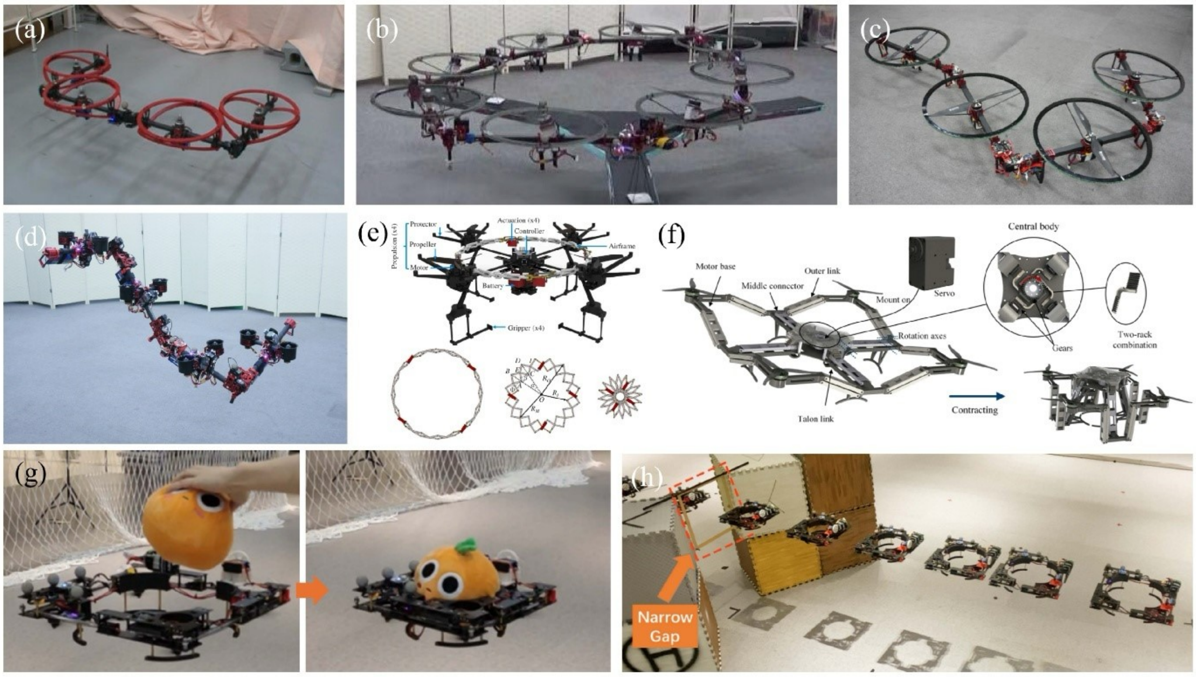


Figure 11: Examples of Linkage-Morphing Designs. Source: Mengtang Li[27]

Revolutionary Aerodynamic Design Concepts aim to achieve higher energy efficiency, miniaturization and better flight performance by optimising rotor layouts and fuselage shaping. They primarily include single or dual/triple minimal actuator configurations, fuselage autorotation, coaxial design, and lifting-wing structures. While lifting-wing configurations improve flight efficiency and performance by leveraging aerodynamic principles, actuator reduction simplifies designs, optimise structures and thus leads to weight reduction. The key challenges are limited payload capacity, control and navigation complexities, and design optimisation. [28]

- **Single-Actuator Design** have been made to imitate plants such as the Samara seed. A notable example is an ultra-underactuated, self-rotating drone, PULSAR. The control by a single motor has ensured 26.7% power savings over quadrotors while simultaneously ensuring panoramic LiDAR-based autonomous navigation and obstacle detection in unknown terrain and combat environments. [29]
- **Dual Actuator Design** drones use only two motors and propellers for control of roll, pitch, yaw, and thrust. A latest example of a dual-rotor drone is AVOCADO which has both tethered and aerial locomotion for navigation. It integrates a control framework, a protective shell, and advanced sensors for trajectory tracking and disturbance rejection. [30]

- **Coaxial Propeller Drone** is innovatively designed for enhanced manoeuvrability and high thrust efficiency. Its unique design of two contra-rotating propellers mounted on a single axis achieves greater thrust per platform area, and balances between energy efficiency, agility and size. It provides stability and dynamic flight performance both within a sUAS too. Despite its compact size, the coaxial design faces two major challenges- increased failure risks and control complexity because of intricate mechanisms and nearly 25–35% thrust loss caused by interaction between coaxially placed propellers. [31]

Small Multirotor UAVs with Folding-Wing Range Extender. Joint research by China's DJI Innovations Technology Co., Ltd and National Key Laboratory of Helicopter Aeromechanics, Nanjing University of Aeronautics and Astronautics, has proposed a design of an adjunctive folding-wing range extender for a small multirotor drone to reduce total power consumption by 20% and improve endurance by 25% at a 20 m/s cruise speed. The innovative integration of a folding-wing range extender with a sliding-rotating two-degree-of-freedom folding wing and a tail-thrust propeller facilitates rapid switch between multirotor and FW modes during flight. This has improved the adaptability and operational flexibility for combat mission scenarios. It is claimed that the host small multirotor drone, with its foldable wings deployed, quadruples the fuselage length yet folds within its profile and exhibits enhanced aerodynamic efficiency with a 52% higher equivalent lift-to-drag ratio and a 34% lower specific power while conserving inherent portability and high manoeuvrability. It utilises wing unloading and incoming horizontal airflow during its cruise phase to reduce rotor power consumption, thereby significantly extending range.[32]

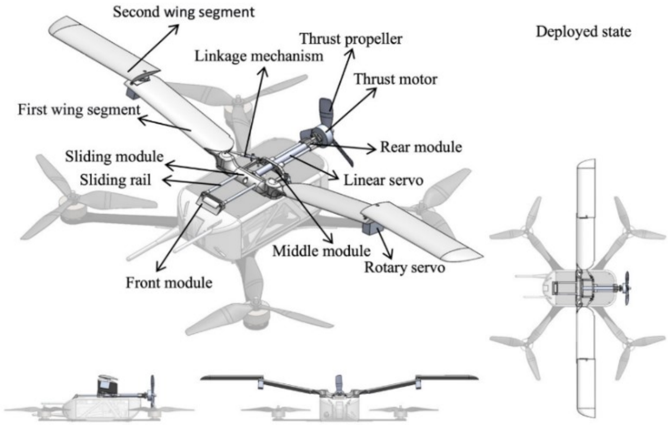


Figure 12: Schematic diagram of Folding-Wing Range Extender in Deployed state. Source: Ronghao Zhang et al[33]

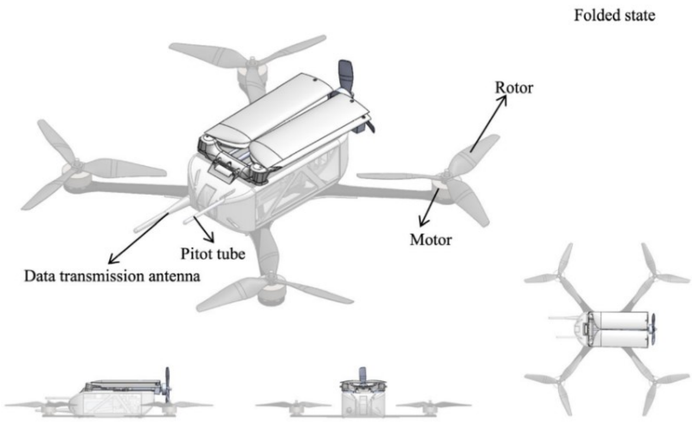


Figure 13: Schematic diagram of the Folding-Wing Range Extender in the Folded state. Source: Ronghao Zhang et al[34]

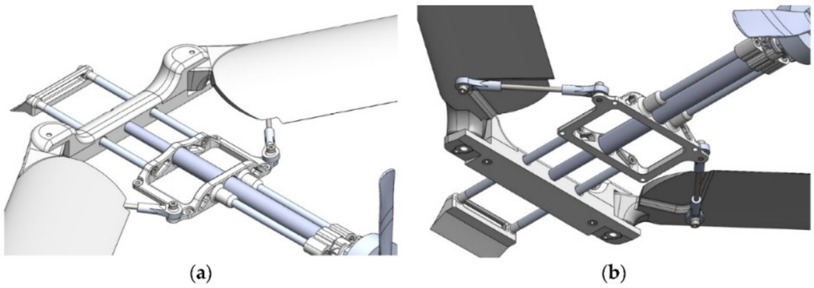


Figure 14: Detailed schematic diagram of the Folding-Wing Range Extender (a) Top view; (b) Bottom view. Source: Ronghao Zhang et al[35]

Multi-Rotor FPV Drones as Interceptors. Russian drone designers are focusing on a multi-rotor drone design that supports a substantial frame for carrying four FPV interceptor drones as AAMs, as illustrated in the figure below. Each of the four drones accommodates four motors in the corners and their corresponding ESCs. In this unique configuration, where the drones work in tandem with each other, the standard FC of each drone receives user commands and input from sensors and sends instructions to ESCs to adjust motor speeds for controlling the drone's movement. [36]

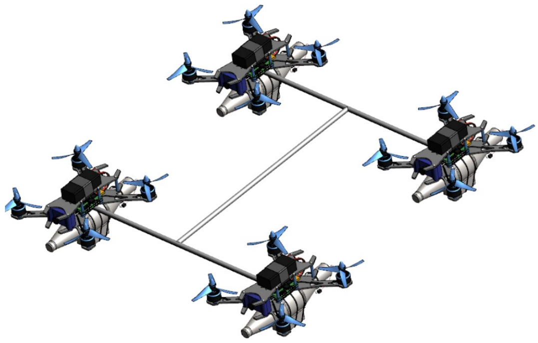


Figure 15: Russian Multi-Rotor Concept for Interceptor FPV Drones. Source: Mohamed Zied Chaari[37]

High Altitude Propellers. It’s a well-known fact that commercially available drones do not perform well at high altitudes because the density of air decreases as the altitude increases, thereby decreasing the drone’s thrust generation. A Nepalese research team did a detailed analysis of Clark Y and S1223 air foil for drone propellers at high altitude levels and found solutions to modify their aerodynamic properties to increase the efficiency. The results of the research are verbatim produced below: [38]

> “*Experimental analysis of the blade gave a thrust of 0.63 N and 0.42 N for the S1223 air foil and Clark Y, respectively, at 3000 RPM at 3610 m. The analytical solution for thrust with the same conditions was 1.45 N and 0.6 N for the S1223 air foil and the Clark Y, respectively. The validation of experimental results was done by the CFD analysis. The CFD analysis was performed in ANSYS Fluent, which gave a thrust value of 1.49 N and 1.09 N for the S1223 air foil and Clark Y, respectively, for the same boundary conditions. The calculation from the Weighted Scoring Method gives the value of 23.406 and 50 for the Clark Y and S1223 air foils, respectively. Thus, the result suggests that the S1223 airfoil is better than the Clark Y for search and rescue flight at high altitudes.*”

PROPULSION AND POWER PACK INCLUDING BATTERIES

The drones’ industry is witnessing rapid technological developments in the electric systems (EP- Electric Powertrain) and hybrid-electric propulsion (HEP- Hybrid-Electric Powertrain) technologies. While electric drones purely have electric propulsion fed from batteries, as elucidated in the figure below, hybrid-electric drones incorporate a hybrid propulsion system combining a thermal engine with an electric motor or an electric propulsion system fed from fuel cells and batteries. Simultaneously, a multitude of advancements are occurring in special electrical components too onboard an electric drone, like batteries, fuel cells, and electric motors. While electric drones ensure zero emissions, the batteries are very heavy for drones. Hydrogen fuel cells offset this limitation as the main power source by considerably reducing the power source's weight. However, electric drones also face the challenges of thermal management of the electrical power components, magnetic fields, particularly in highaltitude areas, critical concerns of electromagnetic compatibility (EMC) and electromagnetic interference (EMI), and insulation issues for higher voltages. [39]

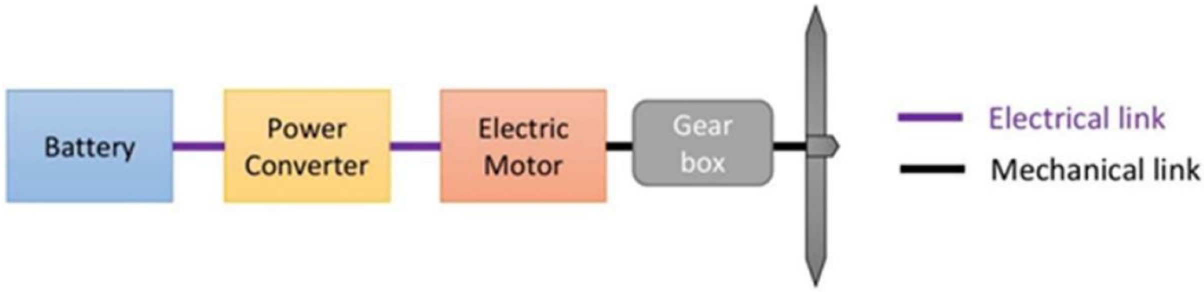


Figure 16: Configuration of the Fully Electric Propulsion (EP) System. Source: Jenica-Ileana Corcau et al[40]

HEP drones integrate fuel engines (gas turbine or internal combustion engine) as an intermediate step between conventional and fully electric systems. They are more complex but require fewer modifications to the energy supply and significantly reduce CO2 emissions with lower fuel consumption. HEP drones also make it possible to completely shut down the internal combustion engine, thereby flying the drone as a fully electric one. The level of hybridization i.e. the hybridisation factor determines the ratio of power provided by the electric motors to the total drone power. HEP drones currently are available in four configurations: series, parallel, series–parallel, and complex hybrid. With the addition of fuel cells, seven possible hybrid structures of hybrid powertrain propulsion systems are elucidated at the figure below. [41]

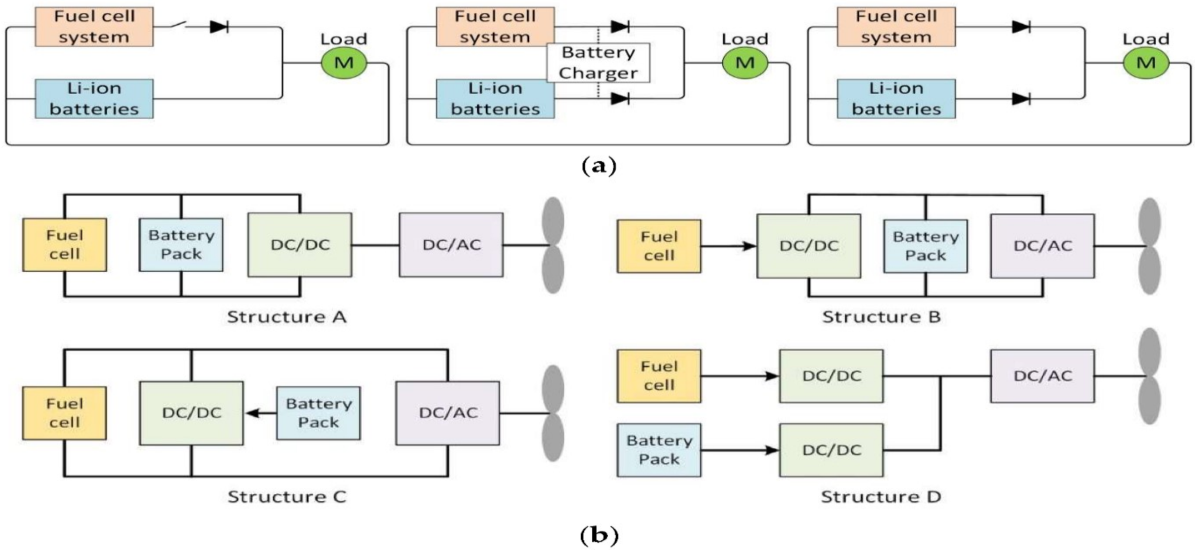


Figure 17: (a) Passive HEP systems with fuel cells and batteries; (b) active HEP systems. Source: Jenica-Ileana Corcau et al[42]

Fuel Cells (FC). Hydrogen reduces carbon footprint when used as fuel in the combustion chamber and can also be applied in FC-based systems within HEP. Additionally, hydrogen's high specific energy (33.3 kWh/kg), as against batteries and traditional fuels, is a major advantage for drones, particularly with weight as a critical factor as elucidated in the figure below. However, its challenge is its relatively low volumetric energy density. FCs offer cleaner and more efficient energy solution, and resolve noise pollution concerns. Comprehensive research has concluded that FC technology in HEP systems could be implemented on drones around 2045, with adequate development of Li–air battery technology and cryogenic H_2 tanks. However, Li-S battery technology and pressurised H_2 tank technology, may incorporate a HEP system based on FCs and batteries around 2035.[43]

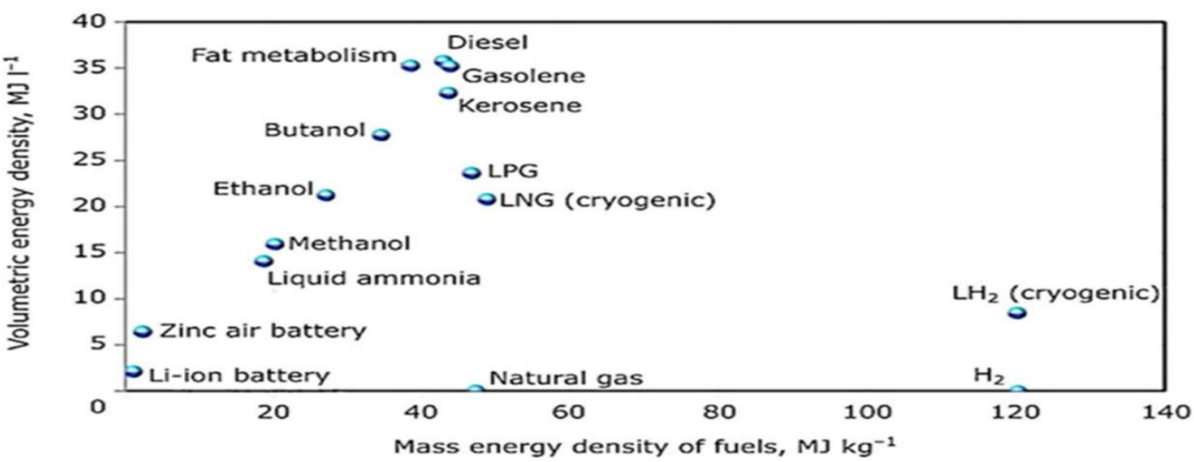


Figure 18: Volumetric and Mass Energy Densities of FC and Electrochemical Batteries. Source: Jenica-Ileana Corcau et al[44]

A major limitation of FC-based propulsion systems is the inadequate solutions for onboard storage of Hydrogen. All current storage methods, primarily based on two main approaches as elucidated in the figure below, pose unique challenges in Hydrogen storage, whether within a specialised material or as a gas or liquid in tanks. While the current industry standard is to store GH2 at 700 MPa, higher-pressure storage is theoretically possible, but any improvement in energy density diminishes with further increases. [45]

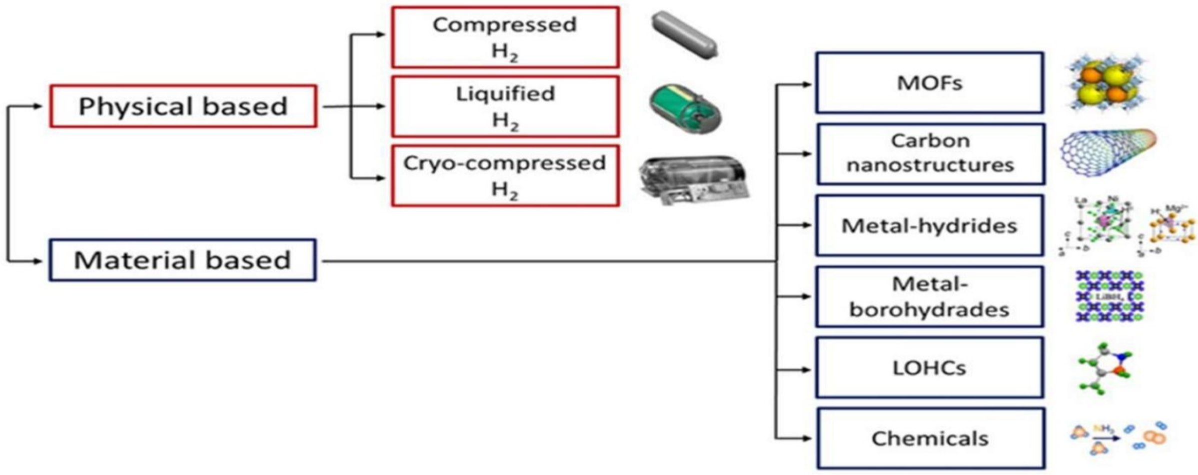


Figure 19: Hydrogen Storage Methods. Source: Jenica-Ileana Corcau et al[46]

Lithium-based Batteries. Although current cutting-edge Li-ion batteries offer maximum energy density of nearly 200 Wh/Kg as elucidated at the figure below, they are more costly. Since Lithium-based batteries offer the most advantages, they are expanding rapidly, with global search under way for new cathode materials to improve their performance. Lithium–oxygen (Li–air), Lithium–sulphur (Li-S) and the solid-state batteries are the promising options available and under development. Li-S battery possibly has attained energy density of 350-500 Wh/kg while it is expected to reach 2567 Wh/kg, The Li–Air batteries are under development, and will be used for drones where low weight is essential. They may achieve around 3500 Wh/kg and are available in two varieties—aqueous and non-aqueous. The newest drone batteries under consideration are the solid-state batteries with solid electrolytes with many global companies conducting research on it for drones. While they provide higher specific energy and very fast charge, the major challenges are a large voltage gap and rapid degradation.

Type	Specific Energy [Wh/kg]	Energy Density [Wh/L]	Short-Term Specific Power [W/kg]	Short-Term Power Density [W/L]	Cycle Life (~80% DoD)
Lead–acid	30–40	50–75	250–500	500–1000	250–1000
NiMH	40–75	75–225	150–1500	300–2500	600–2500
Li ion	60–200	115–500	500–1000	1000–5000	300–3000+

Table 2: Comparison of Main Types of Drone Batteries. Source: Jenica-Ileana Corcau et al[47]

Electric Motors. The technological developments in the field of electric motors for drones have focussed on weight reduction, low noise levels, and advanced cooling systems etc. Overall energy efficiency has been enhanced by generating better power densities ranging from 6 kW/kg onwards and incorporating regenerative braking for energy recovery during descent and deceleration. Few examples of global advancements include 34 kg YASA 750 R motor with a 200-kW power output, 50 kg Siemens's SP260D motor with a power output of 260 kW, 128 kg and 220 kg models of Magni's propulsion motors providing 350 kW and 650 kW respectively.

Pipistrel's NUUVA V300 medium-range cargo transport drone fielded a successful and innovative hybrid-electric propulsion (HEP) model during its first successful flight on 31 January 2025. With a combination of vertical take-off and landing (VTOL) powered by eight battery-operated electric motors and cruise flight by the conventional internal combustion engine, it can carry 300 kg heavy payload for 300 km and lighter payload of about 50 kg over extendable range of 2500 km. The functions of the two propulsion systems overlap during the transition phases between take-off, cruise and landing. [48]

Various researchers have also studied the Brazilian Atoba surveillance drone (MTOW500 kg, payload- 75 kg) for its transition from internal combustion propulsion to two possibilities of a series hybrid-electric propulsion system with an internal combustion engine like NUUVA 300 or a fuel cell powered fully electric propulsion system. The researchers preferred the fully electric fuel cell-powered system over the series hybrid propulsion system because of its disadvantages in terms of fuel consumption. [49]

Distributed Electric Propulsion (DEP) propeller-driven Short Take-off and Landing (STOL) UAV. DEP technology is a one of the latest propulsion technologies providing numerous benefits of high efficiency, low energy consumption, environmental friendliness, and reduced noise levels. More importantly, its power characteristics make it more suitable for extreme environments as they do not degrade with external factors like atmospheric density. The two most famous examples are the NASA's X-57 experimental aircraft and MIT's STOL. X-57 is powered by 2 large electric propellers at the wingtips and 12 small electric propellers placed on the leading edge of the wing thereby reducing the wing area by 2.5 times and enhancing lift, reducing both drag and weight. MIT's super-short take-off and landing model aircraft has 8 propellers along the wing leading edge and can take-off and land on extremely short runways. Chinese have appropriately researched a design of a 350 kg-class DEP drone with STOL capability.[50]

Electric Vertical Take-Off and Landing Fixed-Wing (FW-eVTOL) UAV. The FWeVTOL drones combines the advantages of high cruising efficiency and fast cruising speed of fixed-wing (FW) and VTOL of multi-rotor drones. Amongst the possible tiltrotor, tilt-wing, composite-wing, and tail-sitter configurations, composite-wing VTOL drones have been found to be the most practical FW-eVTOL solution currently by Chinese research. The propulsion system for this unique hybrid FW-eVTOL drone has two sets of power systems- a rotor for VTOL and a propeller for horizontal FW flights, a drive motor and electronic speed controller (ESC). Apropos, the FW-eVTOL UAV has three flight modes- vertical, transition, and horizontal as illustrated in the figure below. [51]

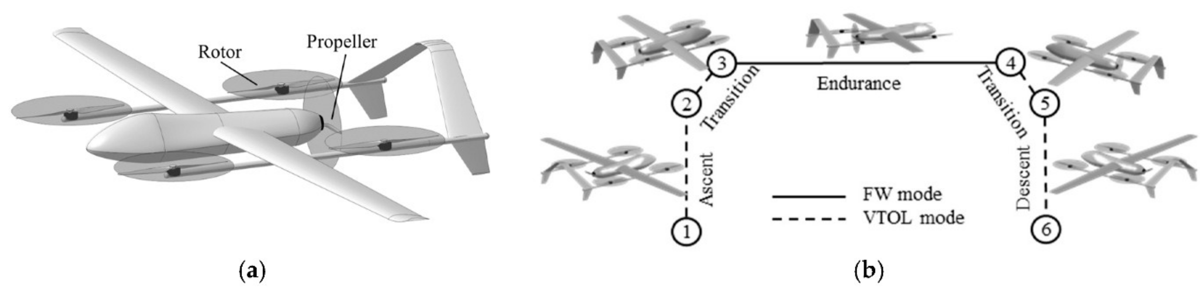


Figure 20: FW-eVTOL UAV Configuration and Typical Flight Profile

(a) FW-VTOL UAV configuration; (b) Typical flight profile. Source:Cheng He et al[52]

The battery packs equipped with FW-eVTOL drones, as per Chinese research, can be constructed in two configurations: dedicated and shared. As explained diagrammatically below, the dedicated configuration uses one battery pack each- A1 to drive the rotors and A2 to drive the propeller, while the shared configuration uses one battery pack only to operate both VTOL and FW modes throughout the flight. [53]

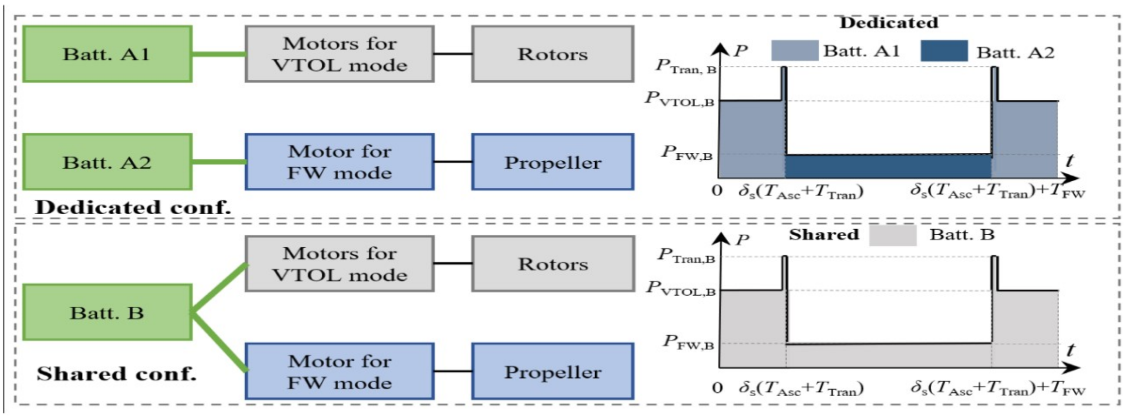


Figure 21: Operating modes and discharge processes for dedicated and shared battery configurations. Source: Cheng He et al[54]

EMALS Launched UAV. China has now modified the Electromagnetically Aircraft Launch System (EMALS) to launch drones from such a mobile platform which can either be placed on land or even onboard any ship whether civilian or military. In a recent series of photographs which have appeared on Chinese social media and thereafter on X and Sino-Defence Forum, ZhongDa 79 civilan vessel could incorporate this EMALS platform for launching drones.

Figure 22: Mobile EMALS Platform for Launching Drones. Source: Sino-Defence Forum[55]

Figure 23: ZhongDa 79 Vessel Possibly Carrying the EMALS Platform for Drones. Source: Sino-Defence Forum[56]

The PRC's Xinhua News Agency has claimed the launch of China's first longendurance FW-VTOL UAV XY-1 in Inner Mongolia for agricultural disaster assessment and smart grazing monitoring. The Xinhua news release claims flexible take-off and landing without a dedicated runway, with wind resistance up to level 6, endurance of 1-6 hours, and can cover up to 333 hectares per sortie. In the field of AI, it has edge computing technology and is equipped with a lightweight AI model to achieve a realtime inference at 32 frames per second. It is claimed to have reduced the false detection rate of target recognition in complex backgrounds by more than 40% by integrating visible light and multispectral data to innovatively introduce a colour-space dual-domain attention mechanism.[57] The PLA already uses Fielong 80A FW VTOL drone in conjunction with the PCL-181 Self-Propelled Howitzers to direct artillery fire.

AI-based Power Optimisation. AI maximises battery efficiency in drones to extend their flight duration by analysing flight patterns to adjust energy consumption. [58]

DRONES' ANTENNAS

The miniaturisation of drones has necessitated the advancements in technology of drones' antennas to overcome the key limitations of size, weight, and air resistance. Thus, globally research is on exploring both structural and material-based methods for miniaturising antennas, polarization strategies, and advanced beamforming solutions. The aim is to extend the efficiency of drones' antennas operating from 5/6 GHz into the sub-THz regime and the 5G / 6G / 7G networks. The R&D in this domain is shifting towards smart adaptive drones' antennas which will adapt their beam shape, direction, RF, or polarization in flight while the drone turns quickly, manoeuvres behind obstacles, or responds to EM interference.[59] Chinese have already drawn a technological vision for fielding 6G completely by 2025 and Quantum enabled 7G by 2050. [60]

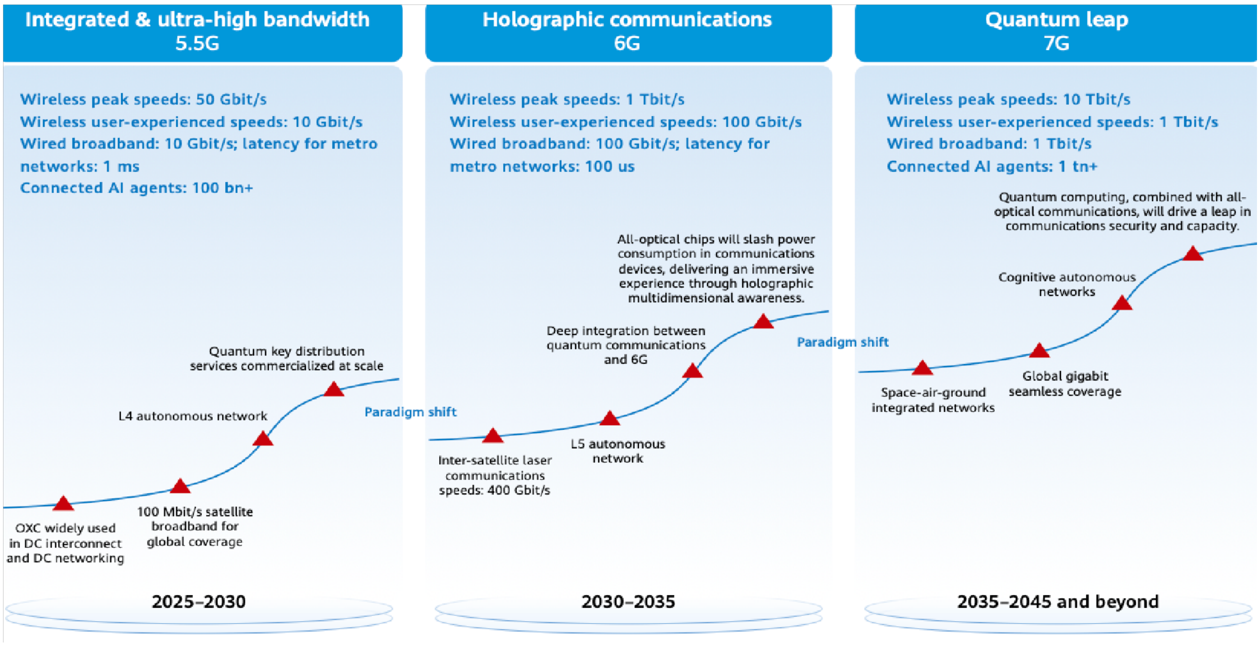
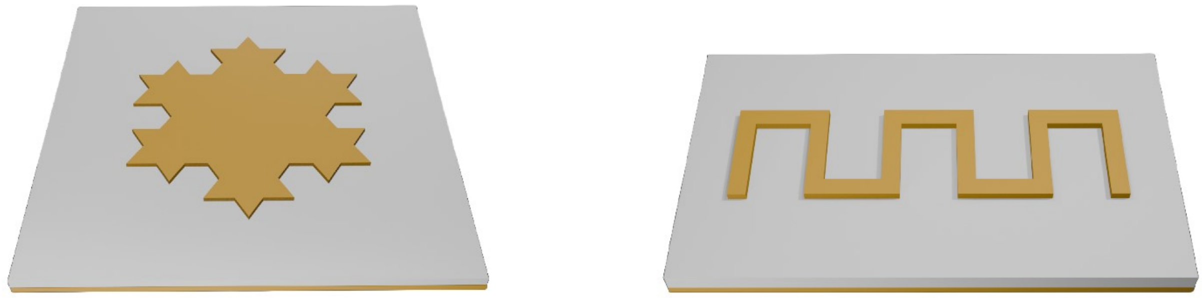


Figure 24: PRC's Vision for the New communications era and the agentic Internet. Source: Rui Ma[61]

Miniaturisation. Extensive research is being undertaken on technological advancements to develop more lightweight antennas, structurally integrated and reconfigurable apertures, thereby achieving miniaturisation through conformal substrates and programmable meta-surfaces. Reduction of the antennas' physical size without impacting operational performance is achieved by various methods, like meander lines, fractal geometries, and slots or through material-based solutions like high-dielectric substrates and metamaterials. Since every additional gram of weight matters, designers are concentrating on very light and energy-efficient parts by using thin plastics, fine ceramics, and 3D-printed lattices. [62]

- **Meander lines and fractal antennas** are space-filling curves methods designed to maintain antenna dimensions without altering EM properties. Meander lines method reduces the antenna size by folding a straight line into zigzag patterns. Fractal antennas instead reduce antenna size by adopting self-similar geometries like snowflakes, trees, and ferns.



(a) (b)

Figure 25: (a) Fractal antenna adapted (b) Meander line antenna. Source: Sara Reiss et al[63]

- **Slots and slits** are structural cuts/modifications on the radiating element or on the ground plane to simultaneously reduce the antenna's size and enhance the EM properties of antennas by increasing the bandwidth, optimising radiation patterns, enhancing gain, facilitating dual-band operation and creating circular polarization. [64]

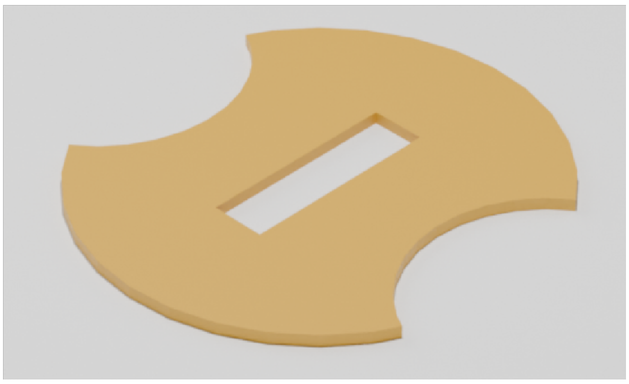


Figure 26: Patch antenna with slots. Source: Sara Reiss et al[65]

- **Material-Based Solutions for Miniaturisation** achieve antenna size reduction by altering the EM properties of wave propagation and impedance characteristics with materials and structural layering. These technical solutions for enhancing antenna's efficiency incorporate high-dielectric constant substrates, vertical stacking, and meta-surfaces. Higher dielectric constant materials reduce antenna sizes and make them lighter by reducing resonant frequencies, thereby slowing the propagation of waves and reducing aerodynamic drag. Vertical stacking, as elucidated in the figure below, enhances the antenna's performance while maintaining a compact design through the incorporation of layering patches or substrates. Thus, it boosts gain, bandwidth, signal quality, multiband operation by minimising interference and sidelobe suppression, and compact integration. The use of meta-surfaces facilitates miniaturisation by enhancing various antenna properties while maintaining antenna’s compact design. While coffee bean-shaped metasurfaces improve gain and radiation efficiency, the Frequency Selective Surfaces improve gain and enhance beamforming by reducing the beamwidth of the main lobe. [66]

Figure 27: Multilayer patch antenna, with two different substrates. Source: Sara Reiss et al[67]

Polarisation. The intention is to achieve linear or circular polarisation by modifying the radiating element or by adjusting the feeding network. These modifications and adjustments are either implemented by the incorporation of couplers, switches, and phase shifters or by employing the standard methods, such as using an inset feed or a coaxial cable. [68]

Beamforming. Various advanced techniques like beam-scanning, beam-steering, arrays, multi-antennas and beam-switching are being developed to enhance communication efficiency and implement better control of the radiation pattern through improvements in signal directionality, and facilitating agile beamforming for dense UAV swarms.[69]

- **Beam-switching** redirects drone’s antenna beams in a discrete manner to enhance communication coverage between the drone and a GCS. It facilitates 360-degree coverage around the UAV by activating antennas individually or together. One method is the activation of individual antennas or groups of antennas to direct the beam by utilising switching networks controlled by microcontrollers. In another researched method, the antenna array can switch between three modes, Uniform Circular Array, Uniform Linear Arra), and Uniform Rectangular Array.
- **Beam-steering** enables dynamic or semi-dynamic control of beam direction by the manipulation of the radiation pattern of antennas, thereby providing flexible

tracking and enhanced connectivity between the drone and its GCS or other drones.

- **Beam-scanning** facilitates dynamic tracking of targets by drones through adjustment of the beam direction in real time in response to the drone's movement.
- **Meta-surfaces** are artificially engineered structures which comprise subwavelength unit cells that manipulate EM waves in a controlled manner without requiring complex phase-shifting networks through wavefront shaping, polarisation control, and beam-steering.
- **Arrays** enhance gain, bandwidth, and directivity in drones' communication and radar applications by combining a structured feeding network, E-shaped slots, and rectangular slots to enhance dual-band operation. They carry out suppression of sidelobes to improve detection accuracy. Multi-band arrays have similarly been designed for high-resolution SAR imaging by incorporating layered patch structures. Integration of L- and Ka-band antennas for precise remote sensing ensures accurate soil moisture and salinity measurements. A few research scholars have also proposed a Multiple-Input Multiple-Output (MIMO) drone antenna system by incorporating a dual-mode circular patch antenna.

EW RESILIENT COMMUNICATION AND NAVIGATION FOR DRONES

In a severely contested EM environment, EW resilience has been the next obvious technology progression. The key technological advancement in EW resilience has been the introduction of OFC drones, graduation to multi-sensor navigation to overcome GNSS Spoofing and Meaconing, AI-enablement etc.

Fibre-Optic (OFC) Drones. The introduction of OFC tethered or guided drones (also called FOG-D) has brought about a paradigm shift in UAV operations at tactical and sub-tactical level. Russian forces employed them in early 2024 with the help of Chinese technological assistance and these drones played an instrumental role during Russia's offensive in Kursk. While the Ukrainians called it the "Technological Debt", they swiftly adopted these drones. OFC drones use ultra-thin fibre cables ranging initially from 5 km to later 20 km and now even claimed distances of 65-80 km to transmit control commands and real-time HD video while ensuring immunity to RF jamming. These tethered UAVs, controlled via several-km-long fibre spools, break the radio horizon and jamming defences and provide enhanced video fidelity, low latency, high bandwidth and enhanced cybersecurity. The added ability to receive electrical power via the tether continuous eliminates the battery limitations and thus facilitates indefinite flight durations in field applications [70] Russia's Ushkuynik enterprise announced "KVN" OFC drone upgrade in December 2025 with a range of 50-65 km with extended-range OFC spools and addition of an electronic target sensor which facilitates drone detonation both from the operator's control panel and upon contact with the target during ambush. [71]

Figure 28: Russian Ushkuynik "KVN" OFC drone. Source: Samuel Bendett[72]

Russian Cerberus System- OFC Drones Swarm. Russian inventors are working on a Cerberus control and charging system for a OFC drone swarm by incorporating a platform with 6 / 12 hangars. The AI-enabled OFC drones are deployed from a truck and released, as elucidated in the figure below. The system may also deploy heat decoys to confuse the adversary’s missiles or synchronise with AD systems to enhance the defensive network. [73]

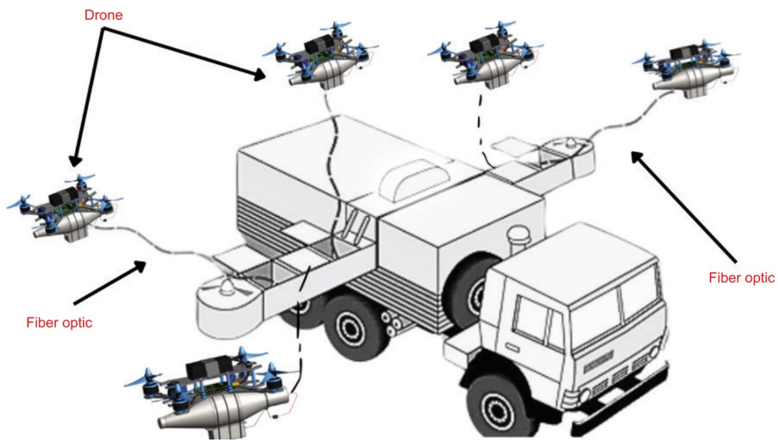


Figure 29: Russian Cerberus system for OFC Drones' Swarm. Source: Mohamed Zied Chaari[74]

Multi-Sensor Navigation. The intense GNSS spoofing capabilities of both Ukrainian and Russian militaries in the ongoing Ukraine war has necessitated a transition from GNSS-centred navigation to GNSS-assisted, multi-sensor navigation. Whenever GNSS signals are spoofed, denied, or corrupted, the drones must rely on onboard integrity checks, fusion of multiple internal sensors, and predefined fallback logic to maintain stable flight. The European Union (EU) has made its own vision for enhancing Positioning, Navigation and Timing (PNT) ecosystem in Europe through a multitude of sensors, as elucidated in the figure below.

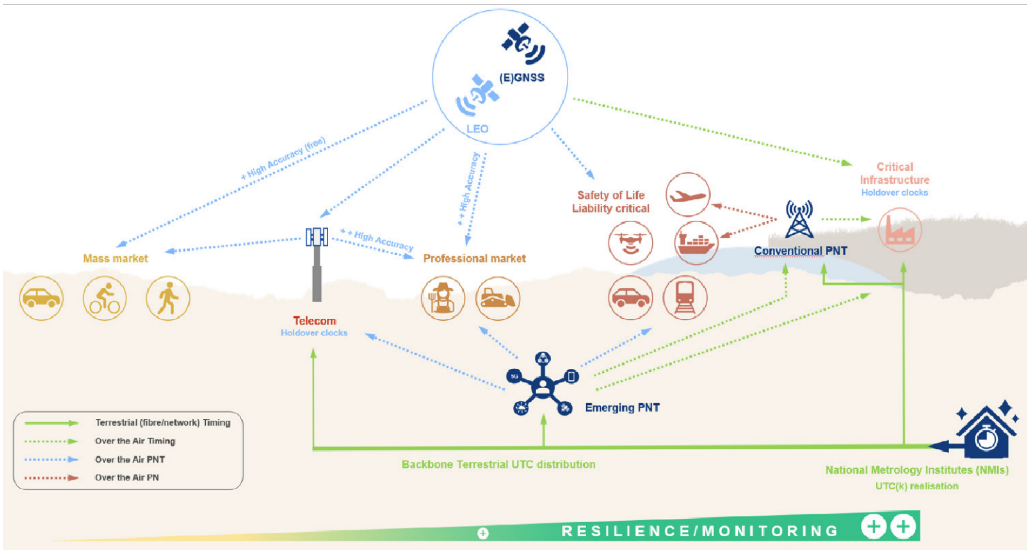


Figure 30: EU's Vision for Multi-sensor PNT Ecosystem Comprising Space (GNSS, LEO) and Emerging PNT Assets (Timing, 5G, Inertial). Source: European Union Agency for the Space Programme[75]

- **Inertial Navigation System (INS)**. This spoof detection cum mitigation technique uses the drone's INS as a reference to validate GNSS signals received. The INS regularly calculates short-term position, velocity, and attitude based on accelerometer and gyroscope data. When the drone's receiver obtains new GNSS updates, the INS's independent measurements are compared with its predicted state within predefined physical and kinematic limits. Whenever the GNSS updates of position, velocity, or timing (PVT) deviate from those predicted by the INS by more than what is physically achievable, the incoming data is classified as non-credible and excluded from the navigation filter. While this approach was earlier employed in high-grade aviation and missile guidance systems only, it has now been miniaturised for sUAS to overcome short period GNSS outages by the incorporation of lightweight MEMS (Micro-Electro-Mechanical Systems)-based inertial sensors. Since these sensors accumulate positional drift over time during complete GNSS loss, they are only capable of sustaining controlled flight for up to a minute by maintaining basic positional continuity, attitude, and heading until alternative navigation inputs become available.[76]
- **Visual-Inertial Odometry (VIO)**. An alternative navigation method for sUAS in a GNSS-denied environment and low-altitude hovers, VIO tracks visual feature changes in the surrounding environment across successive camera frames and fuses inertial measurements of short-term motion in all dimensions at high frequency for approximating the movement. The concept can be elucidated by optical-flow modules which detect motion by examining pixel shifts between successive downward-facing images, thereby providing reliable velocity and position cues. With very low drift levels of 1–2% of the distance travelled, it has comparatively accurate estimate of position and orientation by fusing visual changes with the inertial readings. The miniaturisation of drones has necessitated incorporation of VIO in small size onboard cameras and inertial units, to enable EW resilience to jamming or RF interference. The Return-tohome (RTH), waypoint and geofencing modules rely on inertial position or mission-defined fallback vectors to enhance resilience against GNSS spoofing.[77]
- **High-Speed VIO** is emerging as a core navigation layer for FPV-class and highagility tactical drones. It ensures low-latency visual–inertial fusion pipelines

below 30 milliseconds, thereby enabling stable state estimation particularly in cases of rapid accelerations, high angular rates, and frequent vector changes. These high-speed VIO systems use FPGA-based processors within strict SWaP limits to optimise feature extraction and inertial fusion to remain reliable during aggressive manoeuvring and under motion blur or low-texture conditions. [78]

- **LiDAR-VIO Fusion**. VIO is a challenge in degraded visibility conditions like dense forests or jungles, confined tunnels, or foggy conditions obtainable along India's Northern borders. The addition of compact solid-state LiDAR unit enhances reliability of depth measurements by building a precise 3D point cloud of the surrounding environment to correct visual drift and strengthen terrainrelative navigation thereby compensating for reduced camera visibility. Thus, the fusion of depth measurements with visual terrain tracking and inertial sensor data provides the drone a more reliable estimate of its position, orientation, and motion by reducing cumulative drift, improving obstacle detection, and enhancing terrain-following capability. Many tightly coupled LiDAR–inertial– visual pipelines are estimated to reduce positional drift by 40–70% in 7–10-inch tactical drones operating in EW-contested and GNSS-denied environments. [79]
- **Radar-Inertial Odometry** is the addition of small Millimetre-wave (MMW) radar to improve the precision of sUAS navigation, particularly wherever the performance of optical or LiDAR-based systems is degraded. Since these radars can determine distance, surface structure, and relative motion, even in fog, dust, smoke, electromagnetic clutter, or near-total darkness, the fusion of radar measurements with inertial sensor data produces a reliable odometry solution despite visual ambiguity. The focussed miniaturisation of drones on the Ukrainian battlespace has led to NATO's testing of compact MMW radar–inertial modules under 150 grams, on 10-inch class tactical sUAS for resilient navigation in EM contested and GNSS denied environments where traditional sensor suites fail. [80]
- **Barometric pressure sensors** provide one more option for continuous altitude estimation in sUAS by measuring small variations in ambient air pressure,

thereby enabling the drone to maintain vertical stability even in the absence of visual references. [81]

- **Quantum inertial navigation technology** incorporates quantum sensors for accurate positioning and navigation in GNSS-denied environments by measuring motion with extreme precision. Quantum sensors are claimed to track position over long periods without drift since they are capable of detecting the minutest changes in acceleration and rotation. Although the Technology Readiness Level (TRL) of this technology is currently low, it is likely to improve soon. [82]
- **5G positioning** (and later 6G) is both a GNSS alternative and a complementary technology. In a complementary mode, it works alongside GNSS for improved accuracy, specifically in urban areas. As a GNSS alternative technology, 5G provides independent positioning in GNSS denied environment via its wideband signals and base stations. The 5G positioning technology, as per EU paper on GNSS, is in the early stages of widespread adoption, with technology advancements essential for higher accuracy and reliability. [83]
- **Resilient Maritime Positioning (R-Mode),** is a navigation system in earlystage development in Europe for GNSS-denied environments. It is a terrestrialbased backup navigation system based on existing maritime radio infrastructure (like MF beacons and VHF signals). R-Mode calculates position through signal ranging thereby enhancing safety, reliability and provide costeffective and resilient solution for coastal and nearshore navigation when GNSS signals are compromised. It has a major challenge of limited accuracy when compared to traditional GNSS. [84]
- **Advanced Inertial Sensors** are also possible as per the EU report. They include nuclear magnetic resonance gyroscopes which use quantum spin for precise rotation measurements and may achieve high accuracy within the next 4-5 years; Laser-cooled atom sensors, which facilitate quantum-based inertial measurements for high signal accuracy and low noise; and low-cost Micro-optoelectromechanical systems (MOEMS) sensors, which aim for higher accuracy by reducing traditional sensor errors. [85]

  One startup Bavovna.ai has developed an AI enabled EW-resilient and GNSSindependent INS kit that provides location for accurate positioning, by fusing data from multiple sensors- gyroscope, accelerometer, barometer, compass, and multi-vector airflow sensor. It enhances navigation resilience by having additional capabilities to integrate data from ultrasonic, infrared, and optical sensors too.[86]

Multi-GNSS Navigation. The incorporation of multiple GNSS constellations GPS, GLONASS, NAVIC / Gagan, Galileo, Quasi-Zenith and BeiDou across multiple GNSS frequencies makes spoofing difficult for the adversary forcing him to replicate the distinct modulation schemes, Doppler histories, carrier phases, and time relationships of each GNSS constellation. As multi-GNSS multi-frequency band receivers crosscheck the received navigation signals for consistency in power, geometry, and ionospheric delay, any mismatch is more easily detectable immediately. The proportion of dual and triple GNSS receivers has decreased has decreased as per an EU report, while the GNSS receivers utilising all constellations has reached nearly 60% as elucidated in the figure below. The addition of Signal Authentication Services (SAS) like Galileo OSNMA[87], makes the attacker's task very difficult to forge cryptographic signatures. It is assessed that even many militaries are struggling to generate a coherent, multi-frequency, multi-constellation and physically plausible spoofing environment. The various methods being employed to harden resilience against spoofing are discussed in succeeding paragraphs.

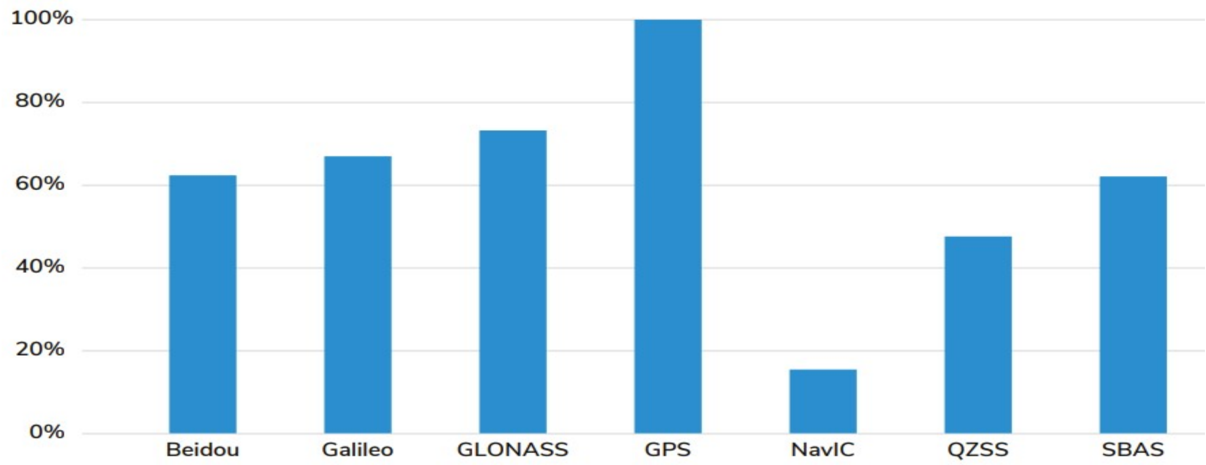


Figure 31: Percentage of GNSS receivers capable of tracking each Constellation.
Source: European Union Agency for the Space Programme [88]

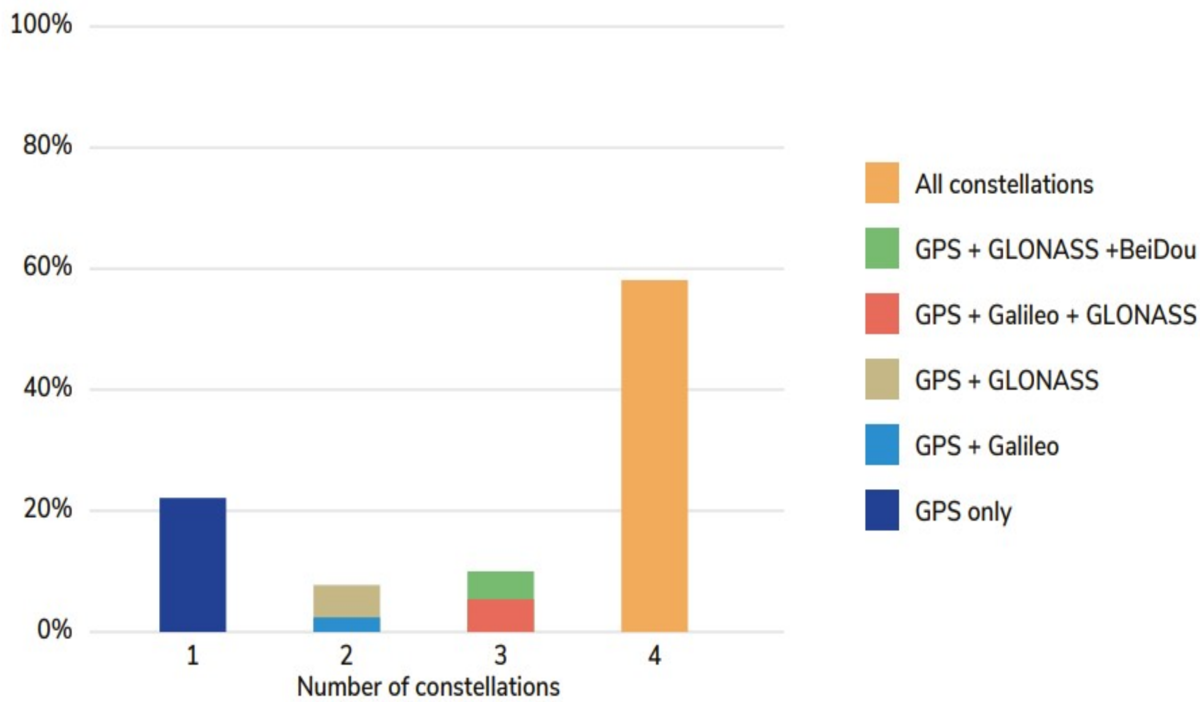


Figure 32: Percentage of GNSS Receivers capable of Tracking 1, 2, 3 or all 4 Global GNSS Constellations. Source: European Union Agency for the Space Programme [89]

- **Receiver-Level Anti-Spoofing**. The GNSS receivers have been upgraded to use multiple layers of signal-integrity monitoring to detect spoofed satellite signals before they are merged into the navigation filter and removes them. The distortion or the doppler shift checks examine the correlation code-phase symmetry and peak shape to confirm artificial or replayed spoofing signals by comparing the incoming carrier frequency against the predicted satellite doppler profiles, flagging inconsistent signals with incoherent frequency evolution. Monitoring multiple angles-of-arrival, using multi-antenna or spatialprocessing techniques facilitates detection of spoofers by differentiating signals from a single ground-based source from multiple satellites distributed across the sky. These receivers also use real-time anomaly scoring to evaluate signal strength patterns, cross-constellation consistency and inter-signal timing coherence. Thus, the system isolates falsified signals, and blocks them from contaminating the navigation solution, thereby triggering autonomous fallback behaviours whenever spoofing is attempted. [90]
- **Signal Authentication Service (SAS)** is a new technology for authenticated Position, Velocity, and Time (PVT) data. It’s a futuristic EU concept as explained by the EUPSA document.[91]

"*Its (SAS) concept relies on the Galileo Service Centre (GSC) selecting E6C Encrypted Code Sequences (ECS) to be transmitted by the Galileo E6C SiS in the future. These ECS are then re-encrypted with yet-undisclosed OSNMA keys, creating Re-Encrypted Code Sequences (RECS). The RECS are periodically uploaded to a secure public server operated by the GSC. This additional encryption layer allows the RECS to be published in advance for a specified period (typically up to one week) and downloaded by receivers, enabling offline operation during this time. Shortly after the E6 encrypted sequences (ECS) are broadcast via the Signal-in-Space (SIS), the OSNMA keys are disclosed. This allows the receiver to decrypt the stored RECS and reconstruct the original ECS. The receiver then applies a process known as "a posteriori correlation", where the ECS from the E6C SIS are matched with the decrypted ECS to generate range measurements. This process, illustrated in the accompanying figure, produces authenticated range measurements without requiring the receiver to decrypt signals or store secure keys. Combined with OSNMA-authenticated clock and ephemeris data, these measurements are used to compute an authenticated PVT solution*".

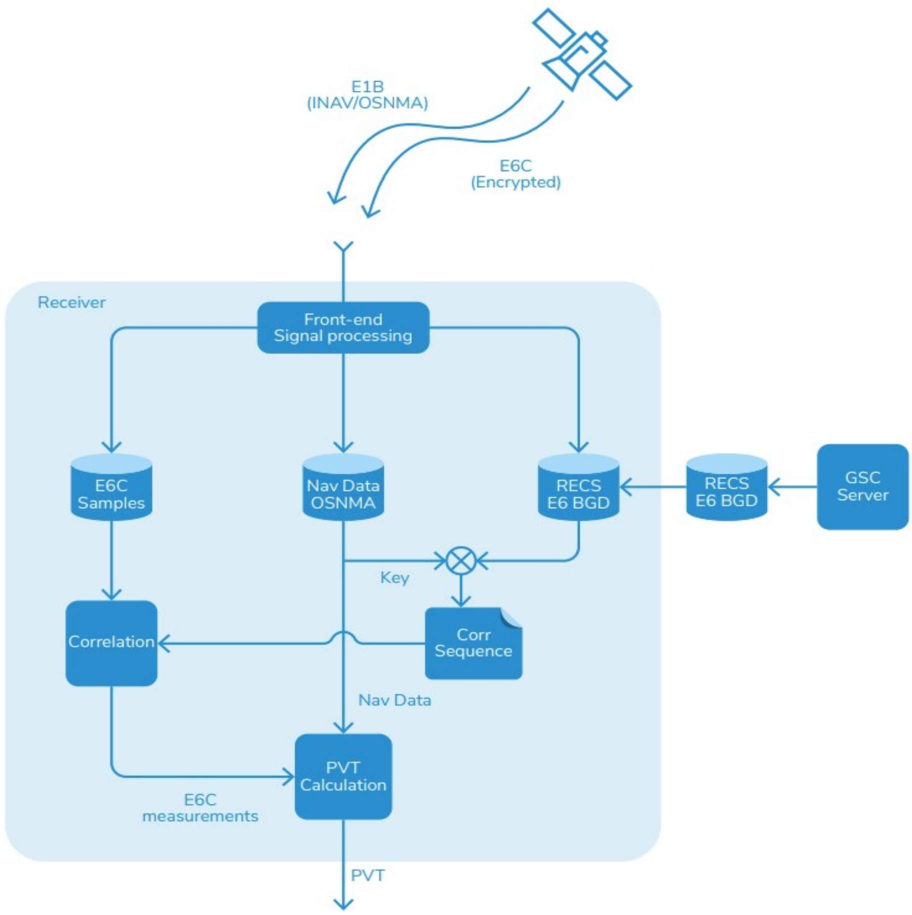


Figure 33: EU's Proposed Operating Principle for SAS. Source: European Union Agency for the Space Programme [92]

- **Cryptographic Authentication and OSNMA Integration** is EU's data authentication application freely available to all Galileo's open service users. It provides a robust, cryptographically anchored anti-spoofing technique for computing an authenticated PVT solution by placing an additional cryptographic layer to facilitate receivers to verify the authenticity of its own satellites' genuine broadcast navigation messages. OSNMA embeds Message Authentication Codes (MACs) to enhance resilience of the navigation data in contested EM environments. Broadcast of OSNMA test signals began in July 2020 and the service was officially launched on 24 July 2025. It employs a TESLA-based delayed key-disclosure protocol, wherein each MAC generated has a secret key which is revealed only after expiry of its validity period. Since the disclosed keys cannot be employed to compute upcoming MACs, this method prevents adversaries' spoofers from forging future navigation messages. In case if the enemy captures both the MAC and its corresponding key, the information obtained cannot be repurposed for spoofing since it will be only valid for historical verification. Resultantly, fake GNSS messages which reproduce signal structure, timing characteristics or power levels fail authentication at the data level. The latest R&D aims to accelerate verification times, reduce computational overhead for sUAS processors, and integrate OSNMA with multiGNSS constellations and multi-frequency receivers to strengthen crosschecking against spoofed signals. [93]

- **Other GNSS and Regional Navigation Satellite Systems (RNSS) Authentication Initiatives** include US GPS's Chips Message Robust Authentication (CHIMERA), which is to be tested on the NTS3 satellite; Japan's QZSS Navigation Message Authentication service (QZNMA) already being broadcast by QZSS since April 2024; India's NavIC Standard Position Service (SPS) Navigation Message Authentication (NMA), which is under testing; and the privately operated Fugro's SatGuard® service. [94]

- **Software-defined radio (SDR) in GNSS receivers** aim to use conventional antenna and frontend hardware while using a platform's digital processing power by employing more computational resources to handle signal and navigation solution processing. This technology is yet to see widespread market adoption. [95]

Multi-Frequency GNSS. The GNSS technological advancements are now moving ahead from multi-GNSS towards multi-frequency navigation to enhance accuracy and interference robustness. [96]

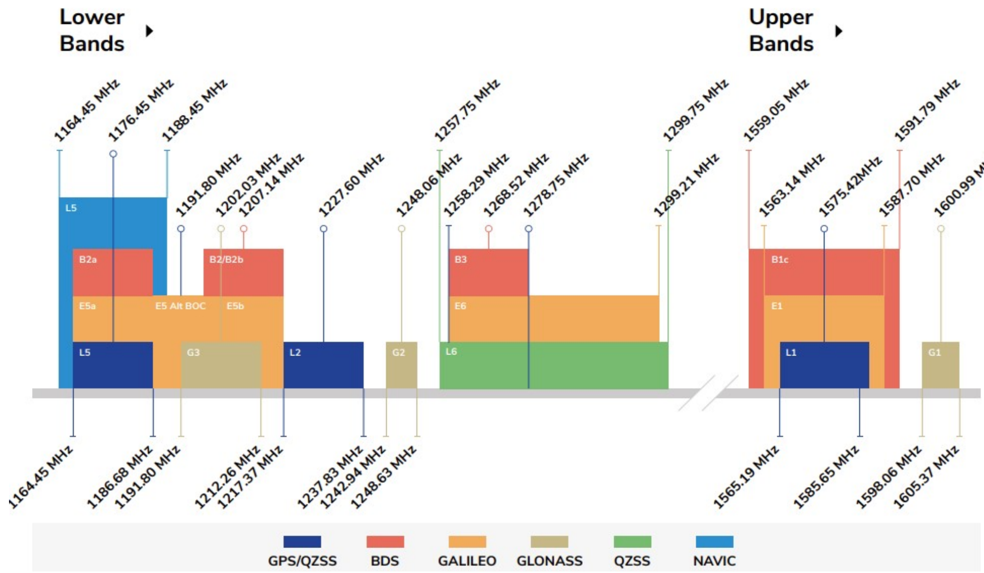


Figure 34: Array of Currently Available GNSS Frequencies. Source: European Union Agency for the Space Programme [97]

Method[1]	SPP	DGNSS	SBAS	RTK	PPP-RTK	PPP
Observable	Code	Code	Code	Carrier	Carrier	Code/Carrier
Positioning	Absolute (in the GNSS reference frame)	Relative	Relative	Relative	Absolute (in the tracking network reference frame)	Absolute (in the tracking network reference frame)
Comm Link	No	Yes	Yes (GNSS like)	Yes	Yes	Yes
Single Frequency (SF) Dual Frequency (DF) Triple Frequency (TF)	SF or DF	SF	SF current DF planned	Mostly DF	(SF) DF or TF	(SF) DF or TF
Time To First Fix (TTFF)	Rx TTFF	As SPP + time to receive corrections	As DGNSS	As DGNSS + time to resolve ambi-guities	Faster than PPP, but slower than RTK	As RTK, but time to estimate ambiguities significantly higher (more unknowns)
Accuracy Horizontal	5-10m DF 15-30m SF	< 1m to < 5m	< 1m	1 cm + 1 ppm baseline	< 10cm	< 10cm to < 1m
Coverage	Worldwide	Up to 100s Km	Up to 1000s Km	Up to 10s Km	Regional	Worldwide

Figure 35: Major GNSS PNT Computation Strategies

DGNSS- Differential GNSS; PPP- Precise Point Positioning; RTK- Real Time Kinematic; SBAS- Satellite Based Augmentation System; and SPP- Single Point Positioning

Source: European Union Agency for the Space Programme[98]

GNSS Augmentation and LEO-Based GNSS Constellations. LEO GNSS constellations for augmenting the GNSS signals of existing MEO constellations is another technique to strengthen GNSS accuracy and assured coverage. Chinese CentiSpace / Xiangriku satellite constellation (1 test satellite in 2018, 4 in 2022, 10 operational satellites in January 2025, plan of 190 satellites) is a LEO navigation system which receives GNSS signals and can broadcast augmentation signals within the same GNSS frequency bands. It provides compatibility for GNSS receivers particularly Beidou GNSS by employing a co-time and co-frequency (CCST) selfinterference suppression technique to mitigate self-interference caused by augmentation signals. Chinese researchers claim that CentiSpace space-borne GNSS receivers cover > 90% visible GNSS satellites and improve positioning accuracy to cm level. [99]

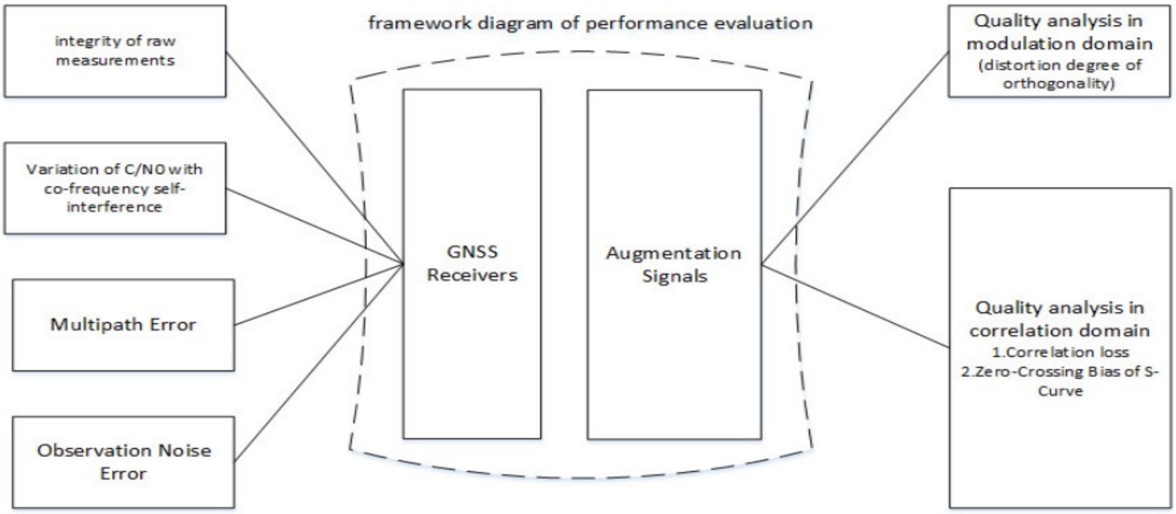


Figure 36: CentiSpace Framework Diagram. Source: Li Chen et al[100]

Rotation and Scale Invariant Map Matching Method (RSIM). Chinese research in December 2025 has proposed a new method RSIM to overcome the limitations of current image-based matching methods in the absolute visual localization process based on onboard cameras and georeferenced data in GNSS denied environments. The proposed RSIM method employs scale- and rotation-invariant map matching algorithm to create robust correspondences between drones' images and e-map data by exploiting the geometric stability of triangular configurations formed by buildings, incorporating both their spatial relationships and shape features. It thus extracts building contour information from drone images as the first step as elucidated in the figure below. The next step is a scene matching process to match the drone image and the existing vector e-map, based on the shape and spatial relationship features of the area and buildings below. Thereafter, the centres of the matched building individuals are selected as control points for drones' position resolution. The Chinese research team has claimed that their RSIM has successfully enabled drone localization in urban scenarios even in the absence of orientation and resolution of drones' images.[101]

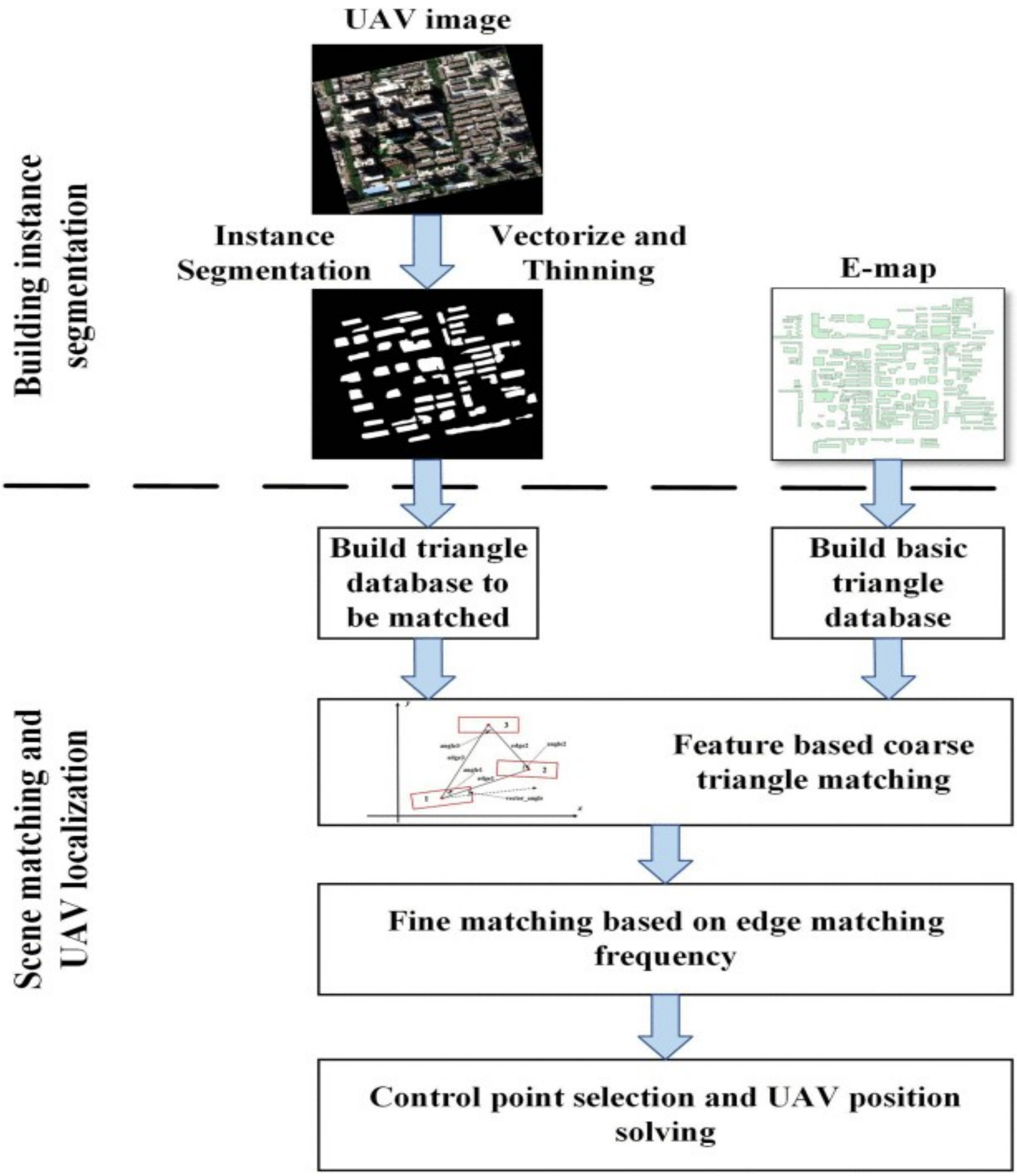


Figure 37: RSIM Flowchart. Source: Y Liu et al[102]

Frequency-Hopping Spread Spectrum (FHSS). This method swiftly switches transmission links across a predefined set of frequencies to prevent a jammer from concentrating its power signals on any single uplink or downlink path long enough to deny it. The synchronisation of coherent hopping sequences between the drone and the GCS allows the link to re-establish whenever the transmission hops are momentarily jammed. The added combination of direct-sequence or other spreadspectrum modulation techniques to FHSS distributes the signal energy over a wider bandwidth, thereby lowering spectral density and making the waveform harder to detect, track, or overwhelm with jamming noise. This dual-layer approach strengthens the robustness of the C2 and data links even in high interference conditions by reducing susceptibility to broadband and narrowband jamming. [103]

Burst telemetry is the transmission of C2 data in short, high-rate packets instead of continuous streams. In severely contested environments, this Low-Probability-ofIntercept (LPI) technique of intermittent transmission profile reduces the exposure window and also makes the RF signal far harder to isolate or track. [104]

Low-duty-cycle communication is another technique to further reduce detection probability by keeping the transmitter active only for brief, strategically timed intervals. This LPI technique reduces the drone's RF footprint to minimum possible and complicates enemy attempts to perform Time Difference of Arrival (TDOA) or Angle of Arrival (AoA) geolocation of the operator, which is a tactic increasingly used in the ongoing conflicts to target launch teams. [105]

Game-Theoretic Channel Selection. Stackelberg games-based approaches, as per Turkish researcher, have demonstrated effective anti-jamming performance in simulation and limited field trials, though latency issues may arise in dynamic environments.[106]

Controlled Radiation Pattern Antennas (CRPA) Antennas. They provide significant anti-jamming capabilities[107] by adjusting reception using multiple elements for maintaining gain for GNSS signals while directions of lowest sensitivity (nulls) are aimed toward a jammer. Thus, adaptive beamforming defeats multiple jammers for stable GNSS reception. The Russian Kometa CRPA receivers have enhanced the resilience of Russian drones, against Ukraine's EW efforts to disrupt and spoof GNSS signal reception. Russian “Geran-3” jet-powered kamikaze drone has been found using latest 16-element CRPA satellite navigation system. [108]

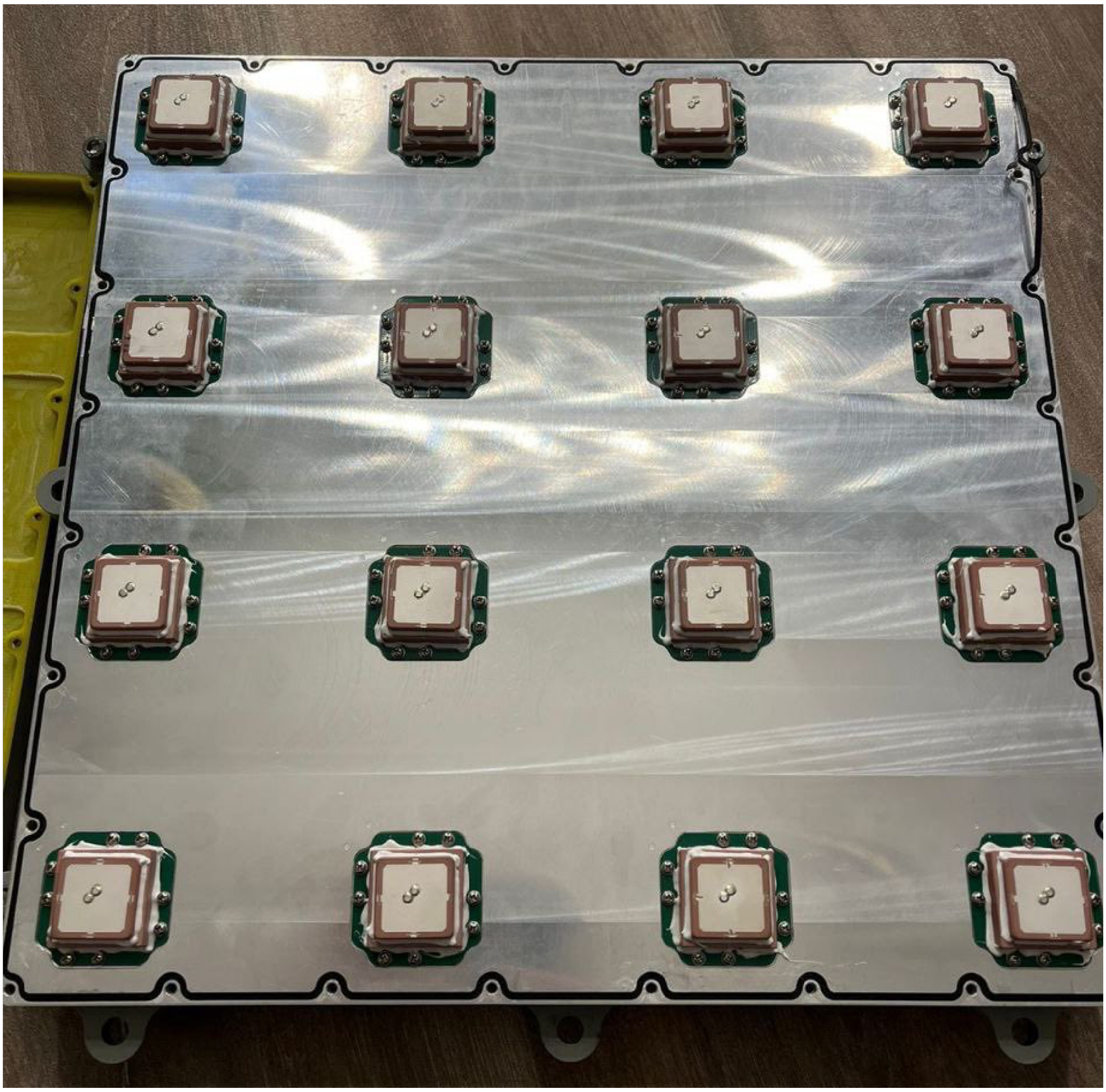


Figure 38: 16 CRPA Onboard Russian Geran-3. Source: Roy[109]

Multi-Media Multi-Path C2 Architecture. In an intensely contested EM environment, there is a need to ensure a multi-media multi-path C2 architecture facilitating control of drones across several independent communication channels. Availability of multiple communication options enable autonomous switching between normal RF, mesh networks, LTE 4G/5G, and satellite channels without interrupting the drones’ control loop. [110]

- **Mesh-based relay networks** use multiple drones or ground nodes as distributed communication points to overcome line-of-sight (LOS) constraints and jamming power levels thereby extending operational range. Mesh routing algorithms evaluate best node availability and EM interference levels to facilitate continuous dynamic routing around local jammers and terrain-based signal blockages by selecting the most reliable path to maintain link integrity.[111]

- **4G Long Term Evolution (LTE) / 5G** links of locally available cellular network are high-bandwidth options which provide strong throughput for telemetry and video transmission. With inherent resistance to narrowband jamming due to their multi-carrier and spread-spectrum nature, they also facilitate automatic handover between towers. [112]
- **Satellite narrowband links** with low-bitrate modems ensure reliable command updates and emergency overrides and extend range of mission by overcoming LOS restrictions when terrestrial RF paths are disrupted by jamming, terrain masking, or infrastructure loss. [113]

AI-Enablement. The major use cases of Intelligentisation to enhance EW resilience for drones are discussed below:

- **Predefined 'EW-safe' corridors** facilitate planning and selection of drones' mission routes that avoid known jamming zones, confirmed spoofing emitters, and known terrain features that historically degrade GNSS performance. These drone flight avenues rely on internal waypoints and geometric constraints stored onboard, thereby ensuring that drones maintain safe routing even when real-time GNSS updates are unavailable. [114]
- **Mission logic** enables drones' automation under sustained EW conditions to execute preassigned tasks like flight to pre-fixed target coordinates, holding desired altitude, or completing terminal manoeuvres in an objective area without any external navigation or operator input. [115]
- **Vision-based Simultaneous Localisation and Mapping (SLAM) algorithms** provide hardware-accelerated feature extraction, asynchronous keyframe selection to reduce bandwidth, and tightly coupled visual–inertial factor graphs. They prioritise sparse, feature-based mapping, incremental pose-graph updates, and lightweight loop-closure detection. Thus, these compact SLAM pipeline, optimised for micro-UAVs, produce sub-meter accuracy local maps for

GNSS-denied urban corridors, indoors, and in repetitive-terrain conditions where traditional VIO drifts accumulate. [116]

- **AI-Driven Integrity Monitoring** is now being considered a core component of advanced drone navigation systems. Used ML models trained on GNSS, inertial, and visual signal patterns, detect spoofing, jamming, sensor faults, or abnormal dynamics far earlier than traditional threshold-based filters. Latest R&D is now focussing on neural filters that estimate measurement credibility, classify spoofing signatures, and adaptively reweight or exclude corrupted inputs within the navigation solution. Defence organisations in advanced militaries are developing lightweight inference engines for enabling sUAS to autonomously identify and isolate compromised sensors in real time and maintain stable navigation in severe EM contestations. [117]
- **Swarm-Level Autonomy** ensures that each drone continuously exchanges its information about position, velocity, heading, and sensor confidence metrics with other drones in the swarm. This distributed situational-awareness network creates a collective understanding of the swarm's geometry and movement independent of external navigation aids. Swarm consensus algorithms like weighted averaging, fault-tolerant filtering, or distributed Kalman fusion ensure that the spoofing or GNSS degradation attempts on a single drone cause divergence of its navigation estimates from the consensus formed by the remaining units by comparing each drone's reported state against the predicted formation model and the internally validated estimates of neighbouring units. The drone identified as providing inconsistent or non-credible data, is isolated by the swarm by reducing its influence in the decision-making graph. Thus, swarm drones maintain coherent formation control and navigational stability in densely contested EM environments by leveraging AI for algorithms for crossvalidation, redundancy, and distributed integrity checks. [118]
- **Jamming Analysis and Signal Classification via Machine Learning** enhances jammer detection probabilities and facilitates faster mitigation of interference.[119]
- **Machine Learning (ML) Algorithms for GNSS receivers** allow learning from signal patterns, and predicts changes for appropriate adjustments; optimise dynamic real-time signal processing for correcting anomalies like multipath

reflections; undertake noise reduction by focusing on useful signal data; and achieve real-time higher accuracy since continuous learning helps refine drones' positioning on the fly. [120]

MUNITIONS

The destructive power of drones completely depends on the explosive power of the munitions carried by the drones. Hence, no discussion of drones' technologies can be complete without discussing the advancements in drones' munitions.

Linear Explosively Formed Penetrator (EFP). Ukrainian munition manufacturers have been developing linear shaped-charge EFP munition as FPV drones' warheads. One such latest product called "Rizak 1.8." has been developed for cutting into the barrels of adversary's artillery and tank guns. [121]

Figure 39: Ukrainian Manufacturer Steel Hornets Linear Shaped-Charge EFP munition "Rizak 1.8.". Source: Roy[122]

Thermobaric Munitions. Russia has advanced ways and means of using thermobaric munitions onboard FPV drones for burning C-UAS nets over roads as also using the same munition onboard Geran series of kamikaze drones.

COUNTER-DRONES (C-UAS)

Since most C-UAS technologies have already been discussed in the C-UAS primer, this monograph shall include only key developments recently.

Interceptor Drones. The single most important technological advancement in the last two years in 2024-25 in the C-UAS domain has been the development of fast speed yet low-cost interceptor drones made with indigenous motors. The main criteria for these drones are their speed and manoeuvrability to intercept the incoming adversarial drones. Ukrainians have supposedly achieved the 400km/h speed limit recently.

Pursuit Evasion for Protection of Airports. A very interesting research paper "*Scalable Pursuit–Evasion Game for Multi-Fixed-Wing UAV Based on Dynamic Target Assignment and Hierarchical Reinforcement Learning"* was published on 23 December 2025 by PLA's Unit 93420 ex Aviation Engineering School, Air Force Engineering University located at Xi'an in China. This PLAAF study was undertaken to improve the protection of airport airspace for employing FW drones to drive away or capture illegally intruding drones. To overcome the limitations of current deep reinforcement learning methods and multi-agent reinforcement learning (MARL), they concluded that drones' pursuit–evasion game is the most suitable for promoting cooperative autonomous decision-making and collaborative control of multi-UAV systems. Their collective research proposed a hierarchical collaborative pursuit– evasion game framework comprising three layers based on hierarchical reinforcement learning (HRL) model.[123]

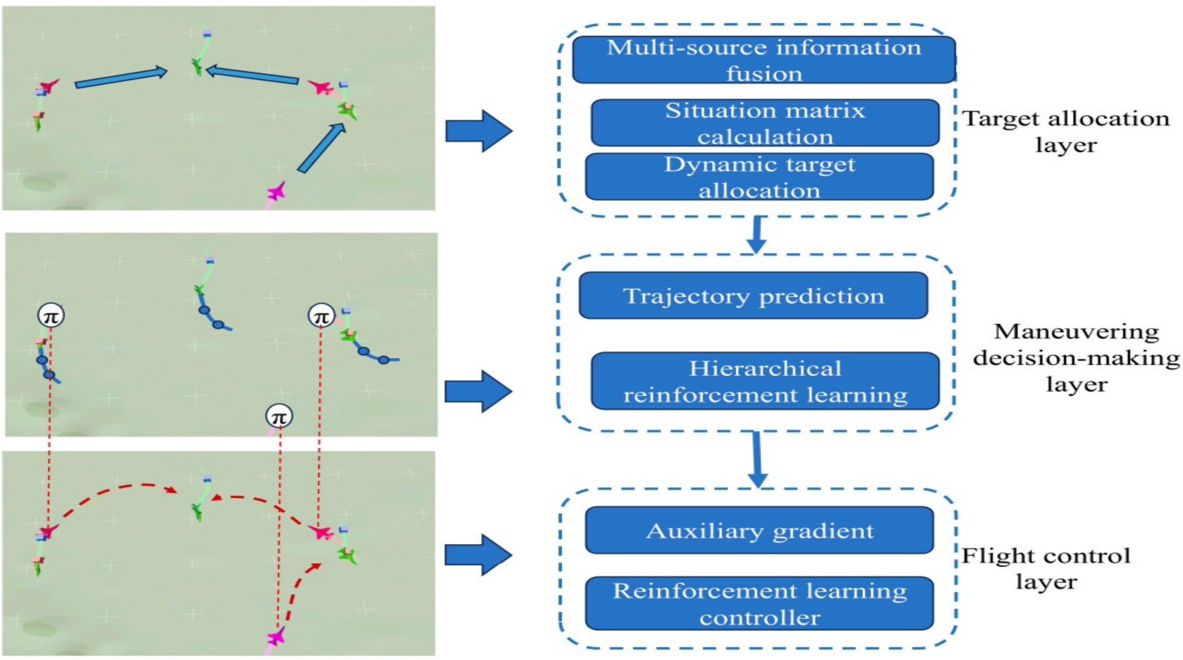


Figure 40: PLAAF's Hierarchical collaborative pursuit–evasion game framework. Source: PLAAF Engineering University[124]

- **Target allocation layer** uses a dynamic target assignment method based on a dynamic value adjustment mechanism, dividing the multi-versus-multi pursuit–evasion game into numerous one-versus-one confrontations.

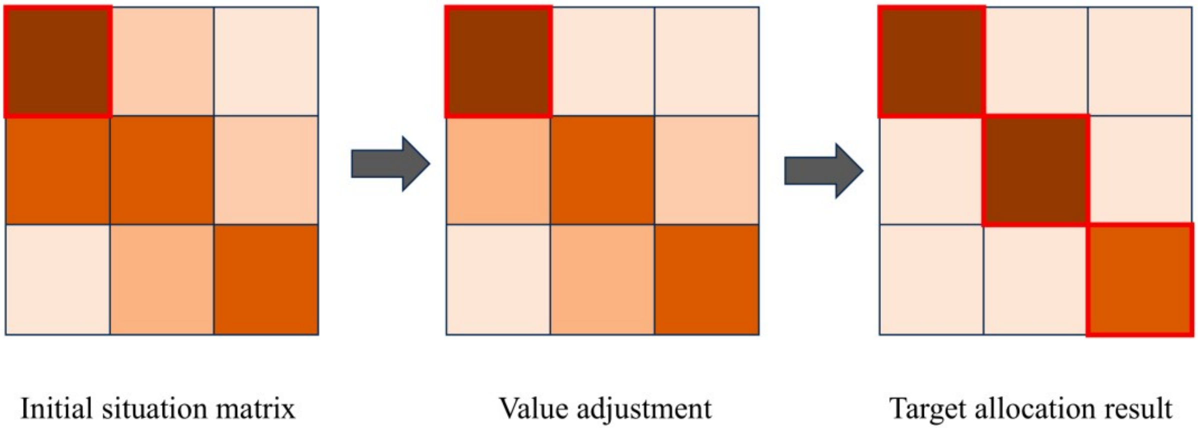


Figure 41: Dynamic Target Allocation Process. Source: PLAAF Engineering University[125]

- **Manoeuvre decision-making layer** has developed a manoeuvre decisionmaking method based on HRL and trajectory prediction to generate adversarial manoeuvre commands using deep reinforcement learning based on the assigned targets.

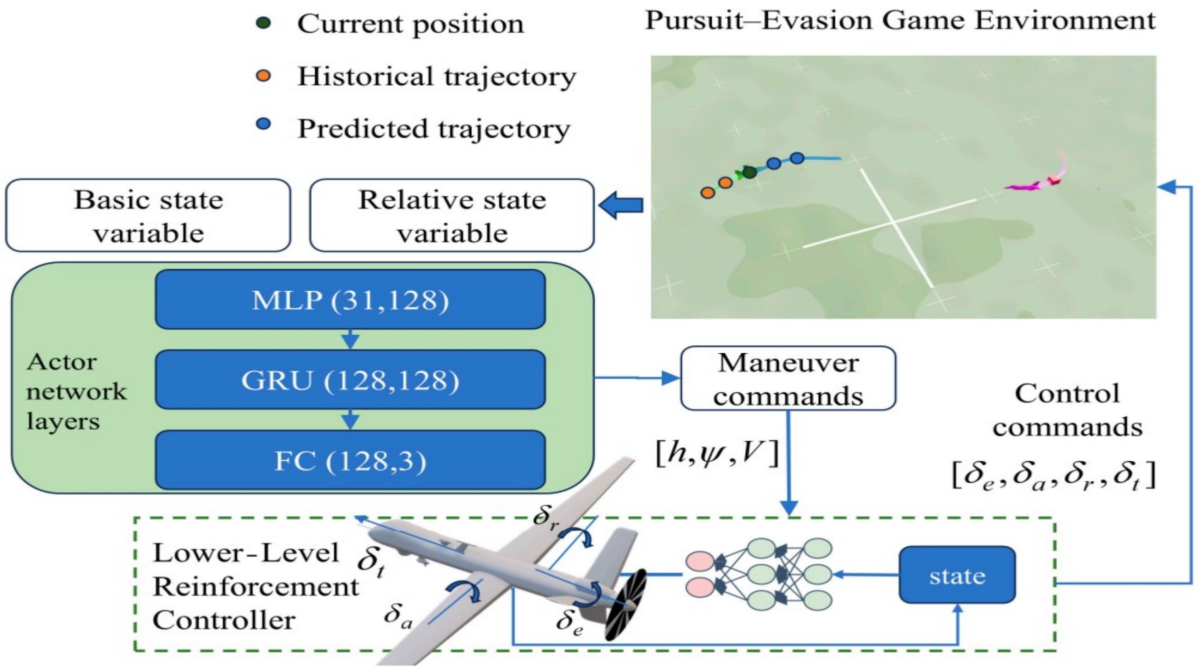


Figure 42: Schematic Diagram of Manoeuvring Layer Based on Trajectory Prediction and Hierarchical Reinforcement Learning. Source: PLAAF Engineering University[126]

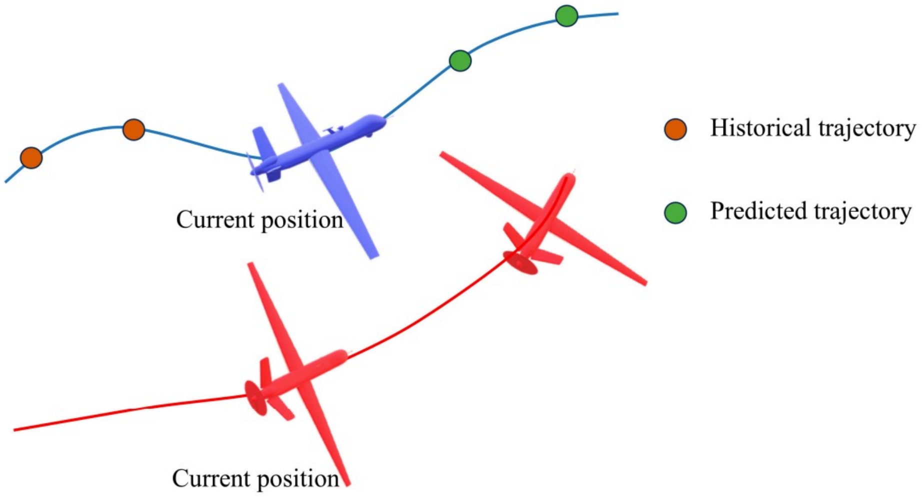


Figure 43: Schematic diagram of the pre-tracking
(Red UAVs are PLA, Blue UAVs are the opponent). Source: PLAAF Engineering University[127]

- **Flight control layer** controls a stable UAV flight, according to the manoeuvre commands, by adopting a stable gradient-assisted reinforcement learning flight controller (FC).

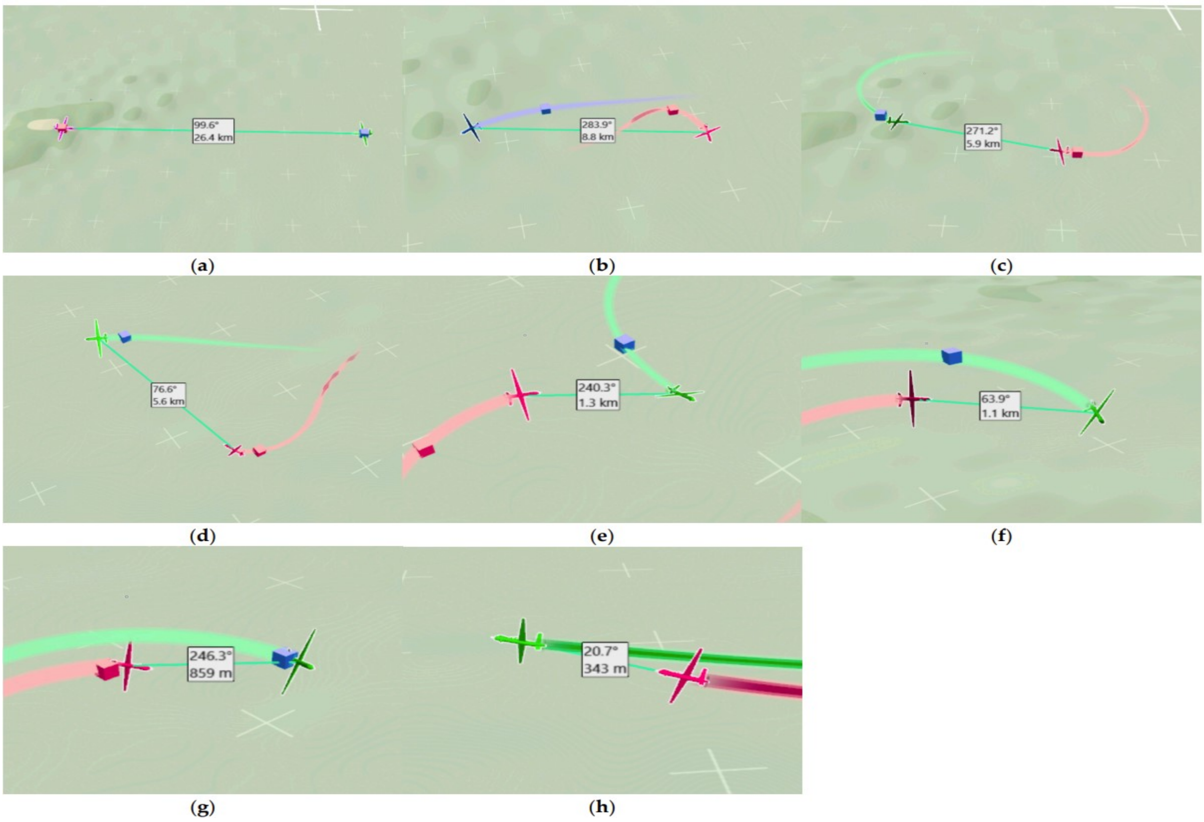


Figure 44: PLAAF's Screenshots of the pursuit–evasion game confrontation process
(a) 0 s; (b) 70 s; (c) 93 s; (d) 143 s; (e) 215 s; (f) 266 s; (g) 390 s; (h) 546 s
Source: PLAAF Engineering University[128]

The challenges identified by the PLAAF research team in multi-UAV pursuit–evasion games are quoted verbatim below:

> "(1) *Flight trajectory oscillation: Hierarchical RL is commonly used to decouple manoeuvre confrontation and flight control, but RL-based flight controllers (focus solely on reaching desired states without considering flight path smoothness) often induce violent trajectory oscillations during high-overload engagements, restricting practicality.*
>
> *(2) Poor scalability across UAV scales: Fixed network architectures of multiagent RL (MARL) methods (e.g., MAPPO, QMIX) require retraining for differentscale scenarios, and their win rates and training efficiency degrade sharply as the number of UAVs increases, due to credit allocation issues and exponential growth in sample/training time.*"

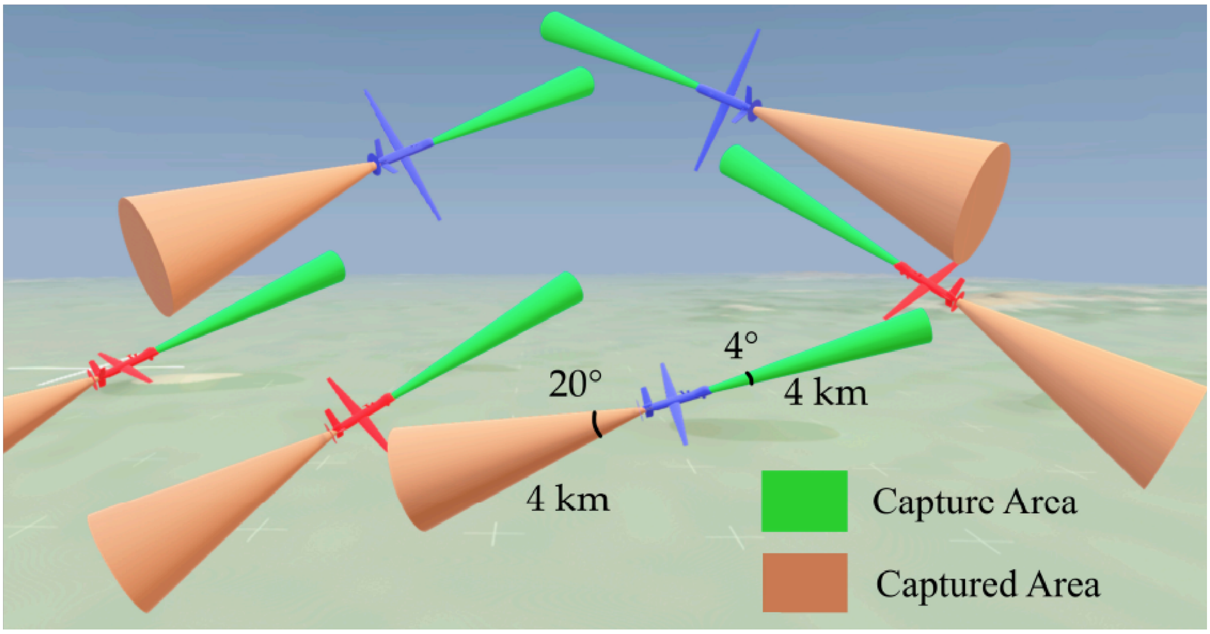


Figure 45: Schematic diagram of the PLAAF Research game scenario
(red UAVs are PLA's interceptor drones, blue UAVs are the opponent's intruding drones).
Source: PLAAF Engineering University[129]

The main findings and recommendations of the PLAAF paper are verbatim summarised as follows:

> "*(1) A modular hierarchical framework that decomposes multi-UAV pursuit–evasion into target allocation, manoeuvre decision-making, and flight control layers, resolving the scalability bottleneck of MARL methods. (2) A stable*

auxiliary gradient (SAG)-enhanced RL flight controller, which introduces angular acceleration constraints to eliminate trajectory oscillations without sacrificing control accuracy. (3) A trajectory prediction-guided hierarchical RL manoeuvre decision-making method, using polynomial fitting to predict opponent positions and shape pre-tracking rewards, significantly improving one-on-one confrontation win rates. (4) Dynamic target allocation algorithm based on situation advantage and threat level, with a dynamic value adjustment mechanism to achieve rapid, coordinated multi-target assignment and avoid resource concentration."

Secured Communication. The enhanced degree of combat cyber and EM interferences requires the various components of C-UAS architecture to have secured communication amongst themselves, with quantum-encrypted communication being available as one of the advanced technological options.

- **Encryption**. Advanced Encryption Standard (AES) is a symmetric block cipher for enhancing resistance to known cryptanalytic attacks. It operates on fixed block sizes of 128 bits and employs multiple rounds of substitution, permutation, and mixing to achieve confusion and diffusion. [130]
- **Authentication**. As C2 of various C-UAS architecture components including sensors and shooters is important, various militaries have advanced the various authentication techniques too to disrupt any data manipulation or poisoning attempts. [131]
    i) **Digital Certificates** assist in verification of the identity of devices thereby ensure that communication only trusted entities within the C-UAS architecture.[132]
    ii) **Challenge-Response Authentication** incorporates issuance of challenges by one party in form of a random code while the other party responds correctly using a shared secret thereby confirming legitimacy. [133]
    iii) **Hash-based Message Authentication Code (HMAC)** uses cryptographic hash functions and secret key to generate a unique code alongside the message. Any potential tampering is immediately flagged since every alteration to the data results in a mismatch. [134]

Software Defined Radio (SDR) Jammers. The advent of SDR for RF links in drones led to mirroring progression in C-UAS architecture through low-cost SDR jammers which can disrupt drone control and telemetry channels over distances of up to 5 km. [135]

Laser Air Defence (AD). Israel is topping up its 'Iron Dome' with 'Iron Beam'. Rafael Advanced Defence Systems is developing a short-range ground-based laser AD complemented by aerial one built by Elbit Systems. These are focussing on drones with aim being to enhance range, and reduce the time required to burn the target.[136]

AI Use Cases. There are many AI use cases in C-UAS architecture too:

- **Behavioural Analysis for Identification**. AI and ML algorithms analyse drones' flight patterns and behaviour, drones' characteristics, their responses to stimuli to differentiate between drones and birds and detect rogue drones.[137]
- **Transmission Signal Features**. A Chinese research paper of June 2025 has presented a novel algorithm which claims to detect and identify drones by leveraging transmission signal features. It has proposed to extract key transmission characteristics like bandwidth, power, duration, and interval time from the drone signals. The researchers having validated their algorithm on the DroneRF820[a] dataset claim that their algorithm can accurately capture the video transmission signals of UAVs. It reduces the likelihood of false alarms through enhanced robustness of the algorithm against noise thereby improving stability across various scenarios. The researchers, based on their experimental results claim that the algorithm can identify the signals of dualfrequency UAVs, like racing drones, within at least 200 ms. [138]

Drones Detection. A Russian volunteer group "Project Archangel", which trains UAV pilots for the Russian Ministry of Defence has asked for AI assistance to train a neural network to detect drones. They are collecting videos of complete varieties of drones (FPVs, FW, Bomber / quadcopters) from the observer's perspective. They appreciate that every video collected will improve the system's accuracy. [139]

Israel's Goshawk C-UAS Architecture. The prime example of operational use of AI for C-UAS in conflicts has been the IDF's use of Goshawk (predatory bird in Hebrew) which was developed by ROBOTICAN. This C-UAS system has specifically made for

[a] DroneRF820 (**https://pan.quark.cn/s/ae18fe3731da**), is a new Chinese dataset collected through dualband simultaneous monitoring to develop and validate detection methods. The database oBers high signal-to-noise ratio data based on RF signals from 8 common UAVs and their flight controllers.

security in urban areas with low risk and is claimed to have intercepted >260 Hamas sUAS till end 2024. Apropos, it incorporates a net effector to neutralize incoming threat drones instead of destroying. Goshawk utilizes and thus, prevents shrapnel risk particularly in civilian residential areas. It detects hostile drones through radar grid at specified ranges and then employs machine vision and AI-ML to examine the threat profile. Goshawk uses heuristic and metaheuristic algorithms to autonomously calculate the orbit of the target drone and thereafter plan the interception route. [140]

Shahed / Geran Series

The Iranian Shahed or Russian Geran series of one-way attack (OWA) / Kamikaze / Strike drones have incorporated most of the technological developments discussed above to evolve and remain as the most potent long-range strike threat to Ukrainian forces in conjunction with Russian ballistic and cruise missiles in deadliest salvo launches of more than 800. A table below has summarised the developments in various fields. It's an interesting progression of delta wing design of Iranian Shahed in to Geran-II incorporating most of the technologies to harden resilience against advancing Ukrainian C-UAS and EW measures while maintaining low-cost.

Technology	Technological Evolution of Shahed / Geran
GNSS / EW Resilience	CRPA in Geran-II
Payload	Trainable front camera for mid-route surveillance and terminal guidance / FPV style visual navigation
C-UAS Resilience against Interceptor Drones	a) Rear view camera for manoeuvring against interceptor drones b) 2 rear-facing PTM-3 anti-tank mines under wings to shoot interceptor drones
Warheads	Iranian 53.5 kg HE 2-stage penetrator; Enlarged to 92 kg HE 2-stage penetrator; Russian 50 kg thermobaric explosive; Enlarged to 90 kg thermobaric explosive; Russian 50 kg HE with incendiary effect
Aerial Battle	Geran-II modification to carry AA-8 APHID Air-to-Air Missiles to ambush and deter helicopters and light aircrafts sent to intercept drones aptly described by HI Sutton as "Hunted Becomes Hunter"
Communication	Use of Starlink antenna mounting on spine in Geran-II and Ukrainian mobile network
Engine Upgrade	Jet engine replaced piston engine of Geran-II in Geran-III for better speed

Table 3: Technological Evolution of Iranian Shahed to Russian Geran Drones. Source: HI Sutton[141]

RECOMMENDATIONS

While a series of monographs written by the author on drones and C-UAS in 2025 have covered a set of recommendations on each topic, the key recommendations here shall focus on the incorporation of key technology-related issues only.

Successful Variety of Drones. The key ongoing conflicts Israel-Iran-HamasHouthis and Russia-Ukraine and even other conflicts in Africa and West Asia have proven the importance of certain variety of successful variety of drones at various levels- Recce, FPVs, Multi-copter Bombers / Multi-Munition Dispenser System (MMDS), Deep and Middle strike Loitering Munitions (LMs) / Kamikaze drones, and Interceptor drones as elucidated below. These drones must be able to serve dual tasking i.e. Recce drones must be able to undertake EW simultaneously while the deep strike kamikaze drones like Russian Geran must do ISR and mapping enroute.

Combat Level	Type of Drone and Range	Key Technologies
Sub-tactical- Section to Battalion	FPV 25-60-80 km	OFC, Mesh RF network, AI-enablement
	Interceptor drones	Speed >400kmph
	Multi-copter bomber drones	Variety of munitions including thermobaric
Tactical- Brigade / Division	Middle Strike – LMs <200 km	
Operational- Corps / Group Army	Deep Strike / OWA —1500 km	Low-cost piston engine cardboard kamikaze drones, AAMs
Strategic – Command / Theatre	Deep Strike / OWA —2500 km	Low-cost piston engine cardboard kamikaze drones, AAMs
National	High Altitude Pseudonymous Satellite (HAPS)	Solar Charging
Common	ISR	Multi-sensor fusion, automatic target detection, recognition, identification & handing over to strike
	Decoys	

Table 4: Successfully Validated Drone Categories

Patents to Prototypes. One biggest hurdle to India's technology indigenisation is the inability of many promising Indian start-ups, defence industry particularly drones, and R&D organisations is to pursue completion of whole patenting procedure post filing. Even post successful filing of patent, a lot of understanding gap between industry and military remains and most innovations do nor successfully lead to prototyping and mass manufacturing. There is thus a need for the Indian government and military to handhold critical innovations particularly in drones and C-UAS and drive it from successful patent filing to rapid prototyping, induction, mass manufacture, doctrinal evolution and organisation structural upgradation. A campaign of "One Unit, One Collaborative Patent", "One Formation, One Finished Product" and "One Arm / Service, One Successful Induction" must be ruthlessly pursued annually.

Underground Tactical Drones Lab. This timed race from patents to prototypes have been expedited manifold by both Russian and Ukrainian sides. One key expediting factor has been the development of underground labs in the tactical battle area for undertaking unique innovations and testing them live during the battle. It's important for Indian military particularly Indian Army and border forces like BSF and ITBP to preferably have tunnelled / underground drones cum UGVs lab at brigade / division level for both defensive and offensive formations. A mobile lab could also be incorporated if underground is not feasible in some cases.

It's important to learn from Ukrainian lessons which maybe a bit additional propaganda but surely the advice is worth every penny. Parts of a Brave 1 LinkedIn post is reproduced below to understand their war time perspective of their commanders and military personnel on drones' labs during one of the panel discussions conducted[142]: -
"*It's no secret that almost every Ukrainian UAV unit now has military labs where soldiers can modify or re-equip drones to meet their specific needs. In some units, these have evolved into real R&D centres, where the military works jointly with manufacturers to create innovative solutions for defence against the Russian invasion – Brave 1 Group.*

> *"The mission of R&D in a unit is to formulate and constantly update the product requirements for manufacturers, as well as engage in joint quality control. It's a continuous cycle: we test, we launch, and immediately move on to the next*

iteration." — "Phoenix," representative of the National Guard of Ukraine special unit "Lasar's Group."

"There is no point in making a 'million' identical drones. Four to five technological iterations needed at the front change within a year, and the lion's share of them quickly loses relevance." — "Balistyka," Head of R&D for the 412th Unmanned Systems Brigade

"We need mass-produced, simple—not specialized—solutions. We have a large part of the ground forces, which, unfortunately, many forget about. We need simple, sometimes even 'wooden' solutions—something you can quickly assemble on the spot, and it will work." — "Irlandets," Deputy Commander of UAV Systems at 59th Separate Assault Brigade

"I never ask manufacturers what product they have. I ask what they are working on, and I forecast how it can be applied. Maybe not today, maybe the day after tomorrow, but it will bear fruit." — "Yankee," UAV Systems Officer, 68th Jaeger Brigade."

NAVIC and GAGAN. Indian NAVIC is trailing behind Chinese and other global GNSS constellations and even Japan on multiple accounts – number of healthy satellites, fielding of augmentation system, number of compatible GNSS receivers, regional coverage, revenue generation, software and APIs etc. Hence, it's absolutely essential for Indian drones to have assured, reliable indigenous GNSS coverage.

Data Collection for Algorithmic Superiority. Any AI software or application is as good as its data. Israel defence forces (IDF) claim that they have "*mobilised entire defence ecosystem and deployed tens of thousands of autonomous systems across the battlefield — from drone swarms to agile ground robotics distributed across vast areas…been able to collect "tens of thousands of hours" of flying drone operations to "thousands of hours" of ground manoeuvre robotics data*" during the last two years of war in Gaza. [143] Indian military has vast operational experience in all types of complicated terrains across all types of operations. Thus, Indian operational and training data, if harnessed correctly, can facilitate deep machine learning and create stronger algorithms in a human-machine collaborative environment where algorithmic superiority is going to matter significantly. Indian military needs to shun age old concept of ~~"We Can't Share Data"~~ and promulgate data harnessing and sharing policies both internally and externally with the government, academia, R&D organisations and drones' industry.

Joint Mapping Exercise. With limited NAVIC coverage and reliability of GNSS across borders, there is an urgent need for DIA, DIPAC, Operations Directorates of various services and border forces, NTRO, Mapping agencies, particularly Survey of India, Remote Sensing Departments of border states, multitude of Space-based Remote Sensing Data Aggregator firms and Drones' Firms in India to fuse their data clouds and stitch maps / DEMs together for AI-enabled drones to fly across in GNSS-denied environments.

Multi-Domain UVs Integration through Intelligentisation. An important technological development is to integrate UVs and munitions across multiple domains- UGVs on land, drones / sUAS in air, USVs in sea, UUVs sub-surface, development into swarms and further incorporation of cruise and ballistic missiles for multi-domain precision strikes. The integration of transport and logistics UGVs / drones and hybrid UVs spanning multiple domains requires integration across the length and breadth of the battle-space for a complete variety of combat and combat support tasks. Intelligentisation of the complete process, whether human-machine for Manned-Unmanned Teams or machine-machine collaboration for swarms, is thus essential and must be undertaken immediately.

Joint AI Division at HQ IDS. The C4I and Cyber Defence Directorate of IDF has created a new division 'Bina', which is fully devoted to AI and is working to ensure multi-Domain operational gain. [144] The HQ IDS, in conjunction with DRDO's CAIR and Niti Aayog, must have a functional Joint AI division to harness the full potential of AI for both multi-domain and multi-dimensional operations.

Start-Up Unit. On the lines of IDF's top-secret start-up unit 'Yiftah' comprising scientists and engineers, the Indian military must build a similar combat unit which ensures collaborative technological development at a rapid pace on the front line, remaining ahead in the technological cat and mouse game. It should be able to harness the collaboration between the Indian military's R&D set-ups at various HQ, Army Base Workshops, civil start-ups, DRDO / ISRO and other R&D organisations, etc., while remaining ahead of the learning curve by bridging the gap between the military, academia and industry. This pioneer unit by inculcating innovative environment can accelerate the Indian military's technological cycles of "innovative path-breaking development – design and prototype development- combat testing – doctrinal upgradation– design modification – combat testing – battlespace adaptation."

War Changers. Whether the Israeli Start-Up unit model is feasible or not, Ukrainian military's another innovative concept of "War Changers" recruitment is certainly worth emulation. Indian military needs to search, select/attract and hire such War Changers at Service, Command and Corps HQ who are passionate to evolve, execute and deliver combat force multiplier techniques and concepts for the nation and the military. The Ukrainian 'Brave1' defence cluster's definition of War-Changers is

> "*A Specialist who helps Ukrainian Military to win through technology: analyse frontline needs with the military; submits requests to manufacturers for innovations; searches the latest technological solutions; and supports grant and competition programmes*"[145].

Unit Level Technological and Innovation Bonuses. With extremely adverse force ratios, asymmetric manufacturing capacities particularly artillery munitions and amidst dwindling US military aid, the Ukrainian military had to evolve innovative means to motivate its military. It came up with a competitive system of "Army of Drones Bonus System" which has expanded to now about 400 plus participating drone units. The basic concept is of linking incentives to proven battlespace successes. In an "Amazonfor-war" Ukrainian online store controlled by Brave1, Ukrainian successful strikes on Russian forces get award points. These award points are thereafter exchanged by the units for procuring 100 plus variety of drones, UGVs and other drones' material from the Brave1's online store. Under this points-for-kills system, killing Russian infantry earns 6-12 points; killing drone operator gets 25 points; and interestingly using a drone / UGV to capture a Russian soldier alive attracts 120 points. Similarly, this points-forkills approach has now been extended to artillery units to exchange their successful firepower engagements to purchase new arms. Another interesting technological advancement is the extension of this system to the reconnaissance units also called "Uber targeting" for spotting enemy targets. From Ukrainian perspective, it is described as "*You basically drop a pin on the map like you would drop yourself on an Uber map for a taxi, but instead of the taxi a drone from* *another unit hits the target*". While logistics teams are earning points for using autonomous UVs rather than manpower to resupply the frontlines, the most interesting aspect is the recent extension of awards system to the use of technology and AI. Apropos, AI usage for target selection and or precise target lock-on during the last moments of a drone's trajectory are being incentivised. The system has now extended the bonus points for integrating new technologies and innovation too. [146] It is another interesting idea which can be applied on Indian GeM portal with suitable modifications for incorporating the military units, para-military, R&D organisations, civil industry and academia on a common competitive platform both during peacetime training and trials and during war time.

Unmanned Force. The last four years of war experience has made both Russian and Ukrainian militaries create a specialised Unmanned Force separately to ensure domain super specialisation. While the combat companies have unmanned squads, battalions have platoons, brigades have companies and division / Corps/ field army have unmanned battalions, a separate force ensures specialised training and special strike operations in contested zones and deep strike areas. Most importantly, this force is significantly contributing towards the technological development of drones in the combat battle-space to match the speed of the technological cat and mouse game between opposing forces and between drones and C-UAS platforms. While the requirement of such specialised service already exists for the space, cyber and cognitive/ information domains on lines of PLA's Aerospace, Cyberspace and Information Support Forces, Indian military must ensure domain specialisation and super-specialisation in certain technologically intensive domains and battlespace dimensions.

Low-Cost Long-Range Strike Drones. Chinese have been quick to build their own array of very low-cost modifications of Iranian Shahed and Russian Geran series of deep strike drones. The geography of India and its neighbours particularly along India's Northern borders necessitates the urgent development of indigenous version of low-cost delta-wing shaped piston-engine based kamikaze drones capable of saturating enemy's AD and striking 1000-2500 km across the borders. These drones must adopt all low-cost technological successes to ensure rapid production of at least 500 such drones normally and more than 1500 during surge period.

Propulsion Systems. The recommendations on propulsion system would be to design a drone with both conventional and VTOL capabilities. For energy efficiency and optimisation, VTOL should only be used wherever space is extremely limited for take-off and landing. A multi-tilt rotor configuration is an ideal solution. The focus must clearly be on propellers and batteries for high-altitude areas.

Mass-Production Catering for Fast-pace Technological Upgrades. Annual massproduction of millions of drones and its components catering for rapid technological upgrades and scaling up is no more fiction but a stark reality. It must be noted and clearly understood that if US is struggling to keep pace with China, Russia and Ukraine in the field of sUAS, India needs to gallop much faster in this domain. Hence, dualpurpose mass production of drones is the only solution. 'DRONES SHAKTI' must be an integral pillar for 'SURAKSHIT AND VIKSIT BHARAT' as also the mainstay for 'Mission SUDARSHAN CHAKRA'. This indigenous capacity should easily blend itself to the immense civilian drones' demand in our neighbouring countries for agriculture and other civilian tasks.

Key Priorities. Whether it was lessons from Operation SINDOOR or the daily lessons from employment along India's northern borders, Indian military needs to priorities its drone requirements to ensure failproof communications, power supply/batteries which are operational in high-altitude areas and extremely cold conditions and most importantly the desired range to hit beyond Tibet and Xinjiang at lowest costs and maximum quantity to overcome PLA's AD threshold.

Components Market. A latest article for RUSI, "*Drones Win Battles, Components Win Wars*", by Mirko Niederkofler, concluded that "*Ukraine's drone success holds a deeper lesson for NATO: technological sovereignty at the component level is essential to future battlefield dominance*" [147] Apropos, Ukrainian Brave 1 Cluster has established a Components Market now. The Indian military needs to go beyond fully packaged drones to drone components since most Indian startups are working on drones' components. A famous Indian proverb "Boond Boond Se Saagar Banta Hai" is most apt here. Chinese completely dominate global drones' component today but they didn't do so few decades back and thus started from scratch at some time. Indian drones' ecosystem needs to be revitalised timed steps wise to keep indigenising each and every component from the easiest to the most difficult one. The components vision must be clearly known to all and ruthlessly executed.

TEAM BHARAT Solutions. Amidst the global geopolitical and military chaos, time is ticking at fast pace for India and its military. The existing turfs and siloed compartments will ensure India loses the golden opportunity which is still available. Its time for wholeof-nation approach integrating and fusing all services, para-military and police forces, all ministries, R&D organisations and academia, public, private and start-ups in defence industry. When the requirement is of mass production of lakhs of drones, L1 system or just indigenised L1 will not work. The silos need to be broken up so that the complete capacity of Indian drones and C-UAS ecosystem needs to be stitched as "TEAM BHARAT" to penetrate the Chinese AD systems' threshold daily both quantitatively and qualitatively in technology. Simultaneously, multi-dimensional CUAS grid as an integral part of Mission Sudarshan Chakra must withstand the onslaught of millions of thousands of Chinese drones daily.

CONCLUSION

"*To keep pace with the speed of modern battlefield innovation, NATO must treat drones not as finished products to be acquired but as evolving architectures to be mastered. Qualification pathways for dual-use technologies, faster integration timelines, modular certification regimes and persistent battlefield feedback loops must all become standard. The goal is not just deterrence, it is to ensure that NATO remains innovation-ready in the domain of drone warfare, with forces capable of adapting as fast as the battlefield demands.*"

- Mirko Niederkofler[148]

Technology has always enhanced standoff ranges of lethal platforms while simultaneously strengthening survivability. Technological advancements in the drones' domain, as witnessed in the ongoing conflicts, are thus gradually expanding the kill zones and the contested zones. While the ever-compressing kill-chains and dynamically evolving kill webs are expanding the non-contact contestation zones, they are increasingly expanding the combat dispersal in the contact battlefield. As combat is gradually progressing from the conceptual contour of “Tactics Determining Technology” to technology-infused battlespace wherein “Technology Determines Tactics”, Indian defence forces and the paramilitary need to upgrade training and doctrine. The organisational structures must be reformed to transform and adapt to an evolving technological paradigm in the domain of drones and C-UAS. To conclude, technology has always been and will remain a key core combat capability. Mirko’s article title can thus be aptly expanded

“*Drones Win Battles,*
But Talent and Components Win Wars;
Industrial Capacities and Rapid Prototyping Sustain Wars,
But Technological Indigenisation, Sovereignty and Battlespace Innovation are the strategic essentials for dominating the combat battlefield in the future”.

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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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