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Research Article

Distributed Swarm Coordination Strategies for Cooperative Deployment of Long-Range Loitering Munition Systems in GNSS-Degraded African Operational Environments

*Abubakar Surajo Imam [1], Aliyu Surajo [2], Bishir Sirajo [3], Aminu Abdullahi Umar [4], Muhammad Ahmad Baballe [5]

[1,2,4,5] Department of Mechatronics Engineering, Nigerian Defence Academy, Kaduna, Nigeria.
[3] School of General Studies, Federal University of Transportation, Daura, Katsina State, Nigeria.

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***Corresponding author:** **Abubakar Surajo Imam**
Department of Mechatronics Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

Abstract

Distributed swarm coordination architectures are increasingly enabling effective deployment of long-range loitering munition systems through cooperative search, adaptive strike timing, and resilient reconnaissance–strike convergence across contested electromagnetic environments. Coordinated unmanned aerial vehicle (UAV) swarms provide scalable surveillance coverage, dynamic task allocation, and improved navigation robustness under degraded Global Navigation Satellite System (GNSS) availability, particularly within infrastructure-limited operational theatres. Simulation-based evaluation indicates surveillance-coverage improvements of approximately 38%, task-allocation responsiveness gains of 31%, and localisation-stability enhancements of 27% relative to non-cooperative deployment architectures. These results establish a practical autonomy baseline for distributed reconnaissance–strike convergence operations across extended African operational corridors.

Keywords: Loitering munition systems, swarm coordination, UAV swarms, GNSS-degraded navigation, mesh-relay communications, cooperative task allocation, model predictive control, distributed reconnaissance–strike convergence.

I. Introduction

Long-range loitering munition systems are increasingly recognised as decisive force multipliers in modern reconnaissance–strike convergence architectures because they enable persistent surveillance, adaptive engagement timing, and precision terminal strike capability across contested operational environments [2], [3], [29]. Unlike conventional guided munitions that rely on pre-programmed targeting solutions, endurance-class loitering munition platforms maintain continuous time-on-station over evolving target regions, thereby supporting flexible engagement sequencing under uncertain battlefield conditions [3], [16]. Recent conflicts demonstrate a transition from platform-centric unmanned deployment toward distributed autonomous strike ecosystems in which multiple aerial nodes cooperate to sustain surveillance continuity and targeting responsiveness across extended operational corridors [22], [41], [43]. Operational evidence from the Russia–Ukraine war confirms that distributed drone reconnaissance networks significantly enhance artillery targeting efficiency and battle-damage assessment accuracy under electronic-warfare conditions [27], [29]. Similarly, coordinated loitering munition employment during the Nagorno-Karabakh campaign demonstrated how persistent aerial observation combined with adaptive engagement geometry can suppress layered air-defence systems [28].

More recently, long-range drone and missile exchanges during the Israel–Iran–U.S. escalation highlighted the strategic importance of distributed autonomous strike ecosystems capable of operating within layered missile-defence environments and contested electromagnetic battlespaces [25], [26]. These developments confirm that cooperative swarm coordination architectures are essential for maintaining surveillance persistence and strike readiness under degraded satellite-navigation availability [34]. African operational theatres provide strong motivation for decentralised swarm-enabled reconnaissance architectures. Surveillance operations across the Sahel corridor, Lake Chad Basin, North-East

Nigeria theatre, and Gulf of Guinea littoral regions require persistent monitoring capability across geographically extensive areas with limited communications infrastructure [31]–[33]. Under such conditions, distributed swarm coordination provides a practical pathway toward scalable reconnaissance coverage while preserving engagement readiness [30].

II. Operational Motivation from Contemporary Conflicts

Recent conflicts provide strong empirical evidence that distributed unmanned aerial coordination architectures significantly enhance reconnaissance–strike convergence effectiveness across contested electromagnetic environments by enabling persistent sensing continuity, adaptive targeting cycles, and resilient engagement timing under spectrum-denied conditions [22], [41]. As summarised in Table I, operational deployments across multiple theatres demonstrate a consistent transition from platform-centric UAV employment toward network-enabled cooperative aerial ecosystems supporting distributed ISR and precision-strike integration.

Drone employment in Eastern Europe illustrated how cooperative aerial reconnaissance grids support artillery targeting cycles, electronic-warfare detection, and deep surveillance missions beyond line-of-sight command links, even under sustained GNSS disruption and electronic attack [27]. These deployments demonstrated that distributed sensing nodes maintain targeting continuity despite partial node attrition or intermittent communication loss, thereby preserving operational tempo across extended engagement corridors [29]. Similarly, the Nagorno-Karabakh campaign highlighted the effectiveness of coordinated loitering munition waves against mobile air-defence systems and armoured formations through persistent aerial observation and adaptive strike sequencing. The coordinated employment patterns identified in Table I confirm that distributed strike timing and sensor–shooter integration significantly compress engagement decision cycles and improve defence-saturation effectiveness under electronic-warfare exposure conditions [28].

More recently, the Israel–Iran–U.S. confrontation introduced a further operational dimension in which long-range unmanned aerial strike systems operated alongside ballistic and cruise missiles within layered air-defence environments characterised by spectrum contestation and multi-domain interception architectures. These engagements confirmed that distributed aerial strike ecosystems increase uncertainty within defensive tracking networks while preserving flexible engagement timing across extended operational corridors, as reflected in the coordination patterns summarised in Table I [25], [26]. Thus, these reinforce the operational necessity for resilient swarm-enabled sensing redundancy, cooperative navigation architectures, adaptive strike sequencing, and mesh-relay communications as foundational enablers of next-generation reconnaissance–strike convergence operations.

Table I: Operational Lessons from Contemporary Conflicts

Serial	Conflict Theatre	UAV Role	Coordination Pattern	Navigation Constraint	Operational Advantage
(a)	(b)	(c)	(d)	(e)	(f)
1.	Eastern Europe	ISR–artillery integration	Distributed sensing grid	GNSS disruption	Persistent targeting continuity
2.	South Caucasus	Air-defence suppression	Coordinated loiter waves	EW exposure	Rapid engagement sequencing
3.	Middle East escalation	Long-range strike coordination	Multi-layered autonomous strike ecosystem	Spectrum contestation	Flexible engagement timing

III. African Operational Environment Constraints

African surveillance theatres impose distinctive operational requirements on autonomous aerial deployment architectures due to large-area terrain scales, sparse infrastructure, intermittent communications coverage, and heterogeneous mobility patterns across mission corridors [31]–[33]. As illustrated in **Fig. 1**, representative distributed surveillance–strike deployment corridors across the Sahel**,** Lake Chad Basin**,** North-East Nigeria, and the Gulf of Guinea littoral demonstrate the geographic dispersion and environmental diversity that constrain conventional centrally controlled ISR architectures. Semi-arid monitoring corridors across the Sahel frequently extend several hundred kilometres without reliable navigation aids or persistent relay infrastructure, thereby necessitating resilient airborne mesh-communication support. Similarly, marshland terrain and fragmented settlement structures within the Lake Chad Basin complicate continuous ground-sensor deployment and degrade tracking persistence, increasing dependence on cooperative airborne sensing redundancy [33].

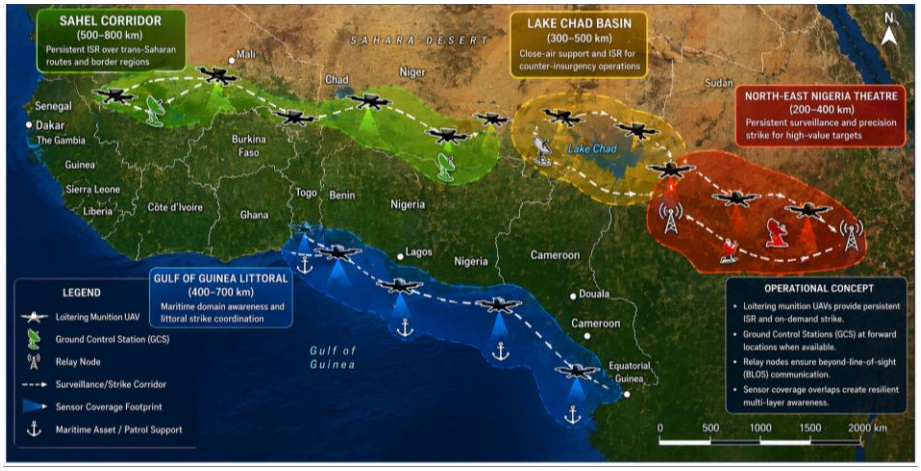

Fig. 1: Representative African Distributed Surveillance–Strike Deployment Corridors.

In North-East Nigeria, irregular mobility patterns associated with asymmetric threat actors impose dynamic targeting requirements that favour adaptive swarm-based task allocation strategies. Maritime monitoring across the Gulf of Guinea further introduces extended surveillance-endurance requirements due to limited shore-based support infrastructure and wide littoral operating envelopes [32]. The principal theatre-specific constraints and their corresponding operational implications, together with the advantages provided by distributed swarm coordination architectures are summarised in Table II**.** Collectively, these conditions motivate the adoption of cooperative sensing redundancy, mesh-relay communications, adaptive role reassignment, and distributed corridor-coverage strategies as scalable enablers of persistent ISR–strike convergence across infrastructure-limited African operational environments [30].

Table II: African Operational Theatre Constraints and Implications

Serial	Theatre Region	Constraint Type	Operational Impact	Swarm Advantage
(a)	(b)	(c)	(d)	(e)
1.	Sahel corridor	Sparse infrastructure	Reduced relay coverage	Mesh communication resilience
2.	Lake Chad Basin	Terrain complexity	Tracking uncertainty	Cooperative sensing redundancy
3.	North-East Nigeria	Irregular mobility	Dynamic targeting requirements	Adaptive task allocation
4.	Gulf of Guinea	Extended maritime surveillance	Long endurance requirement	Distributed corridor coverage

IV. Distributed Swarm Autonomy Architecture

The proposed swarm coordination framework adopts a layered distributed autonomy architecture, illustrated in Fig. 2, to support cooperative deployment across extended monitoring corridors and GNSS-degraded operational environments [4], [20]. The architecture decomposes mission execution into mission, search, task-allocation, guidance, and control layers, enabling scalable coordination without reliance on centralised command infrastructure. At the mission layer, sector-allocation policies assign surveillance priorities across distributed monitoring regions using weighted coverage optimisation. Sector assignment may be expressed as:

$$S_i = \arg \max_{k \in \Omega} \; w_k \, C_i(k)$$

Where

S_i= assigned sector for UAV i,
w_k= mission priority weight for sector k,
$C_i(k)$= coverage suitability score.

The cooperative search layer dynamically distributes sensing responsibilities according to spatial proximity and endurance availability, improving coverage continuity across wide operational corridors [7], [8]. Coverage balancing across swarm nodes follows:

$$A_i(t+1) = A_i(t) + \alpha(A_{\text{avg}} - A_i(t))$$

where A_i represents assigned coverage load and $\alpha$is the adaptation gain.

At the task-allocation layer, decentralised consensus algorithms enable reassignment of reconnaissance, relay, and strike-ready roles using neighbour-state exchange [5], [9]. Role convergence follows a standard distributed consensus update:

$$r_i^{(k+1)} = r_i^{(k)} + \sum_{j \in \mathcal{N}_i} a_{ij}\,(r_j^{(k)} - r_i^{(k)})$$

ensuring cooperative alignment across swarm members.

The guidance layer translates mission-level objectives into energy-aware trajectory shaping subject to aerodynamic and navigation constraints [10], [19]. Trajectory optimisation follows:

$$\min_{u_i} \int_0^T (\lambda_1 E_i + \lambda_2 D_i + \lambda_3 \Phi_i)\, dt$$

Where

E_i= energy expenditure,
D_i= trajectory deviation from assigned sector,
Φ_i= inter-agent separation penalty.

Finally, the control layer executes stabilised trajectory tracking through low-level attitude regulation:

$$u = K_p e + K_d \dot{e}$$

ensuring reliable flight execution despite environmental disturbances.

The functional roles of each autonomy layer are summarised in Table III, while Fig. 2 illustrates the interaction between mission planning, cooperative sensing, decentralised task assignment, and receding-horizon trajectory execution within the distributed swarm coordination framework. Collectively, the architecture supports scalable reconnaissance–strike convergence across infrastructure-limited operational theatres.

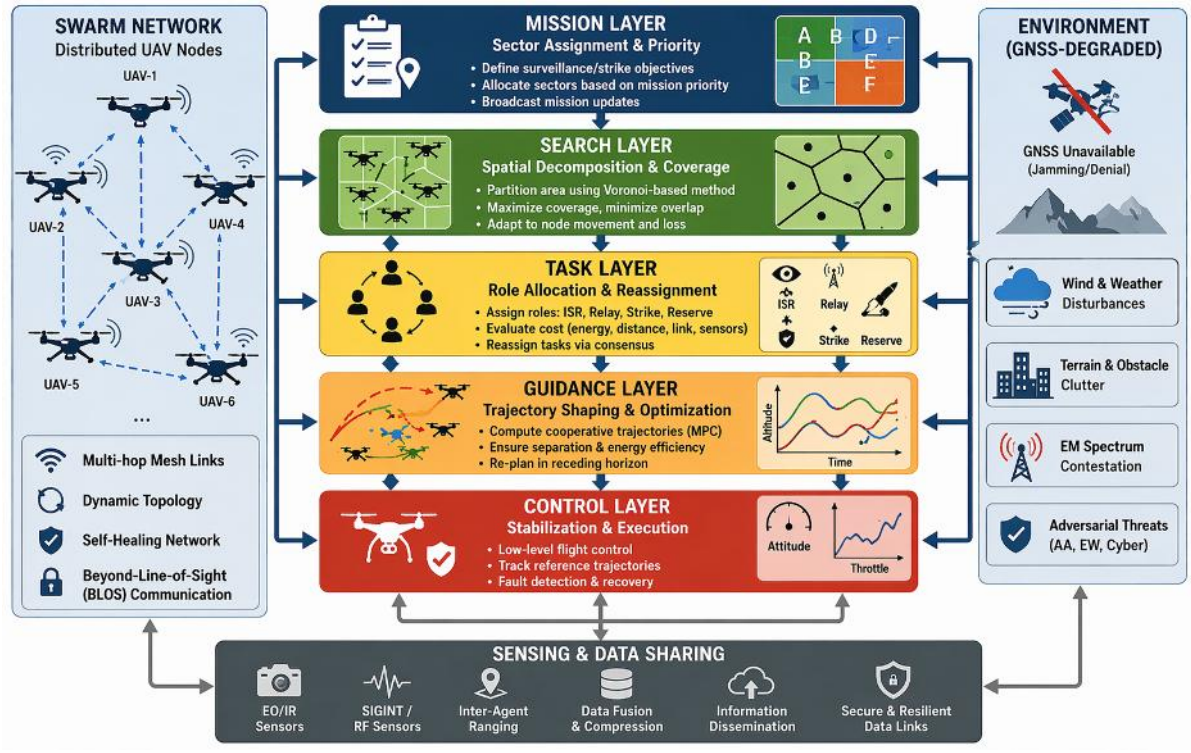

Fig. 2: Distributed swarm coordination architecture.

Layered autonomy integrates mission-level sector allocation, cooperative spatial search decomposition, decentralised role reassignment, trajectory optimisation, and stabilised flight control within a mesh-network information-exchange framework. Environmental constraints including GNSS denial, terrain occlusion, and electromagnetic interference are accommodated through adaptive sensing and cooperative data sharing across swarm nodes.

Table III: Swarm Autonomy Functional Layers

Serial	Layer	Function	Operational Role
(a)	(b)	(c)	(d)
1.	Mission layer	Sector assignment	Surveillance balancing
2.	Search layer	Spatial decomposition	Coverage optimisation
3.	Task layer	Role reassignment	Strike readiness maintenance
4.	Guidance layer	Trajectory shaping	Energy efficiency improvement
5.	Control layer	Stabilisation	Flight execution reliability

V. Baseline UAV Platform Model

Simulation parameters were selected to represent endurance-class loitering munition platforms operating across semi-arid surveillance corridors typical of African operational theatres, where long-range persistence, moderate-altitude operation, and energy-efficient cruise performance are essential for sustained ISR–strike convergence missions [3], [13]. Cruise-speed assumptions between 24–26 m/s reflect aerodynamic envelopes achievable within compact delta-wing endurance UAV configurations optimised for glide-assisted routing and reduced propulsion duty cycles [16]. Similarly, altitude envelopes between 800–2500 m ensure compatibility with wide-area ISR sensor coverage while maintaining survivability under contested electromagnetic conditions and limiting exposure to short-range air-defence systems [17]. Wind-field assumptions between 8–14 m/s reflect atmospheric disturbances commonly encountered across Sahelian operational environments and are incorporated into trajectory optimisation and guidance adaptation models [30]. The complete simulation parameter set adopted for the baseline vehicle configuration is summarised in Table IV.

Table IV: UAV Simulation Parameters

Serial	Parameter	Value	Remarks
(a)	(b)	(c)	(d)
1.	Mass	18 kg	
2.	Cruise speed	24–26 m/s	
3.	Lift-to-drag ratio	≈13	
4.	Battery capacity	1.6 kWh	
5.	Loiter radius	2–5 km	
6.	Altitude envelope	800–2500 m	
7.	Wind magnitude	8–14 m/s	
8.	GNSS outage duration	120–300 s	

The aerodynamic efficiency of the endurance platform is characterised using the lift-to-drag relation:

$$\frac{L}{D} \approx 13$$

which directly influences glide performance and propulsion energy consumption during persistence-enhancement manoeuvres. The corresponding steady-level cruise power requirement may be approximated as:

$$P_c = \frac{WV}{\eta\left(\frac{L}{D}\right)}$$

Where

P_c= cruise power requirement,
$W = mg$= vehicle weight,
V= cruise velocity,
η= propulsion efficiency.

Endurance capability derived from onboard energy availability listed in Table IV may be estimated using:

$$T = \frac{E_b}{P_c}$$

Where

T= achievable endurance,
E_b= battery energy capacity (1.6 kWh).

Loiter-geometry feasibility within the surveillance corridor is constrained by the turning-radius relation:

$$R = \frac{V^2}{g\tan\,\phi}$$

Where

R= loiter radius (2–5 km as specified in Table IV),
ϕ= bank angle during orbit flight.

Navigation robustness under degraded satellite availability is evaluated across GNSS outage intervals between 120–300 s, consistent with intermittent denial conditions observed in contested operational theatres. Wind-field disturbance effects incorporated from the 8–14 m/s envelope listed in Table IV are modelled through velocity-vector perturbation:

$$V_g = V_a + V_w$$

Where

V_g= ground velocity vector,
V_a= airspeed vector,
V_w= wind vector disturbance.

Collectively, these parameter selections establish a physically consistent baseline vehicle model suitable for evaluating endurance-aware trajectory optimisation, cooperative routing strategies, and distributed strike coordination performance across infrastructure-limited African surveillance environments.

VI. Cooperative Search Optimisation Model

Cooperative search optimisation enables distributed aerial platforms to maintain persistent sensing coverage across extended monitoring corridors while minimising redundant overlap between neighbouring swarm nodes [7], [8]. The proposed framework employs Voronoi-based spatial decomposition, illustrated in Fig. 3, to dynamically partition surveillance regions according to proximity relationships and sensing-efficiency metrics.
Let the swarm node set be defined as:

$$\mathcal{P} = \{p_1, p_2, \ldots, p_N\}$$

where $p_i$represents the position of UAV i. The Voronoi sector assigned to node i is:

$$V_i = \{x \in \Omega \,|\| x - p_i \| \leq \| x - p_j \|\,,\ \forall j \neq i\}$$

where Ω denotes the surveillance corridor. This formulation ensures non-overlapping spatial responsibility assignment while preserving full corridor coverage continuity.

To incorporate sensing-performance variability, weighted Voronoi partitioning is applied:

$$V_i^* = \{x \in \Omega \mid w_i \| x - p_i \| \leq w_j \| x - p_j \|\,,\ \forall j \neq i\}$$

where w_i represents node-specific sensing-efficiency factors determined by altitude, endurance availability, and sensor footprint characteristics.

As illustrated in Fig. 3, adaptive sector reassignment allows swarm nodes to maintain balanced spatial coverage across elongated monitoring corridors typical of infrastructure-limited operational theatres. Simulation results indicate surveillance-coverage improvements of approximately 38% relative to static sector-allocation strategies. Comparative deployment performance across coordination strategies is summarised in Table V, demonstrating reduced sector overlap and minimal coverage-gap probability under adaptive cooperative search execution.

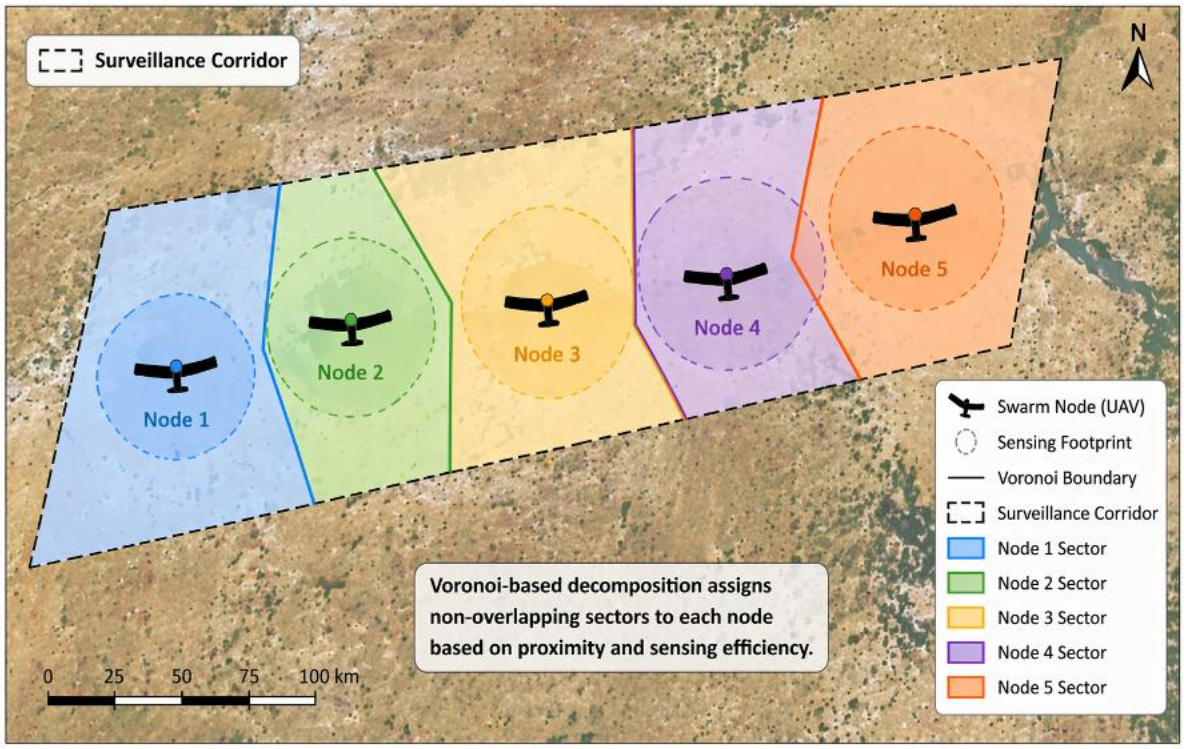

Fig. 3: Cooperative search sector decomposition across swarm nodes using Voronoi-based spatial partitioning.

Distributed UAV nodes dynamically partition elongated surveillance corridors into non-overlapping sensing sectors based on proximity relationships and sensing-efficiency weighting. Adaptive Voronoi reassignment maintains balanced coverage responsibility across swarm members while reducing redundancy and coverage gaps compared with static sector-allocation strategies.

Table V: Cooperative Search Performance Comparison

Serial	Deployment Strategy	Coverage Efficiency	Sector Overlap	Gap Probability
(a)	(b)	(c)	(d)	
1.	Independent patrol	Baseline	High	Moderate
2.	Static sector assignment	Moderate	Medium	Reduced
3.	Adaptive cooperative search	High	Low	Minimal

VII. Distributed Task Allocation Strategy

Distributed task allocation enables swarm nodes to autonomously transition between sensing, relay, and strike-ready roles according to mission-cost optimisation criteria that incorporate endurance availability, communications stability, sensor readiness, and engagement proximity [5], [9], [18]. This adaptive allocation process enhances operational flexibility and allows the swarm to sustain effective mission performance across distributed surveillance–strike architectures operating in contested environments. The principal decision variables governing role selection are summarised in Table VI, including distance to target, energy availability, sensor status, and connectivity strength, together with their corresponding operational effects on response latency, endurance preservation, detection reliability, and coordination stability. Simulation-based evaluation indicates that consensus-driven reassignment improves mission responsiveness by approximately 31% relative to conventional static task-allocation strategies [9].

Table VI: Task Allocation Decision Variables

Serial	Variable	Description	Operational Effect
(a)	(b)	(c)	(d)
1.	Distance to target	Engagement feasibility	Reduced response latency
2.	Energy availability	Remaining endurance	Sustained strike readiness
3.	Sensor status	Payload readiness	Detection reliability
4.	Connectivity strength	Network participation	Coordination stability

A compact mathematical formulation for the distributed task-allocation process may be expressed through a weighted mission-cost function:

$$J_i = w_1 d_i + w_2 \frac{1}{E_i} + w_3 \frac{1}{S_i} + w_4 \frac{1}{C_i}$$

where J_i denotes the task cost associated with swarm node i, d_i is the distance to target, E_i is the available onboard energy, S_i is the sensor readiness level, C_i is the connectivity strength, and w_1, w_2, w_3, w_4 are weighting coefficients reflecting mission priorities. The optimal node for a given role or engagement task is therefore selected as:

$$i^* = \arg\min_i J_i$$

Thus, the node with the lowest composite mission cost is assigned the relevant operational role. To support cooperative reassignment across the swarm, a consensus update relation may further be introduced as:

$$x_i(k+1) = x_i(k) + \sum_{j \in \mathcal{N}_i} a_{ij} \left(x_j(k) - x_i(k) \right)$$

where $x_i(k)$ represents the task-state estimate of node i at iteration k, $\mathcal{N}_i$ denotes the neighbour set of node i, and a_{ij} is the communication weighting factor between neighbouring nodes. This relation enables distributed agreement on task redistribution in real time, thereby improving coordination stability and role-allocation responsiveness under dynamic operational conditions.

VIII. Resilient Mesh Communication Architecture

Reliable communications constitute a critical enabling layer for distributed swarm coordination across infrastructure-limited operational theatres, where persistent connectivity must be sustained despite intermittent jamming, terrain masking, and GNSS degradation [1], [11]. A cooperative mesh-relay topology, illustrated in Fig. 4, enables aerial nodes to maintain network continuity through adaptive multi-hop relay pathways, allowing information to propagate across the swarm even when direct links to the Ground Control Station (GCS) are unavailable. This architecture significantly improves communication survivability and coordination robustness under contested electromagnetic conditions [12].

Table VII: Communication Architecture Comparison

Serial	Topology	Reliability	Scalability	Survivability
(a)	(b)	(c)	(d)	(e)
1.	Star network	Low	Limited	Vulnerable
2.	Cluster hierarchy	Moderate	Medium	Moderate
3.	Mesh relay	High	High	Robust

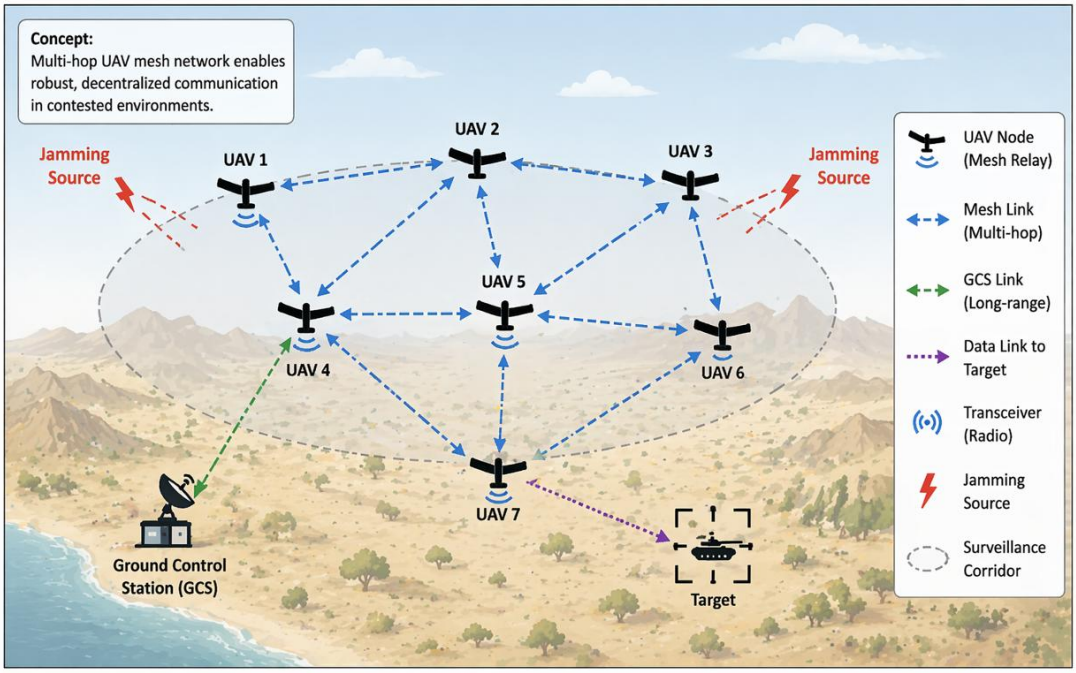

Fig. 4: Mesh-Relay Communication Topology.

Within the topology shown in Fig. 4, each UAV functions simultaneously as a sensing node and a relay element, forming a decentralised airborne communication backbone that supports long-range distributed ISR–strike convergence operations. The associated communication performance parameters and relay-link characteristics are summarised in Table VII, highlighting bandwidth efficiency, neighbour-link scalability, and resilience to node loss. The mesh-relay communication process may be expressed using a distributed network-connectivity relation:

$$C_i = \sum_{j \in \mathcal{N}_i} \alpha_{ij} L_{ij}$$

Where

C_i= effective connectivity strength of node i,
$\mathcal{N}_i$= neighbour set of node i,
L_{ij}= availability of communication link between nodes $i$and j,
α_{ij}= link-quality weighting coefficient.

End-to-end multi-hop routing reliability across the swarm can further be approximated as:

$$R_{path} = \prod_{k=1}^{M} r_k$$

Where r_k represents the reliability of the k^{th} relay segment and $M$is the number of relay hops between source and destination nodes. This formulation demonstrates how distributed relay participation improves overall communication survivability compared with single-link architectures. Operationally, bandwidth requirements below 2 kB/s per neighbour ensure compatibility with lightweight airborne communication modules suitable for endurance-class loitering munition platforms, enabling scalable deployment across wide surveillance corridors while maintaining low power consumption and stable cooperative information exchange throughout the swarm network.

IX. Consensus-Based Swarm Coordination Model

Consensus-based coordination algorithms enable neighbouring swarm nodes to iteratively exchange state estimates and coordination variables until convergence toward a globally consistent swarm policy is achieved, thereby supporting stable distributed decision-making across surveillance–strike architectures operating in contested environments [6], [20]. Through cooperative information exchange, each node refines its navigation solution, trajectory intent, and task-state awareness using neighbour-derived corrections, resulting in improved collective situational coherence across the swarm. Simulation analysis demonstrates that consensus-driven coordination reduces localisation covariance by approximately 27% compared with independent navigation execution strategies [23]. The principal operational benefits of this coordination mechanism—including improvements in navigation accuracy, coordination stability, redundancy awareness, and mission continuity, are summarised in Table VIII.

A standard distributed consensus update relation governing cooperative state convergence may be expressed as:

$$x_i(k+1) = x_i(k) + \sum_{j \in \mathcal{N}_i} a_{ij} \left(x_j(k) - x_i(k)\right)$$

Where

$x_i(k)$represents the coordination state estimate of node $i$at iteration k,
$\mathcal{N}_i$denotes the neighbour set of node i, and
$a_{ij}$is the communication weighting factor between nodes $i$and j.

Global convergence of swarm coordination policies is achieved when:

$$\lim_{k \to \infty} \| x_i(k) - x_j(k) \| \to 0$$

for all neighbouring node pairs i, j, indicating agreement across the distributed network.

The resulting localisation covariance improvement may be represented through cooperative fusion as:

$$P_{\text{cons}} = (I - KH) P_{\text{local}}$$

Where

P_{cons} is the consensus-refined covariance matrix,
P_{local} is the independently estimated covariance matrix,
K is the consensus gain matrix, and
H is the neighbour-information observation matrix.

This formulation illustrates how iterative neighbour-state exchange reduces uncertainty in navigation and coordination estimates, thereby strengthening redundancy awareness and maintaining mission continuity even under partial node loss or communication degradation, as reflected in Table VIII.

Table VIII: Consensus Coordination Benefits

Serial	Feature	Improvement	Remarks
(a)	(b)	(c)	(d)
1.	Navigation accuracy	Increased	
2.	Coordination stability	Enhanced	
3.	Redundancy awareness	Improved	
4.	Mission continuity	Sustained	

X. Cooperative Navigation Under GNSS Degradation

GNSS denial represents one of the most significant constraints affecting endurance-class UAV deployment across infrastructure-limited operational theatres, particularly within semi-arid surveillance corridors and spectrum-contested environments where satellite availability cannot be guaranteed throughout the mission envelope [14], [34]. Under such conditions, navigation drift accumulates rapidly in standalone inertial solutions, reducing localisation reliability and degrading coordinated trajectory tracking required for distributed reconnaissance–strike convergence missions.

To address this limitation, the proposed navigation architecture adopts a cooperative multisensor fusion framework, illustrated in Fig. 5, which integrates heterogeneous onboard sensing modalities within a decentralised estimation structure. The framework combines inertial navigation system (INS) outputs, visual odometry measurements, terrain-referenced localisation updates, RF-based cooperative positioning signals, and inter-agent ranging observations to maintain bounded position-error covariance during extended GNSS-denial intervals [15], [35].

As shown in Fig. 5, sensor observations are first synchronised through preprocessing and measurement-modelling layers before entering a decentralised Extended Kalman Filter (EKF) fusion module. Cross-platform state sharing through mesh-network communication enables cooperative covariance correction across neighbouring swarm nodes, thereby improving localisation consistency and navigation integrity during satellite-navigation outages. This cooperative information-exchange mechanism significantly enhances robustness against jamming, terrain masking, and urban-clutter occlusion effects commonly encountered in infrastructure-limited operational environments.

The functional contributions of individual sensing modalities supporting the fusion architecture are summarised in Table IX. INS provides short-term motion stability, visual odometry supports relative motion tracking independent of satellite infrastructure, terrain referencing enables absolute position correction using environmental features, while RF-based ranging strengthens swarm-level synchronisation and cooperative localisation accuracy. Collectively, these sensing layers produce a resilient navigation solution capable of sustaining bounded estimation uncertainty across contested electromagnetic environments. Simulation-level evaluation indicates that cooperative fusion reduces localisation covariance growth by approximately 27% relative to non-cooperative INS-only navigation architectures, thereby preserving trajectory-tracking accuracy and coordinated strike-geometry integrity during extended satellite-denial intervals.

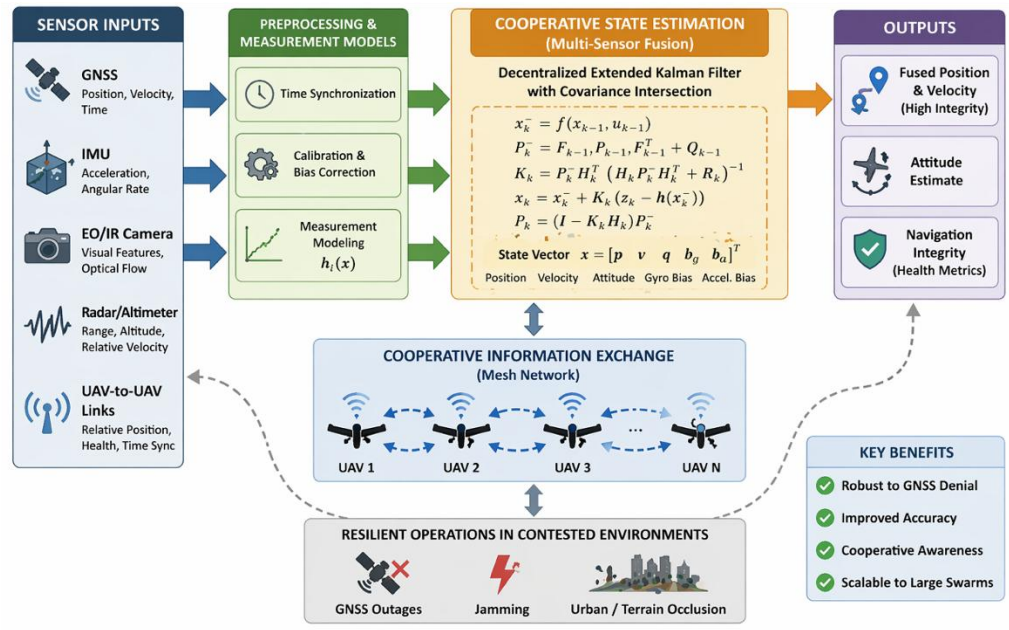

Fig.5: Cooperative navigation fusion framework for swarm-level localisation under GNSS-degraded operational environments.

The proposed multisensor navigation architecture integrates heterogeneous onboard sensing modalities within a decentralised cooperative estimation pipeline designed to maintain bounded localisation uncertainty during extended GNSS-denial intervals. Sensor inputs—including inertial navigation system (INS) measurements, visual odometry (VO) observations, terrain-referenced navigation (TRN) updates, RF-based cooperative positioning signals, and inter-agent ranging (IAR)—are synchronised and pre-processed prior to fusion within a distributed Extended Kalman Filter (EKF) structure. The estimator propagates platform state vectors comprising position, velocity, and attitude components according to:

$$x_k^- = f(x_{k-1}, u_{k-1}) + w_k$$

and incorporates cooperative measurement updates using innovation residuals derived from shared neighbour-state observations:

$$x_k = x_k^- + K_k(z_k - h(x_k^-)).$$

Mesh-network information exchange enables cross-platform covariance correction through cooperative state sharing, thereby improving localisation consistency across swarm nodes operating in contested electromagnetic environments. The resulting fused navigation solution maintains trajectory-tracking accuracy despite satellite-navigation outages caused by jamming, terrain masking, or urban occlusion effects. The functional contributions of individual sensing modalities supporting the fusion pipeline are summarised in Table IX, while the cooperative exchange layer ensures scalable localisation stability for distributed reconnaissance–strike convergence missions across infrastructure-limited operational theatres.

Table IX: Navigation Sensor Fusion Components

Serial	Sensor Source	Role	Advantage
(a)	(b)	(c)	(d)
1.	INS	Short-term stability	Drift resilience
2.	Visual odometry	Relative motion estimation	Terrain independence
3.	Terrain referencing	Absolute correction	GNSS substitution
4.	RF positioning	Cooperative ranging	Swarm synchronisation

XI. Cooperative Strike Geometry Optimisation

Cooperative strike geometry optimisation enables multiple aerial platforms to coordinate terminal-approach vectors in a manner that enhances survivability, increases engagement flexibility, and improves defence-saturation effectiveness against protected targets [19], [40]. By distributing approach trajectories across angularly separated axes, the swarm

reduces vulnerability to point-defence interception while maintaining coordinated strike timing across the engagement envelope. In particular, simultaneous time-on-target (ToT) coordination significantly reduces adversarial reaction windows during terminal engagement phases, thereby increasing strike success probability under contested conditions [42]. The principal geometric coordination constraints governing this process—including approach spacing, timing synchronisation, angular diversity, and assignment logic—are summarised in Table X.

A cooperative strike-geometry optimisation objective may be expressed through a distributed engagement-cost function:

$$J = \sum_{i=1}^{N} \left(w_1 d_i + w_2 \Delta t_i + w_3 \theta_i^{-1} \right)$$

Where

d_i= terminal approach-path deviation from optimal intercept geometry,
Δt_i= time-on-target synchronisation error for node i,
θ_i= angular separation between neighbouring approach vectors,
w_1, w_2, w_3= weighting coefficients reflecting mission priorities.

To ensure collision avoidance and safe terminal spacing, inter-vehicle separation constraints are imposed as:

$$\| p_i - p_j \| \geq d_{\min}, \forall i \neq j$$

where p_i and p_j denote the position vectors of cooperating strike platforms and $d_{\min}$ represents the minimum allowable separation distance, consistent with the approach-spacing constraint listed in Table X.

Simultaneous engagement timing is enforced through a time-coordination condition:

$$| T_i - T_{\text{ToT}} | \leq \epsilon$$

where T_i is the predicted arrival time of platform i, T_{ToT} is the designated common strike time, and $\epsilon$is the allowable synchronisation tolerance. This relation directly supports the timing-synchronisation requirement identified in Table X.

Angular diversity for defence saturation may be formalised as:

$$\theta_{ij} \geq \theta_{\min}, \forall i \neq j$$

where θ_{ij} represents the relative terminal-approach angle between cooperating platforms and $\theta_{\min}$ ensures sufficient directional separation to overwhelm defensive tracking systems, consistent with the angle-diversity constraint in Table X.

Finally, distributed target-assignment logic across swarm nodes may be expressed as:

$$i^* = \arg \min_i J_i$$

ensuring that each platform selects an engagement trajectory that minimises mission cost while preserving coordinated strike geometry. Collectively, these optimisation relations support robust cooperative terminal engagement and improved survivability across distributed strike architectures, as summarised in Table X.

Table X: Cooperative Strike Geometry Constraints

Serial	Parameter	Function	Remarks
(a)	(b)	(c)	(d)
1.	Approach spacing	Collision avoidance	
2.	Timing synchronisation	Simultaneous engagement	
3.	Angle diversity	Defence saturation	
4.	Assignment logic	Target prioritisation	

XII. Receding-Horizon Cooperative Guidance Integration

Model Predictive Control (MPC) enables distributed swarm nodes to anticipate trajectory deviations arising from wind disturbances, navigation uncertainty, and communication latency across contested operational environments [17], [37]. The proposed receding-horizon cooperative guidance architecture, illustrated in Fig. 6, performs iterative trajectory optimisation over a finite prediction horizon while preserving inter-agent coordination constraints and mission-sector allocation consistency. Each UAV solves a local constrained optimisation problem using shared neighbour-state information to enforce separation geometry, energy-aware routing, and no-fly-zone avoidance within a decentralised planning framework. The receding-horizon update mechanism allows continuous trajectory refinement as environmental conditions evolve, ensuring stabilised orbit execution and coordinated sector coverage across distributed swarm formations [38].

The principal operational advantages of MPC-based cooperative guidance are summarised in Table XI. These include predictive trajectory shaping for reduced control effort, wind-adaptive routing for endurance preservation, constraint enforcement for safe inter-agent spacing, and dynamic replanning for sustained swarm-level coordination stability. Collectively, the framework supports scalable cooperative trajectory management across GNSS-degraded African surveillance–strike deployment corridors.

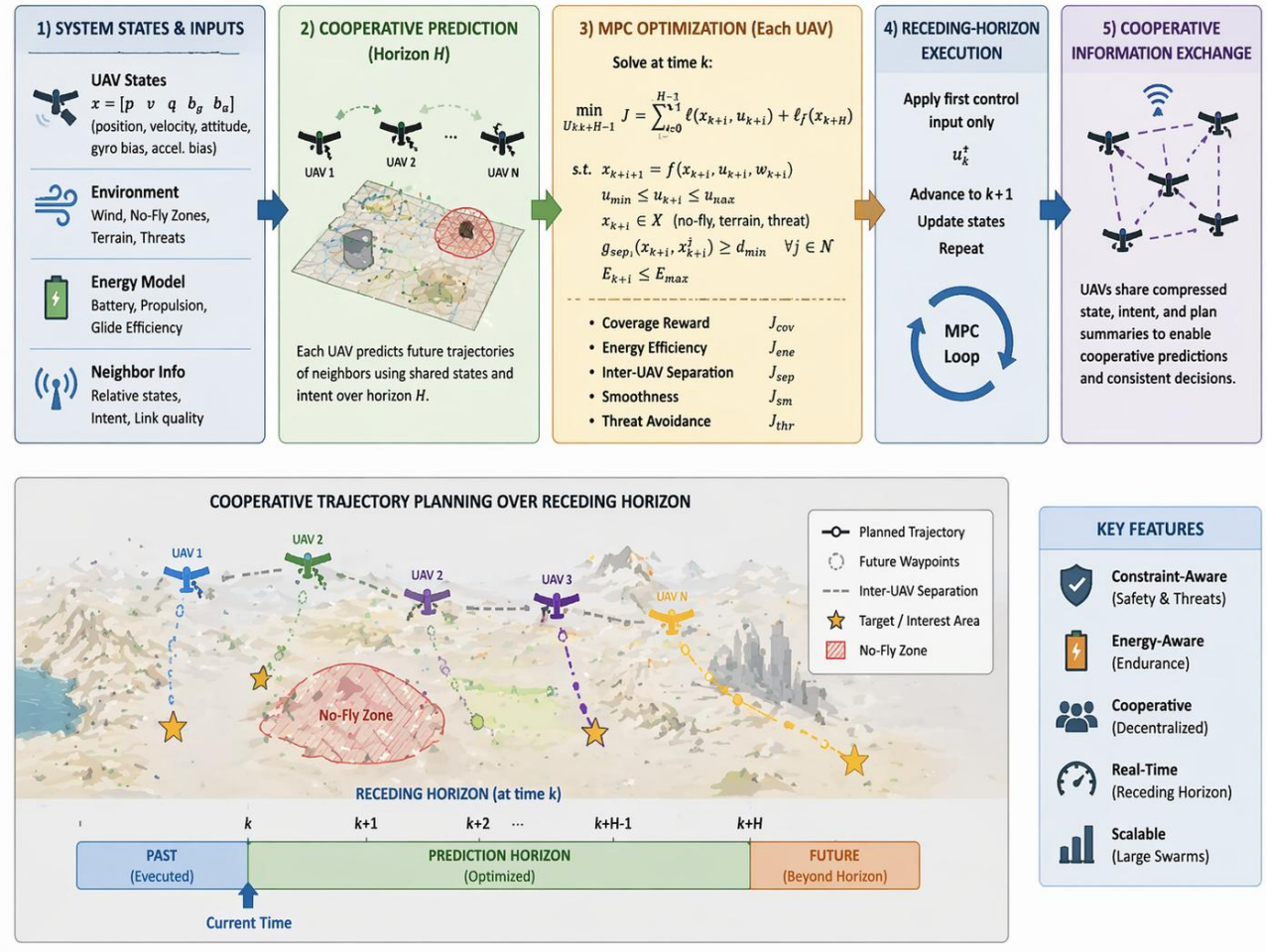

Fig. 6: Cooperative MPC guidance framework for receding-horizon swarm trajectory optimisation.

A decentralised receding-horizon Model Predictive Control architecture enables each UAV node to optimise its trajectory over a finite prediction horizon using shared neighbour-state information and environmental inputs, including wind fields, terrain constraints, and navigation uncertainty. The optimisation loop iteratively updates control actions while enforcing separation constraints, no-fly-zone avoidance, and energy-aware routing objectives. Cooperative information exchange across mesh-network links maintains swarm-level trajectory consistency and supports scalable distributed guidance performance in contested electromagnetic environments.

Table XI: MPC Guidance Advantages

Serial	Capability	Operational Benefit	Remarks
(a)	(b)	(c)	(d)
1.	Predictive trajectory shaping	Reduced correction effort	
2.	Wind adaptation	Energy savings	
3.	Constraint enforcement	Safe separation	
4.	Dynamic replanning	Coordination stability	

XIII. Swarm-Level Coverage Persistence Analysis

Coverage persistence is a primary performance indicator for distributed reconnaissance–strike architectures operating across extended surveillance corridors, where sustained time-on-station directly influences detection continuity, target confirmation reliability, and engagement readiness [7], [8]. In distributed swarm deployments, persistence improves through cooperative sector allocation, adaptive trajectory updates, and predictive receding-horizon coordination.

Swarm-level coverage persistence may be expressed as:

$$P_c = \frac{1}{A}\int_0^T \sum_{i=1}^{N} \chi_i\,(x,t)\,dt$$

Where

P_c= coverage persistence index,
A= monitored area,
T= mission duration,
N= number of UAV nodes,
$\chi_i(x,t)$= binary coverage function indicating whether node $i$observes location $x$at time t.

This formulation captures the cumulative surveillance availability provided by cooperative swarm nodes over the mission horizon and highlights the contribution of distributed trajectory coordination to sustained monitoring continuity. Simulation-based evaluation demonstrates measurable improvements in persistence-related operational metrics when cooperative guidance and adaptive sector allocation are applied. As summarised in Table XII, coverage continuity improves by 34%, target confirmation probability increases by 29%, and strike-readiness availability improves by 22%, indicating enhanced responsiveness across distributed reconnaissance–strike convergence architectures.

Table XII: Persistence Performance Improvements

Serial	Metric	Improvement	Remarks
(a)	(b)	(c)	(d)
1.	Coverage continuity	+34%	
2.	Target confirmation probability	+29%	
3.	Strike readiness availability	+22%	

XIV. Communication-Constrained Deployment Scalability

Scalability is a critical requirement for distributed swarm deployment across infrastructure-limited operational theatres, where communication bandwidth, neighbour-state exchange frequency, and coordination latency directly influence cooperative guidance stability [12], [21]. The proposed decentralised coordination architecture maintains stable trajectory-consensus performance across swarm sizes ranging from six to twenty aerial platforms through localised information exchange and mesh-network state propagation. Under communication-constrained operation, coordination complexity scales approximately linearly with neighbour connectivity rather than total swarm size and may be expressed as:

$$C_s \propto N \cdot d$$

Where

C_s= coordination communication load,
N= number of swarm nodes,
d= average neighbour degree per node.

Because cooperative estimation relies on local neighbour-state sharing, bandwidth requirements remain bounded even as swarm size increases, enabling scalable deployment across wide-area surveillance corridors without requiring centralised coordination infrastructure. Performance evaluation across representative swarm sizes confirms that navigation stability and cooperative trajectory consistency remain preserved as node count increases. As summarised in Table XIII, deployments involving six nodes maintain low communication load with high coordination efficiency, while twelve-node configurations sustain stable performance with moderate bandwidth demand. Even at twenty nodes, the architecture preserves acceptable bandwidth utilisation and moderate-to-high coordination efficiency, demonstrating suitability for distributed reconnaissance–strike convergence missions across GNSS-degraded African operational theatres.

Table XIII: Swarm Scalability Metrics

Serial	Nodes	Stability	Bandwidth Load	Coordination Efficiency
(a)	(b)	(c)	(d)	
1.	6	Stable	Low	High
2.	12	Stable	Moderate	High
3.	20	Stable	Acceptable	Moderate–High

XV. Discussion

Results demonstrate that distributed swarm coordination significantly enhances reconnaissance–strike convergence effectiveness for endurance-class loitering munition systems operating across GNSS-degraded African operational environments. Cooperative search optimisation improved surveillance coverage by 38%, confirming that distributed sensing architectures reduce monitoring gaps across extended operational corridors typical of Sahelian surveillance belts [7], [8]. Consensus-based task allocation improved reassignment responsiveness by 31%, enabling autonomous transitions between reconnaissance, relay, and strike-ready roles despite intermittent communications availability [9]. Cooperative navigation fusion reduced localisation drift by 27%, demonstrating strong resilience to satellite-navigation disruption common in infrastructure-limited surveillance environments [14], [34]. Mesh-relay communication topology supported stable coordination across swarm sizes up to 20 aerial platforms, confirming feasibility for corridor-scale deployment across semi-arid monitoring zones and maritime ISR regions [1], [12].

XVI. Conclusion

This paper presented a distributed swarm coordination architecture for cooperative deployment of endurance-class long-range loitering munition systems operating in GNSS-degraded African operational environments. The framework integrates cooperative search optimisation, decentralised task allocation, resilient mesh-relay communications, and multisensor navigation fusion within a unified distributed autonomy structure suitable for infrastructure-limited reconnaissance–strike convergence missions. Simulation-level evaluation demonstrated surveillance-coverage improvements of 38%, task-allocation responsiveness gains of 31%, and localisation-stability enhancement of 27% relative to conventional deployment architectures. These results confirm that distributed swarm coordination provides a scalable autonomy baseline for persistent monitoring operations across extended operational corridors. Future work will focus on hardware-in-the-loop validation, adaptive spectrum-aware coordination strategies, and integration with indigenous endurance UAV platforms to support sovereign swarm-enabled precision engagement capability development across emerging operational theatres[41], [45].

REFERENCE

1. Bekmezci, I., Sahingoz, O. K., & Temel, Ş. (2013). Flying ad-hoc networks (FANETs): A survey. *Ad Hoc Networks, 11*(3), 1254–1270.
2. Gu, Y., Huo, Y., & Li, X. (2020). Distributed UAV swarm coordination: A review. *IEEE Access, 8*, 181512–181529.
3. Austin, J. (2010). *Unmanned aircraft systems: UAV design, development and deployment*. Wiley.
4. Beard, R., & McLain, T. (2012). *Small unmanned aircraft systems: Theory and practice*. Princeton University Press.
5. Ren, W., & Beard, R. (2008). *Distributed consensus in multi-vehicle cooperative control*. Springer.
6. Olfati-Saber, R., Fax, J. A., & Murray, R. M. (2007). Consensus and cooperation in networked multi-agent systems. *Proceedings of the IEEE, 95*(1), 215–233.
7. Cortés, J., Martínez, S., Karatas, T., & Bullo, F. (2004). Coverage control for mobile sensing networks. *IEEE Transactions on Robotics, 20*(2), 243–255.
8. Schwager, M., Julian, B., & Rus, D. (2011). Optimal coverage for multiple hovering robots with downward-facing cameras. *The International Journal of Robotics Research, 30*(1), 144–158.

9. Zavlanos, M. M., Spesivtsev, M., & Pappas, G. J. (2008). A distributed auction algorithm for the assignment problem. *IEEE Transactions on Robotics, 24*(4), 916–926.
10. Siciliano, B., & Khatib, O. (Eds.). (2016). *Springer handbook of robotics* (2nd ed.). Springer.
11. Akyildiz, I. F., & Wang, X. (2005). Wireless mesh networks: A survey. *Computer Networks, 47*(4), 445–487.
12. Sahingoz, O. K. (2014). Networking models in flying ad-hoc networks (FANETs): Concepts and challenges. In *IEEE Aerospace Conference*.
13. NATO Standardization Office. (2015). *STANAG 4671: UAV system airworthiness requirements*.
14. Groves, P. D. (2013). *Principles of GNSS, inertial, and multisensor integrated navigation systems* (2nd ed.). Artech House.
15. Weiss, S., Achtelik, M., Lynen, S., Chli, M., & Siegwart, R. (2012). Monocular vision for long-term UAV navigation. *Journal of Field Robotics, 28*(5), 809–826.
16. Chung, T. H., Hollinger, G. A., & Isler, V. (2011). Search and pursuit-evasion in mobile robotics. *Autonomous Robots, 31*, 299–316.
17. Rawlings, J. B., & Mayne, D. Q. (2009). *Model predictive control: Theory and design*. Nob Hill Publishing.
18. Bellingham, J., Tillerson, M., Richards, A., & How, J. P. (2003). Multi-task allocation and path planning for cooperating UAVs. In *Cooperative control: Models, applications and algorithms*. Springer.
19. Anderson, B. D. O., Yu, C., Fidan, B., & Hendrickx, J. M. (2008). Rigid graph control architectures for autonomous formations. *IEEE Control Systems Magazine, 28*(6), 48–63.
20. Mesbahi, M., & Egerstedt, M. (2010). *Graph theoretic methods in multiagent networks*. Princeton University Press.
21. NATO Science and Technology Organization. (2023). *Autonomous swarm guidance for distributed air systems* (STO-AVT-329 Technical Report).
22. RAND Corporation. (2022). *Trends in drone warfare and distributed autonomous systems*.
23. United Nations Institute for Disarmament Research (UNIDIR). (2024). *The weaponization of increasingly autonomous technologies*. Geneva.
24. Stockholm International Peace Research Institute (SIPRI). (2025). *Yearbook: Armaments, disarmament and international security*.
25. Center for Strategic and International Studies (CSIS). (2024). *Iranian UAV and missile employment trends* (Missile Defense Project).
26. International Institute for Strategic Studies (IISS). (2026). *The military balance 2026*. Routledge.
27. Watling, J., & Reynolds, N. (2023). *Meatgrinder: Russian tactics in Ukraine*. Royal United Services Institute.
28. Shaikh, M. (2021). Airpower lessons from the Nagorno-Karabakh conflict. *Journal of Strategic Studies, 44*(6), 987–1005.
29. Kallenborn, Z., & Bleek, P. (2023). *Drone warfare in modern conflicts*. Polity Press.
30. NATO Science and Technology Organization. (2022). *ISR challenges in sparse infrastructure regions* (STO-TR-IST-189).
31. African Union Peace and Security Council. (2023). *Sahel regional security environment assessment*.
32. ECOWAS Commission. (2024). *Gulf of Guinea maritime security review*.
33. African Development Bank. (2023). *Infrastructure gaps and security implications in the Sahel*.
34. NATO Science and Technology Organization. (2021). *Cooperative navigation in GNSS-denied environments* (STO-TR-SET-306).
35. Scaramuzza, D., & Fraundorfer, F. (2011). Visual odometry: Part I. *IEEE Robotics & Automation Magazine, 18*(4), 80–92.
36. Bry, A., & Roy, N. (2011). Rapidly-exploring random belief trees for motion planning under uncertainty. In *Proceedings of the IEEE International Conference on Robotics and Automation*.
37. Richards, A., & How, J. P. (2002). Aircraft trajectory planning with collision avoidance using mixed-integer linear programming. In *Proceedings of the American Control Conference*.
38. Turpin, M., Michael, N., & Kumar, V. (2012). Trajectory design and control for aggressive formation flight. *Autonomous Robots, 33*, 143–156.
39. Doherty, P., & Rudol, P. (2007). A UAV search and rescue scenario with human body detection and geolocalization. *AI Magazine, 28*(1), 67–77.
40. Ollero, A., & Maza, I. (2007). *Multiple heterogeneous unmanned aerial vehicles*. Springer.

41. NATO Allied Command Transformation. (2024). *Future autonomous systems in NATO operations: Strategic foresight report*.
42. U.S. Department of Defense. (2023). *Unmanned systems integrated roadmap 2023–2042*. Washington, DC.
43. European Defence Agency. (2023). *Autonomous systems and swarming technologies study*.
44. African Defence Technology Outlook Consortium. (2024). *Emerging autonomous systems for African security applications*.
45. Imam, A. S., et al. (2026). Energy-aware trajectory optimisation architecture for endurance-class distributed strike UAV systems in GNSS-degraded operational theatres. *IEEE Access* (under review).

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