



Research Article

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A Review of Modern Air Defence Systems: Architectures, Sensors, Interceptors and Emerging Threat Environments with Implications for Infrastructure-Limited Defence Environments

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Abstract

Air defence systems have undergone a profound transformation from platform-centric anti-aircraft artillery arrangements to distributed, sensor-fusion-enabled defensive ecosystems capable of countering aircraft, ballistic missiles, cruise missiles, Unmanned Aerial Vehicles (UAVs), and loitering munitions across contested electromagnetic environments. This paper presents a comprehensive technical review of modern air-defence architectures, examining surveillance sensor networks, fire-control and tracking systems, command-and-control frameworks, interceptor guidance strategies, gun-based SHORAD platforms, Directed-Energy (DE) interception technologies, and Proportional-Navigation-based engagement modelling. Particular emphasis is placed on the operational requirements of infrastructure-limited theatres, where sparse radar coverage, constrained electrical power, fragile communications networks, and dispersed protected assets demand adaptive and modular defensive solutions. The review integrates analytical formulations governing radar detection performance, Kalman-filter-based trajectory estimation, proportional navigation interception, and distributed sensor-fusion probability modelling to establish a rigorous systems-engineering perspective on layered air-defence performance. Emerging technological directions, including AI-enabled engagement prioritisation, GNSS-denied navigation architectures, passive sensing networks, mesh-network communication frameworks, and high-energy laser interception systems, are evaluated in the context of counter-UAV defence and expeditionary protection operations. Special attention is given to the protection of civilian infrastructure, humanitarian logistics corridors, forward operating bases, and energy installations increasingly exposed to asymmetric aerial threats in Sub-Saharan and comparable operational environments. The paper further identifies critical capability gaps affecting developing defence ecosystems, including radar-coverage discontinuities, interceptor-cost constraints, communication fragility, and limited indigenous integration capacity. Based on these findings, the study establishes a technical foundation for modular distributed air-defence system architectures optimised for scalable deployment across resource-constrained operational theatres. The framework supports survivable, cost-effective, and human-supervised layered interception capability suitable for both military force protection and civilian-infrastructure security missions.

Keywords: Integrated Air Defence Systems (IADS); Distributed Sensor Fusion; Counter-UAV Defence; SHORAD; Proportional Navigation Guidance; Directed-Energy Systems; GNSS-Denied Operations; Infrastructure-Limited Theatres; Civilian Infrastructure Protection.



I. INTRODUCTION

Control of the air domain has remained a decisive factor in warfare from the Second World War to contemporary hybrid conflicts. Recent advances in precision-guided munitions, low-observable platforms, and especially low-cost unmanned aerial systems (UAS) and loitering munitions have significantly altered the aerial threat landscape, enabling both state and non-state actors to conduct surveillance and strike operations with reduced warning timelines [1]–[6]. Modern Integrated Air Defence Systems (IADS) are therefore transitioning from centralised radar-based architectures toward distributed sensing networks, adaptive engagement algorithms, and resilient communication frameworks capable of operating in electronically contested and GNSS-degraded environments [7]–[9]. This shift reflects the growing need for scalable and mobile defensive solutions.

In many regions, particularly across Africa, air defence operations must address infrastructure limitations such as sparse radar coverage, unreliable power supply, constrained communications networks, and dispersed protected assets. These conditions increase reliance on cost-effective and modular protection architectures suitable for defending forward operating bases, border corridors, energy infrastructure, and civilian population centres against asymmetric aerial threats. Recent operational lessons from Eastern Europe and the Middle East further highlight the importance of passive sensing layers, mobile interceptor platforms, and AI-assisted engagement decision support for maintaining effectiveness under electronic warfare pressure and saturation-style attacks [10]–[12]. In African operational theatres, air defence systems increasingly support civilian-protection missions alongside traditional force protection roles. Accordingly, this paper presents a structured technical review of modern air defence architectures, with emphasis on distributed sensing, interceptor guidance methods, command-and-control frameworks, and emerging technologies supporting Modular Distributed Air Defence System (MDADS) architectures for infrastructure-limited operational environments and civilian-infrastructure protection missions.

II. HISTORICAL EVOLUTION OF AIR DEFENCE SYSTEMS

The evolution of air defence systems reflects continuous adaptation to changes in aircraft performance, strike precision, sensing technology and battlefield communications. Early air defence relied primarily on manually aimed anti-aircraft artillery with optical tracking, which provided limited engagement range and reaction time. Subsequent developments introduced radar-guided interception and surface-to-air missile systems that significantly improved detection capability and engagement accuracy. As illustrated in Fig. 1, modern air defence architectures have further transitioned toward integrated and distributed sensor-fusion-enabled interception networks capable of countering low-altitude and asymmetric aerial threats such as Unmanned Aerial Vehicles (UAVs) in infrastructure-limited operational environments.



Fig. 1: Evolution of air defence systems from optical anti-aircraft artillery networks to radar-guided missile systems, integrated air defence architectures, and distributed counter-UAV sensor-fusion protection frameworks suitable for infrastructure-limited operational theatres.

Understanding this technological progression is essential for designing scalable and resilient air defence architectures that reduce engagement latency while extending surveillance coverage across dispersed protection zones. These advances underpin contemporary Modular Distributed Air Defence System (MDADS) concepts intended for expeditionary deployments and civilian-infrastructure protection missions.

A. Anti-Aircraft Artillery Era

Early air defence systems relied primarily on optical tracking instruments, acoustic direction finders and mechanically computed firing solutions to intercept hostile aircraft. During the Second World War, analogue fire-control predictors enabled estimation of interception points by solving relative-motion equations based on aircraft velocity, altitude, and heading. These predictors significantly improved engagement effectiveness compared with purely visual aiming methods and marked the first transition toward computation-assisted air defence decision support [13]. Although Anti-Aircraft Artillery (AAA) systems were limited by short engagement ranges and dependence on visual acquisition, they established the foundational principle of layered defensive coverage around high-value assets such as Forward Operating Bases (FOBs) industrial facilities, logistics hubs and urban centres. In many contemporary African operational environments, modernised gun-based Short-Range Air Defence (SHORAD) systems continue to provide cost-effective protection against low-altitude aerial threats, particularly small Unmanned Aerial Vehicles (UAVs) operating below radar coverage envelopes.

B. Radar-Guided Missile Era

The introduction of radar-guided Surface-to-Air Missile (SAM) systems during the early Cold War fundamentally transformed air defence doctrine by extending engagement ranges and enabling all-weather interception capability independent of visual acquisition constraints [14]. Systems such as the Nike-Ajax and SA-2 Guideline demonstrated the operational feasibility of radar-directed interception networks capable of defending strategic airspace against high-altitude bomber threats.

Radar-guided missile architectures introduced several critical innovations including, continuous target tracking using fire-control radar, command-guided and semi-active homing interception methods, coordinated engagement zones around protected assets, as well as early integration of radar surveillance with interceptor control. These developments marked the transition from localised point defence to coordinated sector-level airspace denial architectures. However, such systems typically required extensive fixed infrastructure, reliable electrical power supply, and centralised command facilities, a conditions that remain challenging in many emerging defence ecosystems across Sub-Saharan Africa today.

C. Integrated Air Defence Systems

Modern Integrated Air Defence Systems (IADS) combine multiple sensing, decision-making, and interception layers into coordinated engagement frameworks capable of defending large territorial regions against diverse aerial threats. Typical IADS architectures integrate, early-warning radar networks, tracking and fire-control radar systems, interceptor aircraft, SAM batteries, electronic warfare assets and command-and-control communication networks. These components operate as a unified defensive ecosystem supporting sensor fusion, engagement prioritisation, and coordinated interceptor allocation across multiple threat vectors [15]. The operational effectiveness of IADS architectures depends heavily on communication reliability, radar coverage density and infrastructure resilience. While technologically advanced nations deploy nationwide layered missile-defence networks, many African countries face geographically dispersed threat environments that require more mobile and modular defensive configurations rather than static radar-centric architectures. Consequently, distributed sensor networks and expeditionary interceptor platforms are increasingly becoming central to regional air defence modernisation strategies.

D. Counter-UAV Defence Transition

The rapid proliferation of small UAVs has introduced a new class of low-altitude, low-radar-cross-section threats that challenge traditional radar-centric air defence architectures. Commercial quadcopters, improvised surveillance drones, and loitering munitions now enable non-state actors to conduct reconnaissance, targeting support, and limited strike operations with minimal logistical footprint [16]. Unlike conventional aircraft threats, UAV platforms typically operate below radar horizon limits, within cluttered urban terrain, with intermittent communication signatures, and at low acoustic and thermal observability. These characteristics have driven a transition toward distributed detection architectures incorporating passive radio-frequency sensing, acoustic arrays, electro-optical surveillance towers, and solar-powered perimeter monitoring nodes. Such architectures are particularly relevant for protecting forward operating bases, border corridors, humanitarian logistics routes, and Internally Displaced Persons (IDP) camps across infrastructure-limited operational theatres. As a result, modern air defence evolution is increasingly characterised by the shift from centralised missile-centric interception networks toward adaptive, layered, and sensor-distributed protection systems capable of countering both conventional aircraft and asymmetric aerial threats simultaneously. This transition provides the conceptual basis for modular distributed air defence architectures designed to support scalable deployment across emerging defence ecosystems in Africa and comparable operational environments.

III. SENSOR ARCHITECTURES IN MODERN AIR DEFENCE

Modern air defence effectiveness depends fundamentally on the performance, diversity, and survivability of its sensing architecture. Contemporary defensive systems no longer rely solely on single long-range radar installations but instead employ layered multi-sensor detection networks integrating active radar surveillance, passive radio-frequency (RF) sensing, electro-optical/infrared (EO/IR) tracking, and acoustic detection arrays. These heterogeneous sensing modalities enable persistent monitoring across complex operational environments, including low-altitude cluttered terrain and infrastructure-limited theatres typical of many emerging defence ecosystems. The transition toward distributed sensing architectures is particularly critical for countering low-radar-cross-section threats such as small Unmanned Aerial Vehicles (UAVs), loitering munitions, and improvised aerial surveillance platforms operating below traditional radar coverage envelopes.

A. Radar Detection Principles

Radar systems remain the primary detection mechanism for airborne threats due to their ability to provide long-range surveillance independent of illumination conditions and weather constraints. Detection performance is governed by the radar range equation [13], [14]:

$$R = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{\min}} \right)^{1/4}$$

where:

P_t represents transmitted power

G antenna gain

λ signal wavelength

σ radar cross-section (RCS)

S_{\min} receiver sensitivity

This relationship demonstrates that detection range varies with the fourth root of radar cross-section, explaining why stealth platforms significantly reduce detection probability through RCS minimisation techniques such as shaping, radar-absorbent materials, and emission control strategies [17]. In infrastructure-limited operational theatres across Africa and similar regions, long-range radar coverage is frequently constrained by terrain masking, limited electrical power availability, and sparse fixed surveillance infrastructure. As a result, mobile radar platforms and short-range perimeter surveillance sensors are increasingly deployed to complement national early-warning radar networks and improve coverage continuity around forward operating bases, border corridors, and critical infrastructure nodes.

B. Phased Array Radar Systems

Electronically scanned phased-array radar systems represent a major advancement over mechanically steered antennas by enabling rapid beam steering through controlled phase shifts across antenna elements rather than physical rotation of the antenna structure [18]. This capability allows simultaneous execution of surveillance, tracking and fire-control support functions within a single operational cycle. Phased-array radar systems provide several operational advantages including, track-while-scan multi-target monitoring capability, adaptive beam shaping for clutter suppression, rapid sector reallocation during saturation attacks, improved resistance to electronic countermeasures, and enhanced detection of low-altitude manoeuvring targets. These characteristics make phased-array radar particularly suitable for countering UAV swarm threats and low-observable aerial targets that require rapid angular repositioning of surveillance beams for continuous tracking. However, the acquisition, maintenance and energy requirements of large fixed phased-array installations limit their widespread deployment across many developing defence ecosystems. Consequently, compact mobile phased-array radar variants are increasingly being explored for expeditionary deployments and modular distributed air defence architectures capable of supporting scalable regional coverage.

C. Passive RF Detection Systems

Passive RF detection systems provide an emission-free sensing capability by exploiting reflections from non-cooperative transmitters such as commercial broadcast stations, cellular communication infrastructure, satellite downlink signals, and tactical radio transmissions. Unlike conventional radar systems, passive sensors do not emit electromagnetic energy and are therefore inherently resistant to detection by anti-radiation missiles and electronic support measures [19]. Thus, passive RF sensing architectures enable covert surveillance operations, persistent monitoring of communication-enabled UAV platforms, triangulation-based emitter localisation, detection of control-link transmissions associated with remotely piloted aerial systems. In infrastructure-limited operational environments, passive RF detection networks offer a cost-effective alternative to high-power radar installations and can be deployed as solar-powered perimeter monitoring nodes supporting border security operations, pipeline surveillance corridors, and protection of dispersed infrastructure assets.

D. Electro-Optical and Infrared Tracking Systems

Electro-optical and infrared (EO/IR) sensing systems complement radar coverage by enabling detection and classification of low-altitude aerial threats operating below radar horizon limits or within terrain-cluttered environments [20]. These sensors provide high-resolution visual confirmation of detected targets and support target identification processes essential for engagement authorisation in human-supervised command environments. Thermal imaging sensors further enhance detection capability under low-light and night-time operating conditions by identifying heat signatures associated with propulsion systems, onboard electronics, and aerodynamic friction effects. EO/IR surveillance towers are increasingly deployed as part of distributed perimeter protection architectures supporting FOBs, humanitarian logistics corridors, Internally Displaced Persons (IDP) camps, energy transmission infrastructure, and border surveillance corridors. Their relatively low power consumption enables integration with solar-assisted sensing nodes, making them particularly suitable for persistent surveillance applications across remote regions lacking reliable electrical infrastructure.

E. Acoustic Detection Arrays for Low-Altitude Threat Surveillance

Acoustic sensing arrays have recently emerged as an effective complementary detection modality for identifying low-altitude UAV threats operating below radar coverage thresholds. These systems detect characteristic propulsion noise signatures produced by rotary-wing platforms and fixed-wing loitering munitions. Acoustic detection architectures provide early warning capability within radar-shadow zones, passive surveillance functionality in emission-restricted environments, low-cost deployability across distributed perimeter monitoring networks, and resilience against electromagnetic interference conditions. When integrated with EO/IR sensors and passive RF detection nodes, acoustic arrays significantly improve detection probability against small UAV threats operating in cluttered environments typical of stabilisation operations and infrastructure-protection missions.

F. Multi-Sensor Fusion Architectures for Distributed Detection Networks

Modern air-defence systems increasingly rely on multi-sensor fusion frameworks to improve detection reliability and reduce false-alarm rates in complex electromagnetic and low-altitude threat environments. Sensor fusion integrates heterogeneous observations from radar surveillance nodes, passive RF sensors, EO/IR tracking systems, and acoustic arrays into a unified threat-recognition pipeline capable of supporting real-time engagement decision-making. As illustrated in Fig. 2, distributed sensing nodes cooperate to provide layered detection coverage across short-, medium-, and long-range surveillance zones within infrastructure-limited operational theatres. A simplified detection fusion model may be expressed as [26], [28]:

$$P_D = 1 - \prod_{i=1}^n (1 - P_i)$$

where:

P_D Represents Overall Detection Probability

P_i Represents Detection Probability of the i^{th} Sensor

This relationship illustrates how distributed sensing networks improve detection confidence compared with single-sensor architectures. Such layered sensing configurations form the foundational detection layer of modular distributed air defence architectures designed for scalable deployment across infrastructure-limited operational theatres and civilian-infrastructure protection missions.

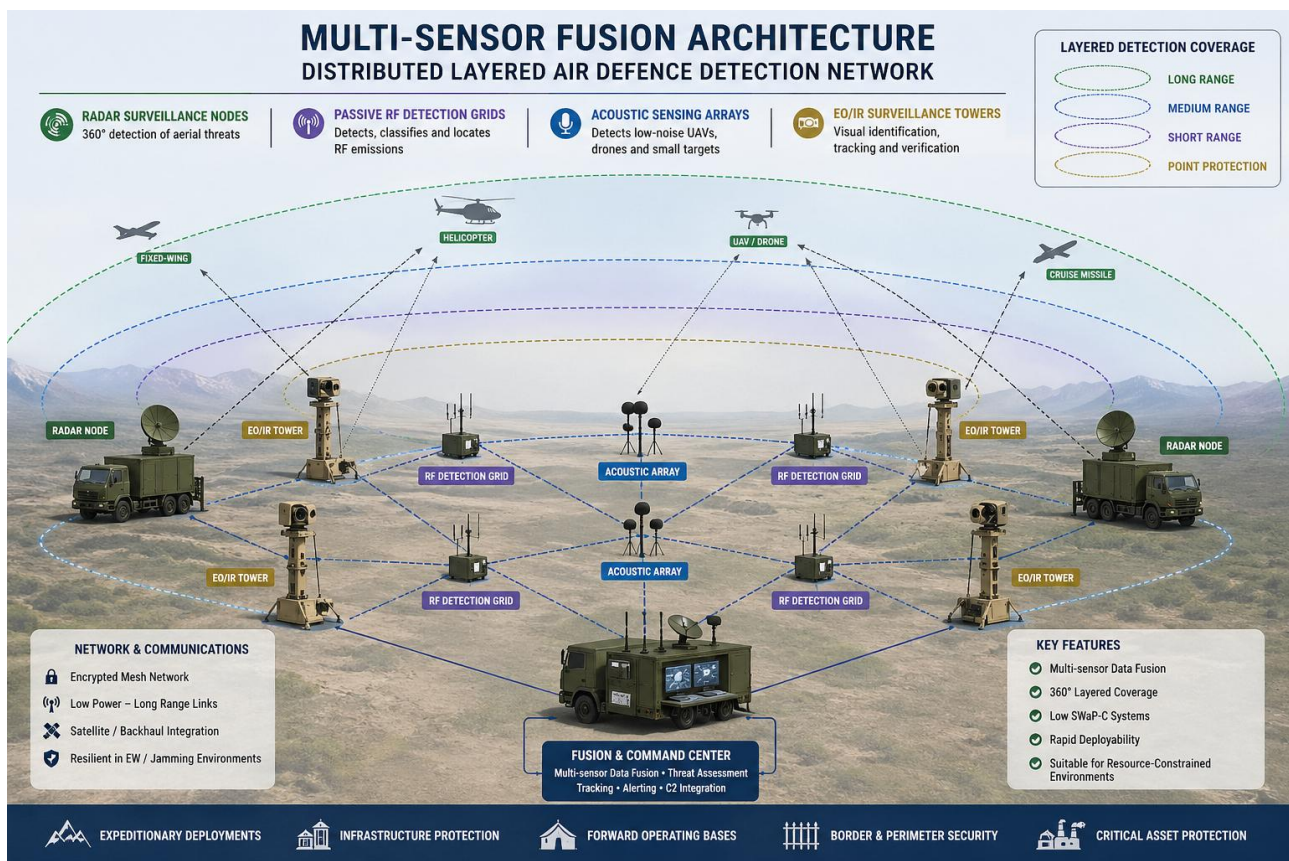


Fig. 2: Multi-sensor fusion architecture combining radar surveillance nodes, passive RF detection grids, acoustic sensing arrays, and EO/IR surveillance towers within a distributed layered air defence detection network suitable for expeditionary deployments and infrastructure-protection operations in resource-constrained environments.

IV. FIRE-CONTROL AND TARGET TRACKING SYSTEMS

Fire-control and target-tracking subsystems form the computational core of modern air defence architectures by enabling accurate estimation of target trajectories and supporting timely interceptor guidance decisions. Contemporary systems rely on recursive state-estimation algorithms, adaptive tracking radars, and multi-target engagement scheduling frameworks to maintain interception effectiveness against manoeuvring aerial threats operating across heterogeneous environments. In distributed operational theatres, particularly those characterised by intermittent communications infrastructure and limited radar coverage continuity robust tracking architectures must operate reliably under conditions of incomplete observations, delayed sensor updates and degraded navigation references.

A. State Estimation Using Kalman Filtering

Accurate prediction of target motion is achieved through recursive state-estimation algorithms such as the Kalman filter, which enables continuous refinement of trajectory estimates using sequential sensor measurements. The discrete-time state transition model is expressed as [15], [16]:

$$x_{k+1} = Ax_k + Bu_k + w_k$$

where:

- x_k represents the target state vector (position, velocity, acceleration)
- A represents the state transition matrix
- B represents the control-input matrix
- u_k represents control input (if applicable)
- w_k represents process noise

Measurement updates follow:

$$z_k = Hx_k + v_k$$

where:

- z_k represents measurement observations
- H represents the observation matrix
- v_k represents measurement noise

Kalman filtering enables optimal trajectory estimation under Gaussian noise assumptions and forms the foundation of modern radar tracking systems used in interceptor guidance pipelines [21]. In distributed African operational environments where sensor coverage may be intermittent, Extended Kalman Filters (EKF) and Unscented Kalman Filters (UKF) are particularly valuable for handling nonlinear UAV manoeuvres and irregular measurement availability.

B. Monopulse Radar Tracking Techniques

Monopulse tracking radars significantly improve angular measurement accuracy by comparing amplitude or phase differences between multiple antenna lobes generated simultaneously during target illumination [22]. Unlike earlier sequential lobe-switching techniques, monopulse systems provide instantaneous angle-error estimation, reducing susceptibility to electronic countermeasures and tracking noise. Operational advantages of monopulse tracking include high angular precision during terminal engagement phases, improved resistance to deception jamming, reduced tracking latency, and enhanced interceptor guidance accuracy. These characteristics make monopulse radar particularly effective for tracking small UAV platforms and low-altitude manoeuvring aerial threats within short-range engagement envelopes. For infrastructure-limited deployments, compact monopulse tracking modules mounted on mobile interceptor platforms provide a practical alternative to large fixed fire-control radar installations.

C. Track-While-Scan Surveillance Architectures

Track-While-Scan (TWS) radar architectures enable simultaneous monitoring of multiple aerial targets while continuing wide-area surveillance operations [23]. Unlike traditional single-target tracking radars that dedicate antenna resources to one engagement at a time, TWS systems allocate beam time dynamically across surveillance and tracking tasks. This capability allows air defence systems to maintain continuous situational awareness across large sectors, monitor swarm-type UAV incursions, prioritise engagement sequences dynamically, and support layered interceptor allocation strategies. TWS architectures are particularly important in counter-loitering munition defence scenarios where multiple low-altitude threats may approach protected infrastructure simultaneously.

Within distributed sensor-fusion environments, TWS radar outputs are typically integrated with passive RF sensing nodes and EO/IR tracking systems to improve trajectory confidence before engagement authorisation.

D. Multi-Sensor Track Fusion for Distributed Fire-Control Networks

Modern air defence systems increasingly rely on multi-sensor track fusion to improve trajectory estimation accuracy across heterogeneous sensing environments. Track fusion combines observations from radar, EO/IR sensors, passive RF detectors and acoustic arrays into a unified target state estimate. A simplified weighted fusion formulation may be expressed as:

$$x_f = \sum_{i=1}^n W_i x_i$$

where:

- x_f represents fused state estimate
- x_i represents individual sensor state estimates
- W_i represents weighting coefficients

Fusion-based tracking improves robustness against sensor outages, terrain masking, communication delays, and electronic warfare interference. This capability is particularly valuable for distributed protection of border corridors, forward operating bases, and civilian infrastructure in remote regions with sparse radar coverage.

E. Engagement Prediction and Intercept Geometry Estimation

Fire-control systems compute interception trajectories by solving relative-motion equations between interceptor platforms and manoeuvring targets. A simplified interception condition can be expressed as:

$$\vec{r}_T + \vec{v}_T t = \vec{r}_I + \vec{v}_I t$$

where:

\vec{r}_T represents target position vector

\vec{v}_T represents target velocity vector

\vec{r}_I represents interceptor launch position

\vec{v}_I represents interceptor velocity

Solving this equation determines the predicted intercept point used for guidance-law implementation. In GNSS-degraded operational environments, common in electronic-warfare-contested theatres, intercept prediction increasingly relies on inertial navigation updates combined with distributed sensor-fusion tracking inputs rather than satellite-based positioning alone.

F. Human-Supervised Fire-Control Architectures for Responsible Engagement

Modern engagement doctrines increasingly incorporate human-supervised decision loops to ensure compliance with rules of engagement and protection of civilian populations during interception operations. Fire-control architectures therefore integrate automated trajectory estimation with operator-validated engagement authorisation pipelines. Thus, human-supervised engagement frameworks enable confirmation of target classification before interceptor release, mitigation of false-positive engagements, compliance with international humanitarian law, and improved accountability within distributed command structures. These supervisory mechanisms are particularly important in stabilisation operations and peace-support environments where air defence systems may operate near civilian infrastructure such as transport hubs, refugee camps, and energy facilities.

V. COMMAND AND CONTROL FRAMEWORKS

Command and Control (C2) frameworks constitute the decision-making backbone of modern air defence systems by coordinating sensor inputs, threat classification processes, interceptor allocation strategies and engagement authorisation pipelines across distributed operational environments. Contemporary air defence effectiveness depends not only on detection capability but also on the speed, resilience and adaptability of engagement decision architectures operating under conditions of incomplete information and contested communications. The transition from centralised command hierarchies to distributed network-centric engagement frameworks represents one of the most significant structural evolutions in modern Integrated Air Defence Systems (IADS), particularly in response to low-altitude UAV threats and saturation attack scenarios.

A. Centralised Command Architectures

Early IADS relied on centralised command nodes responsible for coordinating engagement decisions across entire defensive sectors [24]. These command centres aggregated radar observations, performed target classification, and issued interceptor tasking instructions through hierarchical communication networks. Centralised command architectures provided several operational advantages including unified situational awareness across wide surveillance regions, coordinated allocation of interceptor resources, structured engagement authorisation chains, and simplified doctrinal control structures. However, such architectures were highly dependent on fixed infrastructure including hardened command bunkers, long-range communication backbones, and uninterrupted electrical power supply. As a result, centralised air defence systems remained vulnerable to electronic warfare disruption, communication node degradation, precision-strike targeting of command facilities, and network segmentation during mobile operations. These limitations are particularly significant in infrastructure-limited operational theatres where resilient national-scale communication architectures may not be continuously available.

Sensor Inputs → Tracking & Estimation → Human-Supervised Decision → Engagement

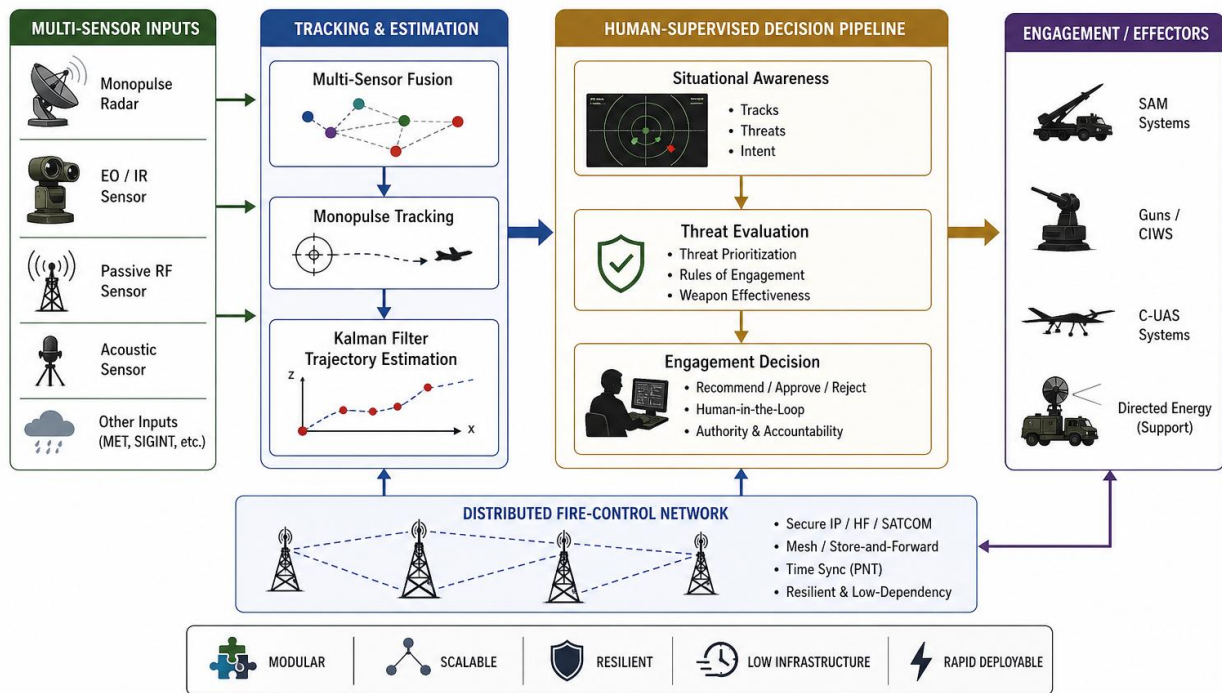


Fig. 3: Distributed engagement decision pipeline integrating sensor fusion, probabilistic threat classification, intent-based prioritisation, and adaptive interceptor allocation within resilient hybrid command-and-control architectures suitable for infrastructure-limited operational theatres.

B. Distributed Network-Centric Architectures

Modern air defence systems increasingly adopt distributed engagement decision frameworks supported by resilient communication links, local sensor-fusion nodes and adaptive interceptor coordination algorithms [25]. In network-centric architectures, decision authority is partially decentralised across multiple operational layers, allowing local engagement nodes to respond rapidly to emerging threats while maintaining coordination with higher-level command elements. Distributed command frameworks enable reduced sensor-to-decision latency, continued operation under communication degradation, adaptive engagement sequencing across multiple threat vectors, improved survivability against command-node targeting, and scalable deployment across geographically dispersed operational theatres. Such architectures are particularly suitable for defending border corridors, FOBs, humanitarian logistics routes, and dispersed infrastructure assets common in Sub-Saharan operational environments. Additionally, in distributed air defence networks, engagement authority may be dynamically reassigned depending on communication availability, sensor confidence levels, and threat proximity, enabling flexible mission execution even under degraded network conditions.

C. AI-Enabled Engagement Decision Support

Artificial-Intelligence-assisted engagement decision support systems enable rapid prioritisation of multiple aerial threats based on trajectory prediction, behavioural pattern recognition and probabilistic intent estimation. Bayesian inference models are commonly used to evaluate hostile classification likelihood based on multi-sensor observations:

$$P(H | Z) = \frac{P(Z | H)P(H)}{P(Z)}$$

where:

H represents hostile classification hypothesis

Z represents observed sensor evidence

$P(H)$ represents prior hostility probability

$P(Z | H)$ represents likelihood of observations given hostile intent

This probabilistic formulation enables ranking of detected targets according to engagement urgency within multi-threat operational environments [26]. AI-assisted prioritisation pipelines are particularly valuable in counter-UAV defence scenarios involving swarm incursions, low-altitude reconnaissance drones, loitering munition approach corridors, and simultaneous infrastructure-targeting attempts. By reducing operator cognitive workload, these systems improve decision consistency and response speed while maintaining human supervision within engagement authorisation loops.

D. Hybrid Command Architectures for Infrastructure-Limited Operational Theatres

Hybrid command frameworks combine centralised strategic coordination with decentralised tactical execution to improve operational resilience in contested environments. Within such architectures, higher command nodes provide threat intelligence integration, engagement policy enforcement, airspace coordination directives; while local engagement units perform sensor fusion, trajectory estimation, interceptor allocation, and terminal engagement execution. This layered command structure supports scalable deployment across regions where communication reliability varies significantly across operational sectors. Hybrid command architectures are particularly suitable for African operational theatres characterised by dispersed infrastructure protection requirements, intermittent communication coverage, mobile FOBs, and border surveillance corridors spanning large geographic areas. These frameworks ensure continuity of defensive operations even when higher-echelon communication links are temporarily unavailable.

E. Intent-Based Engagement Frameworks

Modern air defence systems increasingly incorporate intent-based engagement logic to distinguish between surveillance platforms, non-hostile aerial traffic, and imminent strike threats. Intent estimation integrates trajectory behaviour, velocity profiles, communication signatures, and approach geometry relative to protected assets. A simplified intent evaluation function may be expressed as:

$$I = \alpha d^{-1} + \beta v + \gamma \theta$$

where:

d represents distance to protected asset

v represents target velocity magnitude

θ represents approach-angle alignment with defended infrastructure

α, β, γ weighting coefficients

Thus, intent-based classification improves engagement selectivity and reduces false-positive interception risks during operations conducted near civilian infrastructure. This capability is especially important in stabilisation missions and humanitarian protection operations where air defence systems operate within mixed civil–military airspace environments.

F. Resilient Communication Architectures for Distributed Air Defence Networks

Reliable communication links are essential for maintaining coordination between sensing nodes, tracking systems, interceptor platforms and command elements. Modern distributed air defence systems therefore incorporate multi-layer communication architectures combining radio-frequency tactical data links, mesh-networked sensor nodes, satellite communication redundancy, line-of-sight microwave relays. Such redundancy improves survivability against electronic warfare interference and infrastructure disruption. More so, solar-powered sensor nodes with low-bandwidth burst-transmission capability are increasingly deployed to support persistent early-warning surveillance across remote operational corridors lacking fixed communication infrastructure. These architectures form the communication backbone of modular distributed air defence systems designed for scalable deployment across emerging defence ecosystems.

VI. SURFACE-TO-AIR MISSILE GUIDANCE SYSTEMS

Surface-to-Air Missile (SAM) guidance systems determine interception accuracy, engagement flexibility, and survivability against electronic-warfare countermeasures. Modern air-defence architectures employ multiple guidance strategies, including command guidance, semi-active radar homing, active radar homing, infrared tracking, and inertial navigation to ensure reliable engagement across diverse threat environments. As summarised in Table 1, each guidance method presents distinct advantages and operational limitations depending on engagement range, target manoeuvrability, electronic-warfare conditions, sensor availability, cost, logistical constraints, and infrastructure maturity.

Table 1: Surface-to-Air Missile Guidance Methods

Serial	Guidance Type	Advantages	Limitations	Typical Deployment Role	Remarks
(a)	(b)	(c)	(d)	(e)	(f)
1.	Command Guidance	Low onboard complexity; low cost; adaptable for local production	Requires continuous tracking	Short-range base defence	
2.	Semi-Active Radar Homing	High accuracy; mature technology	Vulnerable to jamming and radar suppression	Medium-range sector defence	
3.	Active Radar Homing	Autonomous terminal tracking; multi-target capability	Higher cost and complexity	Mobile layered interception	
4.	Infrared	Passive operation;	Weather sensitivity;	Point defence against	

	Homing	resistant to RF jamming	limited range	UAV threats	
5.	INS-Assisted Hybrid Guidance	GNSS-independent mid-course stability	Requires sensor integration	Distributed engagement environments	

A. Command Guidance Systems

Command guidance systems rely on external tracking radars or electro-optical sensors to compute interceptor trajectories and transmit steering commands from a ground control station to the missile during flight [27]. The interceptor trajectory correction signal may be expressed as:

$$u(t) = K(x_T(t) - x_M(t))$$

where:

- $x_T(t)$ represents target position
- $x_M(t)$ represents missile position
- K represents control gain matrix

Because trajectory computation occurs outside the interceptor, onboard avionics complexity remains minimal, making command-guided systems attractive for low-cost short-range air-defence deployments in infrastructure-constrained environments. However, continuous tracking requirements expose command-guided missiles to communication disruption, radar suppression attacks, and tracking-node degradation. Despite these limitations, command guidance remains highly suitable for protecting fixed infrastructure such as airbases, logistics depots and energy installations across emerging defence ecosystems.

B. Semi-Active Radar Homing Guidance

Semi-Active Radar Homing (SARH) missiles rely on target illumination provided by ground-based radar systems while the onboard seeker detects reflected energy to guide interception. The received echo signal strength is proportional to:

$$P_r \propto \frac{P_t G^2 \sigma}{R^4}$$

where:

- P_t Transmitted illumination power
- G Antenna gain
- σ Radar cross-section
- R Target range

SARH guidance provides high interception accuracy and remains widely used in medium-range air-defence systems. However, continuous illumination requirements increase vulnerability to electronic countermeasures, anti-radiation missiles, emitter geolocation. These constraints motivate the integration of alternative mid-course navigation modes in modern interceptor architectures.

C. Active Radar Homing Guidance

Active Radar Homing (ARH) missiles incorporate onboard radar seekers capable of autonomous terminal-phase tracking after mid-course guidance updates from ground control systems. Operational advantages include fire-and-forget engagement capability, reduced dependence on ground illumination radar, improved multi-target engagement capacity, and enhanced survivability against electronic attack. Active seekers are particularly effective against manoeuvring UAVs and loitering munitions operating within distributed threat corridors. However, higher system complexity and acquisition cost limit their widespread deployment in many developing defence environments. Compact active-seeker interceptors mounted on mobile launcher platforms nevertheless represent a promising solution for expeditionary layered air-defence protection.

D. Infrared Homing Guidance Systems

Infrared (IR) homing missiles detect thermal emissions generated by propulsion systems and aerodynamic heating signatures. Because they operate passively, IR-guided interceptors provide strong resistance to electromagnetic jamming. Its advantages include emission-free tracking capability, suitability for counter-UAV engagements, effectiveness in GNSS-denied environments, and reduced radar signature exposure. However, IR systems remain sensitive to adverse weather conditions, atmospheric attenuation, and background thermal clutter. Short-range IR interceptors are particularly effective for point defence of civilian infrastructure, including airports, command posts, and humanitarian logistics hubs.

E. Inertial and Mid-Course Navigation Guidance

Modern interceptors frequently incorporate Inertial Navigation Systems (INS) to support mid-course trajectory stabilisation prior to terminal-phase seeker activation. INS guidance enables missile operation in environments affected by GNSS denial, electronic warfare interference, and communication latency. The inertial state propagation equation may be expressed as:

$$x_{k+1} = Fx_k + Ga_k$$

where:

- x_k represents missile state vector
- F represents transition matrix
- G represents control matrix
- a_k represents measured acceleration

INS guidance ensures trajectory continuity between launch and terminal homing phases within distributed engagement architectures.

F. Hybrid Guidance Architectures for Contested Electromagnetic Environments

Modern air-defence interceptors increasingly combine multiple navigation modes within layered guidance pipelines such as including INS + command guidance, INS + SARH, INS + ARH, INS +, and IR terminal homing. These architectures improve interception reliability by maintaining engagement continuity when one sensing modality becomes degraded or unavailable. Such configurations are particularly valuable in infrastructure-limited operational theatres where radar coverage continuity cannot always be guaranteed. The strategies also support counter-loitering munition defence corridors, perimeter protection grids, and distributed airspace monitoring networks.















Guidance Method	Command Guidance (CGC)	Semi-Active Radar Homing (SARH)	Active Radar Homing (ARH)	Infrared Homing (IR)	Inertial Navigation (INS)
					
 Principle	Ground radar tracks target and sends commands	Homes on radar echo illuminated by ground radar	Uses own radar to detect, track and home	Uses IR seeker to detect and track heat signature	Guided to predicted point using inertial sensors (optional updates)
 Typical Range	Short to Long	Medium to Long	Medium to Long	Short to Medium	Medium to Long
 Maneuverability Handling	High	Moderate	High	Moderate	Low to Moderate
 EW Resistance	Moderate	Low to Moderate	High	Moderate to High	High
 Sensor / Infrastructure	Needs tracking radar and data link	Needs illuminating radar	Needs onboard active radar	Needs onboard IR seeker	Needs inertial unit (optional updates)
 Cost	Low to Moderate	Moderate	High	Moderate	Low to Moderate
 Logistical Complexity	Moderate	Moderate to High	High	Moderate	Low
 Key Advantage	Flexible, multi-target capable	Proven, high range and lethality	Fire-and-forget, high ECCM	Passive, effective against emissions	All-weather, not emission-dependent
 Key Limitation	Needs continuous link and operator support	Vulnerable to EW and illumination loss	Higher cost, seeker limits	Affected by weather, flares, background	Drift over time, needs updates

Fig. 4: Operational characteristics of major SAM guidance systems.

Figure 4 presents a comparative overview of major SAM guidance methods, highlighting their operational principles, engagement ranges, manoeuvrability handling capability, resistance to electronic warfare (EW), infrastructure requirements, and relative cost-complexity trade-offs. As illustrated in Fig. 4, command guidance offers flexibility and multi-target engagement support but depends heavily on continuous radar tracking and data links, whereas SARH provides extended engagement range at the expense of vulnerability to illumination disruption. In contrast, ARH enables fire-and-forget capability with strong ECCM performance, though at higher system complexity and cost. Infrared homing supports passive engagements against low-emission targets but remains susceptible to environmental interference and countermeasures, while INS provide all-weather mid-course guidance with minimal emissions dependence, typically requiring terminal updates for improved accuracy.

VII. GUN-BASED SHORT-RANGE AIR DEFENCE SYSTEMS

Gun-based Short-Range Air Defence (SHORAD) systems remain an essential component of layered air-defence architectures, particularly for terminal-layer protection against low-altitude threats such as small UAVs, loitering munitions, rockets, and improvised airborne surveillance platforms. Unlike missile-based interceptors, gun systems provide rapid engagement response, lower per-shot cost, and high sustainability during saturation attacks, making them especially suitable for defending FOBs, logistics corridors, and civilian infrastructure nodes in infrastructure-limited operational theatres [28]. As illustrated in Fig. 5, modern SHORAD gun-based architectures integrate radar cueing, electro-optical tracking modules, and programmable airburst ammunition control to improve interception probability against small, manoeuvring aerial targets within distributed terminal-layer protection networks.



Fig. 5: Gun-based (SHORAD) architecture for terminal-layer protection against low-altitude threats.

A. Operational Role of Gun-Based SHORAD in Layered Air Defence Architectures

Gun-based SHORAD systems typically operate within the **terminal engagement layer** of a multi-tier air-defence structure, complementing medium-range missile interceptors and distributed sensor networks. Their primary operational roles include counter-UAV terminal interception, protection against rocket and mortar threats, defence against low-flying helicopters, close-in defence of high-value infrastructure, and redundancy support when missile inventories are limited. Because gun systems rely on kinetic engagement rather than seeker-guided interception, they remain effective even in environments affected by GNSS denial, electronic warfare interference, and radar illumination degradation. This resilience makes them particularly valuable for stabilisation operations and perimeter-defence missions across dispersed operational corridors.

B. Ballistic Intercept Geometry for Gun-Based Engagement Systems

Successful interception using gun-based SHORAD platforms requires accurate prediction of projectile–target intersection geometry under time-of-flight constraints. A simplified intercept condition may be expressed as:

$$\mathbf{r}_T(t) = \mathbf{r}_G + \mathbf{v}_p t$$

where:

- $\mathbf{r}_T(t)$ represents predicted target position
- \mathbf{r}_G represents gun location
- \mathbf{v}_p represents projectile velocity vector

Because projectile velocity is finite and subject to aerodynamic drag, fire-control systems must compute lead-angle corrections based on target velocity, engagement distance, projectile time of flight, and atmospheric conditions. Modern radar-assisted fire-control computers automate these corrections in real time, enabling engagement of manoeuvring UAV targets within short reaction windows.

C. Programmable Airburst Ammunition Technologies

Programmable airburst ammunition represents one of the most significant advancements in gun-based SHORAD capability. These munitions detonate at a calculated distance from the target, dispersing sub-projectiles or fragmentation patterns within a predefined engagement volume.

Airburst detonation distance may be approximated as:

$$d_b = v_p \cdot t_f$$

where:

- d_b represents burst distance
- v_p represents projectile velocity
- t_f represents programmed fuse delay

This mechanism significantly increases interception probability against small quadcopters, fixed-wing loitering munitions, rocket artillery threats, and swarm UAV formations. Compared with point-impact ammunition, programmable airburst rounds create a volumetric lethality envelope that compensates for tracking uncertainty and target manoeuvrability.

D. Radar-Cueing and Electro-Optical Fire-Control Integration

Modern SHORAD gun systems increasingly rely on sensor-fusion-enabled fire-control architectures integrating short-range tracking radar, EO/IR targeting modules, laser range finders, and acoustic detection arrays. Improves engagement accuracy by enabling continuous target tracking across cluttered environments where radar-only detection may be insufficient. This capability is particularly important in urban defence environments, and border-corridor monitoring operations, infrastructure-protection missions, and humanitarian stabilisation theatres. Solar-powered EO/IR towers can also provide passive cueing support for gun-based interception systems deployed in remote regions without fixed electrical infrastructure.

E. Mobile SHORAD Platforms for Expeditionary Deployments

Truck-mounted and tripod-mounted SHORAD gun systems provide flexible protection for mobile formations and temporary operational bases. These platforms enable rapid repositioning in response to evolving threat corridors and support distributed deployment across wide surveillance sectors. Typical expeditionary deployment configurations include pickup-mounted autocannon platforms, trailer-mounted stabilised gun systems, remote weapon stations with EO tracking, and tripod-mounted perimeter defence guns. Such configurations are particularly suited to African operational environments characterised by dispersed infrastructure assets, extended border surveillance requirements, limited fixed radar coverage, mobile logistics protection needs. Mobile SHORAD platforms therefore represent a critical component of scalable distributed air-defence architectures.

F. Counter-UAV Swarm Defence Using High-Rate-of-Fire Gun Systems

The emergence of coordinated UAV swarm threats has renewed interest in high-rate-of-fire autocannon systems capable of engaging multiple targets within short engagement intervals. Gun-based SHORAD systems provide advantages over missile interceptors in swarm scenarios due to rapid engagement cycling, lower cost per engagement, reduced dependence on seeker tracking, and volumetric lethality with airburst ammunition. When integrated with **track-while-scan** radar and EO cueing nodes, these systems form an effective terminal defensive layer for protecting airfields, command centres, energy infrastructure, and civilian transport hubs.

G. Role of Gun-Based SHORAD in Infrastructure-Limited Defence Ecosystems

In many developing defence environments, the cost, maintenance requirements and logistical complexity of missile-centric air-defence systems constrain large-scale deployment. Gun-based SHORAD systems therefore provide a practical and scalable alternative for achieving baseline airspace protection capability. Its advantages include low acquisition cost, simplified maintenance requirements, compatibility with locally supported platforms, suitability for indigenous upgrade programmes, and adaptability to distributed deployment architectures. These characteristics make gun-based SHORAD systems particularly attractive as foundational components of modular distributed air-defence architectures designed to protect both military installations and civilian infrastructure across emerging security environments.

VIII. DIRECTED-ENERGY AIR DEFENCE SYSTEMS

Directed-Energy (DE) air-defence systems represent an emerging interception technology class capable of engaging aerial threats using concentrated electromagnetic energy rather than kinetic projectiles. High-Energy Laser (HEL) systems are particularly attractive for counter-UAV defence due to their near-instantaneous engagement response, precision targeting capability, and extremely low marginal cost per shot compared with missile-based interceptors [29]. As illustrated in Fig. 6, DE interceptors are increasingly integrated into layered air-defence architectures as terminal-layer protection systems supporting defence against small Unmanned Aerial Systems (sUAS), loitering munitions, and improvised aerial surveillance platforms within distributed infrastructure-protection environments.

A. Operating Principles of HEL Interceptors

HEL air-defence systems disable aerial targets by depositing concentrated thermal energy onto structural or propulsion components. Target neutralisation occurs when absorbed laser energy exceeds the material damage threshold:

$$E_d = P_L \cdot t_e$$

where:

E_d represents delivered energy on target

P_L represents laser output power

t_e represents dwell time on target

Successful engagement therefore depends on maintaining sufficient beam stability and tracking accuracy during the illumination interval. Laser interceptors are particularly effective against quadcopters, fixed-wing tactical UAVs, loitering munition airframes, and exposed sensor payloads. These targets typically possess lightweight composite structures vulnerable to thermal degradation.

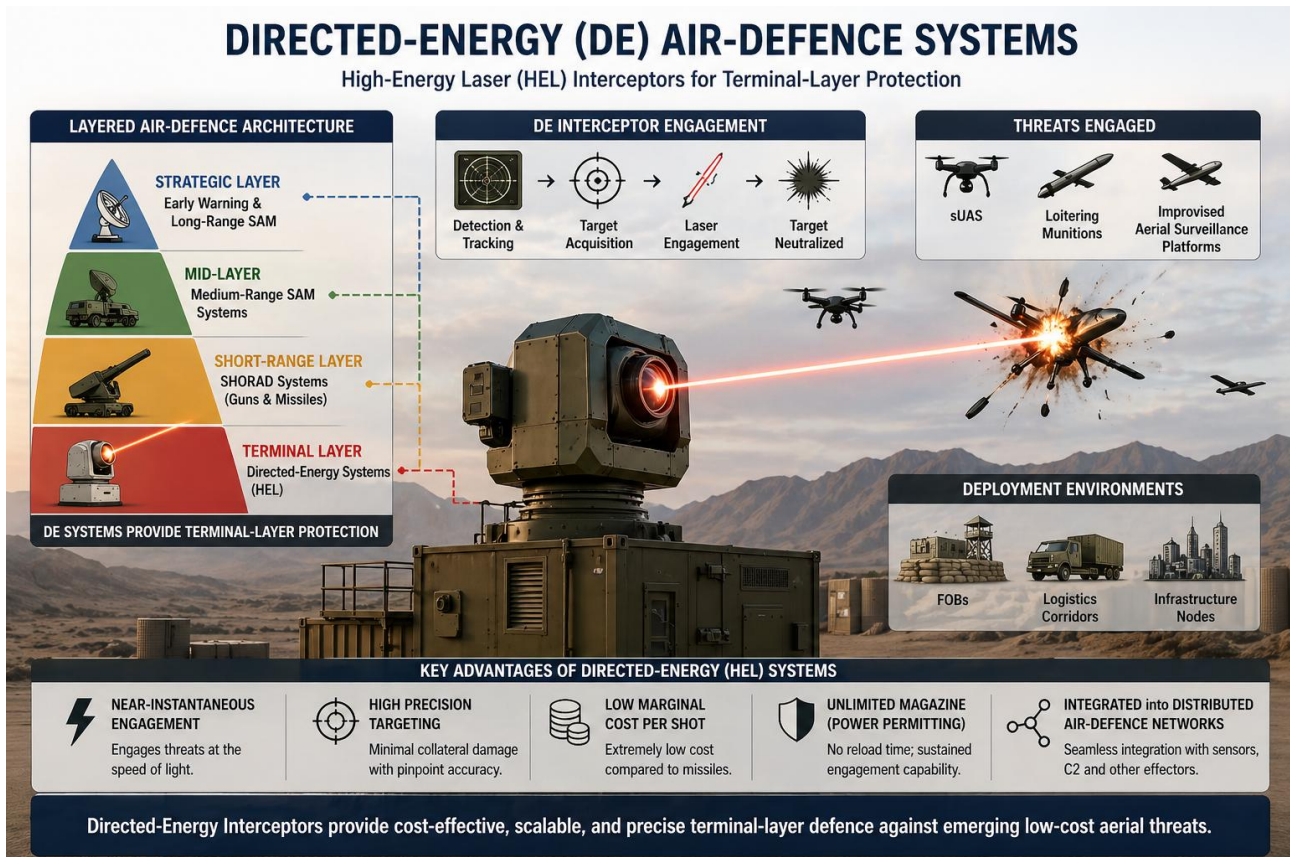


Fig. 6: DE (HEL) air-defence architecture for terminal-layer protection against low-altitude aerial threats.

B. Advantages of DE Air Defence Systems

DE interception technologies provide several operational advantages within distributed air-defence architectures, including: near-instantaneous engagement speed, negligible ballistic flight time, deep engagement magazines limited primarily by electrical power availability, reduced logistics burden, compared with missile interceptors, and high precision with minimal collateral damage risk. These characteristics make HEL systems especially suitable for protecting: FOBs, airfields, logistics hubs, communication infrastructure, and civilian population centres. Their scalability also supports deployment within modular distributed air-defence networks.

C. Atmospheric Propagation Constraints

Despite their advantages, laser interception performance is strongly influenced by atmospheric attenuation effects including aerosol scattering, water vapour absorption, turbulence-induced beam distortion, and dust-particle interference. Beam propagation loss may be approximated using:

$$P_r = P_t e^{-\alpha R}$$

where:

- P_r represents received power at target
- P_t represents transmitted laser power
- α represents atmospheric attenuation coefficient
- R represents engagement distance

These constraints are particularly relevant in desert, coastal and humid tropical environments common across many African operational theatres. Consequently, DE systems are most effective when integrated as terminal-layer interception components within hybrid air-defence architectures rather than as standalone engagement platforms.

D. DE Systems in Distributed Air Defence Architectures

Within modular distributed air-defence systems, laser interceptors provide silent engagement capability, rapid response against swarm UAV threats, redundancy when missile inventories are constrained, AND precision neutralisation near protected infrastructure. Solar-assisted mobile laser platforms represent a promising research direction for persistent perimeter defence applications across infrastructure-limited regions lacking continuous grid power availability. Such architectures align naturally with emerging indigenous distributed air-defence concepts suitable for Sub-Saharan operational environments.

IX. INTERCEPTION GEOMETRY AND GUIDANCE MODELLING

Accurate interception of manoeuvring aerial targets requires predictive trajectory estimation and adaptive guidance-law implementation within fire-control systems. Modern interceptor guidance architectures rely on kinematic prediction models combined with proportional navigation control strategies to ensure convergence toward predicted intercept points under dynamic engagement conditions. As illustrated in Fig. 7, interception geometry based on PN enables continuous correction of the interceptor trajectory relative to target motion, forming the mathematical foundation of both missile-based and gun-based air-defence interception pipelines.

INTERCEPTION GEOMETRY AND GUIDANCE MODELLING

Predictive Estimation and Adaptive Guidance for Manoeuvring Target Interception

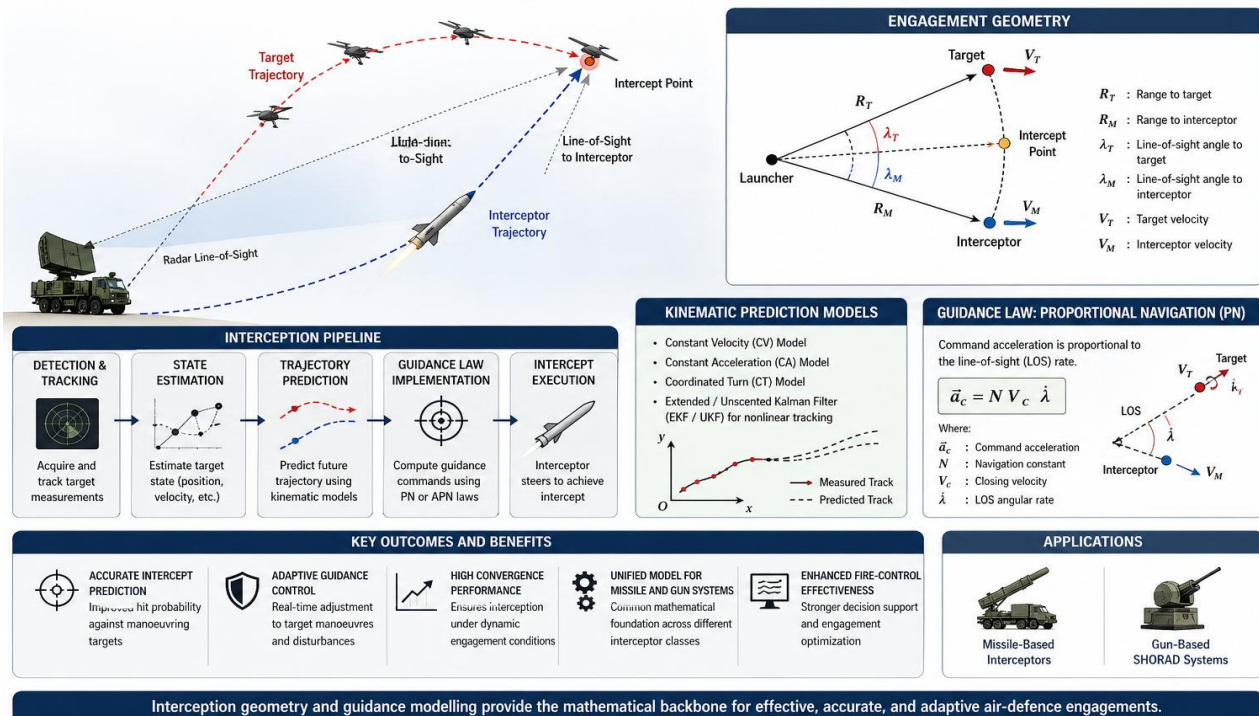


Fig. 7: Interception Geometry and PN-Based guidance modelling for manoeuvring target engagement.

A. Target Motion Modelling

The motion of an aerial target under constant acceleration may be expressed using classical kinematic equations:

$$x(t) = x_0 + vt + \frac{1}{2}at^2$$

where:

- x_0 represents initial target position
- v represents target velocity
- a represents acceleration
- t represents elapsed time

Such models enable prediction of future target position within radar tracking pipelines and Kalman-filter-based estimation frameworks. Trajectory prediction accuracy directly influences interception probability in distributed sensor-fusion environments.

B. Time-to-Intercept Estimation

Time-to-intercept estimation provides a first-order approximation of engagement feasibility and determines whether interceptor launch conditions are satisfied. A simplified expression is given by:

$$t = \frac{d}{V_{\text{rel}}}$$

where:

- d represents relative distance between interceptor and target
- V_{rel} represents closing velocity

This parameter supports engagement prioritisation within multi-target interception scenarios typical of counter-UAV swarm defence operations.

C. Proportional Navigation Guidance Law

Proportional Navigation (PN) guidance remains the dominant control strategy used in modern interceptor systems due to its computational efficiency and robustness against manoeuvring targets. The lateral acceleration command is expressed as [19]:

$$a_n = NV_c \dot{\lambda}$$

where:

- a_n represents commanded normal acceleration
- N represents navigation constant
- V_c represents closing velocity
- $\dot{\lambda}$ represents line-of-sight angular rate

This guidance law ensures that interceptor acceleration remains proportional to the rate of change of the line-of-sight angle between interceptor and target. PN guidance provides stable interception trajectories, reduced control complexity, robustness against moderate target manoeuvres, compatibility with radar and EO-based tracking inputs. For distributed air-defence architectures operating under intermittent sensor updates, augmented PN variants incorporating Kalman-filtered trajectory estimates further improve interception reliability.

D. Latency-Aware Guidance in Distributed Engagement Networks

In distributed air-defence environments, communication latency between sensing nodes and interceptor platforms can degrade trajectory prediction accuracy. Latency-compensated interception models therefore incorporate delayed-state correction terms:

$$x(t + \Delta t) = x(t) + \dot{x}(t)\Delta t$$

where:

- Δt represents communication delay interval

Such compensation mechanisms are essential for maintaining engagement accuracy across mesh-networked sensor grids, remote EO surveillance towers, passive RF detection nodes, and mobile interceptor launch platforms. Latency-aware PN frameworks are particularly relevant for modular distributed air-defence systems designed for geographically dispersed infrastructure-protection operations.

X. LAYERED AIR DEFENCE CLASSIFICATION

Layered air-defence architectures improve interception probability by engaging aerial threats across multiple defensive envelopes arranged according to engagement range, response time and interceptor capability. Rather than relying on a single interception tier, modern systems deploy complementary detection and engagement layers that increase survivability against manoeuvring targets, saturation attacks, and low-altitude penetration threats [31]. As illustrated in Fig. 8, these layered structures integrate SHORAD, MRAD, and LRAD engagement zones to provide continuous protection across terminal, sector, and strategic defence envelopes, particularly in infrastructure-limited operational theatres where sensor coverage continuity may vary across geographic sectors.

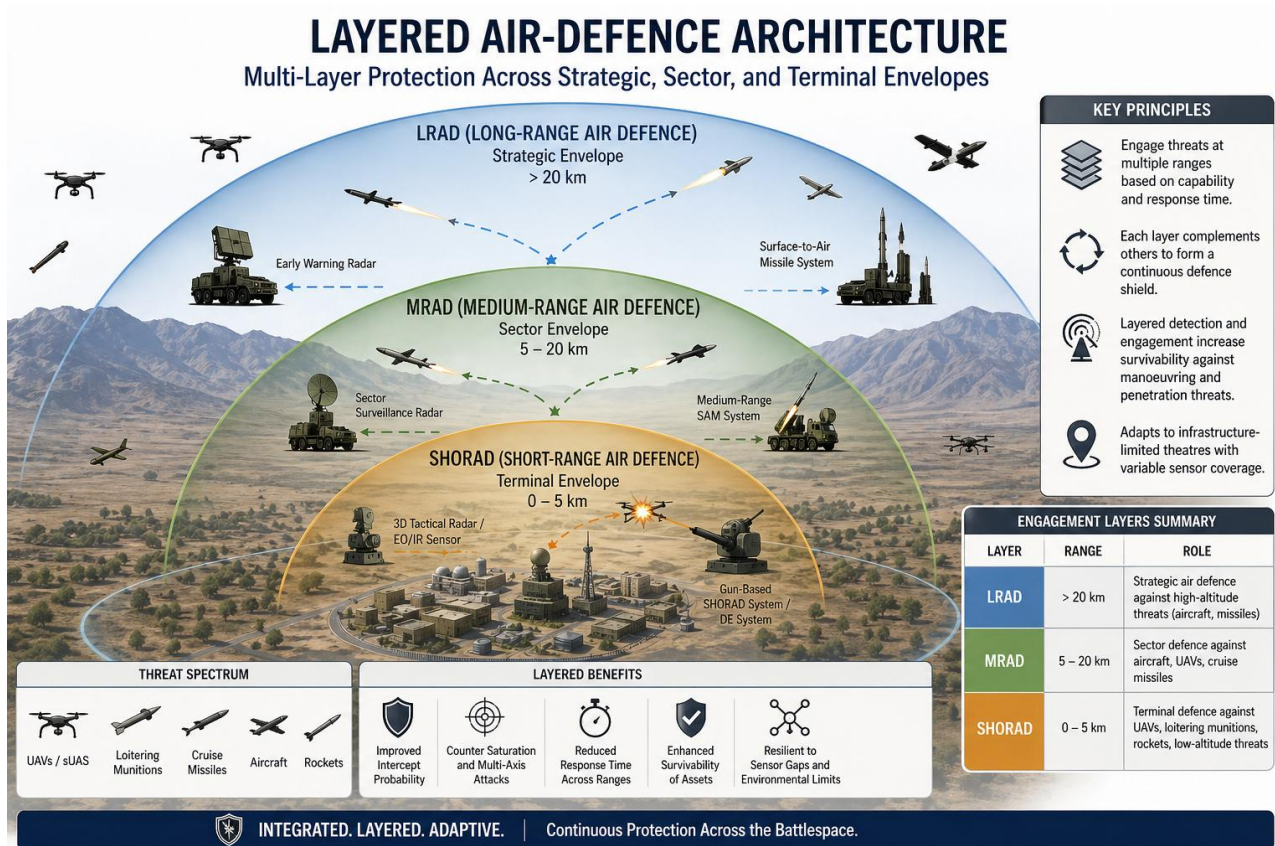


Fig. 8: Layered SHORAD–MRAD–LRAD air-defence architecture for multi-envelope protection in infrastructure-limited operational theatres.

A. Concept of Multi-Layer Engagement Envelopes

Layered air defence operates by allocating threats to engagement zones defined by interceptor capability and reaction timelines. Each layer contributes redundancy to the overall defence architecture and reduces the probability of successful target penetration. A simplified cumulative interception probability model may be expressed as:

$$P_{kill,total} = 1 - \prod_{i=1}^n (1 - P_{kill,i})$$

where:

$P_{kill,total}$ represents total interception probability

$P_{kill,i}$ represents interception probability of the i^{th} defensive layer

This formulation illustrates how multi-layer engagement architectures significantly improve overall defensive effectiveness compared with single-layer interception systems. Such redundancy is especially important when defending airbases, logistics depots, energy infrastructure, transport corridors, humanitarian protection zones across geographically dispersed operational environments.

B. SHORAD) Layer

The SHORAD layer typically covers engagement ranges between 0 km and 15 km and provides terminal protection against low-altitude aerial threats including small UAVs, loitering munitions, helicopters and short-range rocket systems. Typical SHORAD components include gun-based interception platforms, infrared-guided interceptors, short-range radar tracking modules, and EO/IR surveillance towers. Because SHORAD systems operate within the terminal defence envelope, they provide the final interception opportunity before threat impact on protected infrastructure. In many African operational environments, SHORAD architectures represent the most deployable and cost-effective baseline air-defence capability.

C. Medium-Range Air Defence (MRAD) Layer

Medium-range air defence (MRAD) systems typically operate within engagement distances between 15 km and 75 km and provide protection against tactical aircraft, cruise missiles, larger UAV platforms, and stand-off precision-guided munitions. MRAD architectures rely heavily on radar cueing networks integrated with semi-active or active radar homing interceptors. These systems provide area-defence coverage across extended operational sectors and support coordinated engagement sequencing with SHORAD layers. Distributed MRAD nodes mounted on mobile launcher platforms enable flexible repositioning across evolving threat corridors.

D. Long-Range Air Defence (LRAD) Layer

Long-Range Air Defence (LRAD) systems extend engagement coverage between approximately 75 km and 400 km and are primarily designed to counter high-altitude aircraft, ballistic missile threats, and strategic reconnaissance platforms. These architectures depend on early-warning radar networks, high-power tracking systems, and advanced interceptor guidance pipelines. Although large-scale LRAD deployments remain infrastructure-intensive, modular variants incorporating mobile radar units and distributed interceptor batteries are increasingly being explored for scalable regional protection architectures across emerging defence ecosystems.

Table 2: Air Defence Engagement Layers

Serial	Layer	Engagement Range	Typical Targets	Operational Role	Remarks
(a)	(b)	(c)	(d)	(e)	(f)
1.	SHORAD	0–15 km	UAVs, helicopters, rockets	Terminal infrastructure protection	
2.	MRAD	15–75 km	Tactical aircraft, cruise missiles	Sector-level airspace denial	
3.	LRAD	75–400 km	Ballistic missiles, ISR aircraft	Strategic early interception	

Table 2 summarises the functional classification of layered air-defence engagement zones SHORAD, MRAD and LRAD, showing how interception responsibilities are distributed across increasing engagement ranges to counter different categories of aerial threats. The table highlights the complementary operational roles of each layer, from terminal protection of critical infrastructure against UAVs and rockets, through sector-level denial against tactical aircraft and cruise missiles, to strategic early interception of ballistic missiles and high-value ISR platforms, thereby illustrating the importance of multi-layered defence architectures for comprehensive airspace protection.

XI. COUNTER-UAV AIR DEFENCE SYSTEMS

The rapid proliferation of commercial and improvised UAVs has fundamentally transformed the threat landscape confronting modern air-defence systems. Low-cost UAV platforms now enable surveillance, targeting support and precision-strike operations by both state and non-state actors, requiring the development of specialised counter-UAS detection and interception architectures [32]. As illustrated in Fig. 9, effective counter-UAV defence increasingly depends on distributed sensing networks integrating radar, passive RF monitoring, EO/IR tracking, and acoustic detection to address the low altitude, small radar cross-section, reduced acoustic signature, and intermittent communication behaviour typical of UAV threats. These characteristics necessitate multi-layered detection approaches rather than reliance on traditional radar-centric surveillance architectures.

Counter-UAV Threat Landscape and Multi-Layered Detection Architecture

Integrated, Distributed Sensing for Effective Detection of Low-Altitude, Small, and Advanced UAV Threats

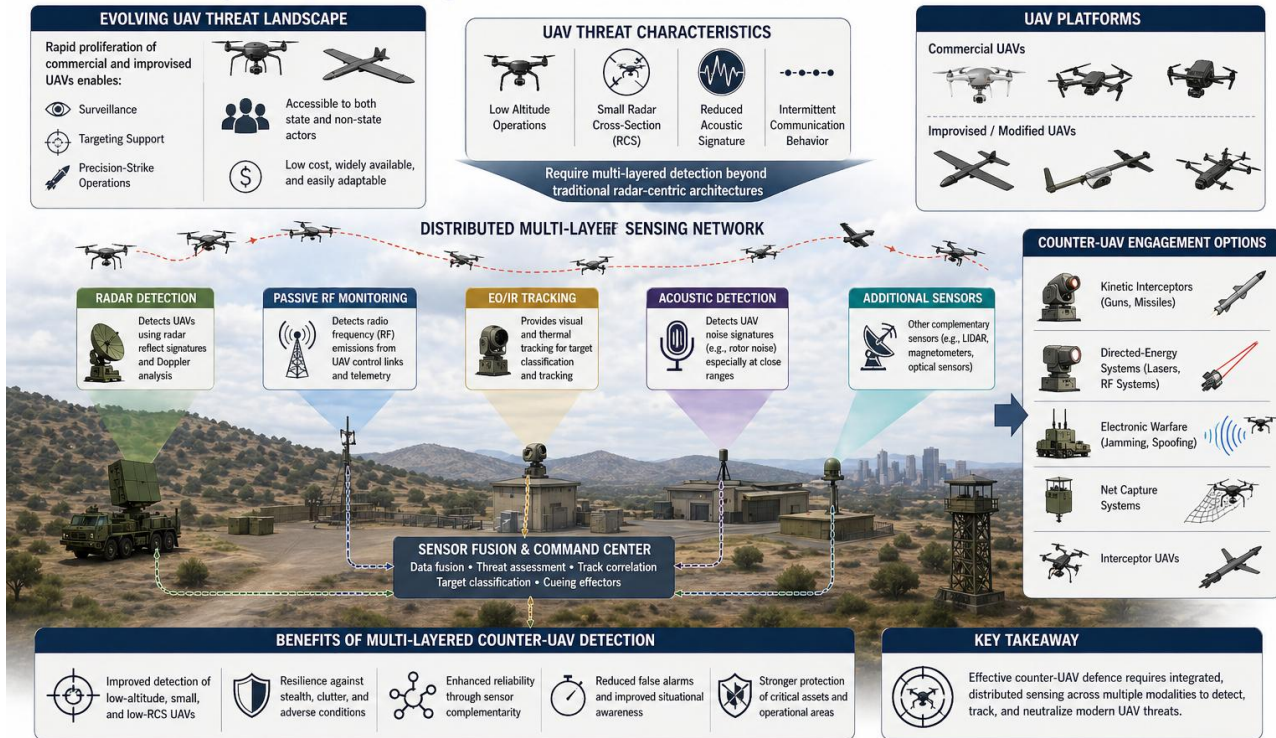


Fig. 9: Distributed multi-sensor counter-UAV detection architecture integrating radar, passive RF, EO/IR and acoustic surveillance for low-altitude threat environments.

A. RF Signal Monitoring for UAV Detection

Radio-frequency signal monitoring systems detect communication links between UAV platforms and ground-control stations by analysing transmission signatures across operational frequency bands. RF monitoring enables early warning of UAV presence, identification of control-link directionality, localisation of operator position, and detection of swarm coordination signals. Passive RF detection nodes are particularly effective for deployment within solar-powered perimeter monitoring grids supporting surveillance across remote infrastructure corridors.

B. Micro-Doppler Radar Classification Techniques

Micro-Doppler radar classification exploits characteristic rotor-blade modulation signatures produced by rotary-wing UAV propulsion systems to distinguish drones from birds and other airborne clutter objects. Micro-Doppler frequency signatures may be approximated as:

$$f_{md} = \frac{2v_r}{\lambda}$$

where:

f_{md} represents micro-Doppler frequency shift

v_r represents rotor radial velocity

λ represents radar wavelength

These signatures support automated classification pipelines within AI-assisted detection architectures. Micro-Doppler radar sensing is especially effective in cluttered urban environments where conventional radar classification performance may be degraded.

C. Acoustic Detection Arrays

Acoustic detection arrays identify UAV propulsion signatures using distributed microphone networks capable of detecting characteristic spectral patterns associated with rotor-based aerial platforms. Its advantages include passive operation, low deployment cost, suitability for GNSS-denied environments, and compatibility with solar-powered sensing nodes. Such arrays are particularly useful for perimeter defence of FOBs, refugee protection zones, border observation corridors, and remote infrastructure installations.

D. Electro-Optical Target Recognition Systems

Electro-optical target recognition systems enable visual confirmation and classification of detected aerial objects using computer vision pipelines supported by machine-learning-based object detection algorithms. EO-based classification improves engagement confidence levels, false-alarm suppression, and target intent estimation reliability. These systems are especially important within human-supervised engagement architectures operating near civilian airspace environments.

E. Distributed Counter-UAV Defence Grids

Distributed sensing architectures significantly improve detection reliability against swarm-based aerial threats by combining heterogeneous sensor observations across multiple surveillance nodes [33]. A simplified distributed detection confidence model may be expressed as:

$$P_D = 1 - \prod_{i=1}^n (1 - P_i)$$

where:

P_D represents overall detection probability

P_i represents detection probability of individual sensing nodes

Distributed counter-UAV grids therefore provide scalable protection across airfield perimeters, logistics corridors, border surveillance sectors, and humanitarian infrastructure protection zones. These architectures form a critical component of next-generation modular distributed air defence systems designed for emerging defence ecosystems.

XII. AIR DEFENCE IN INFRASTRUCTURE-LIMITED ENVIRONMENTS

Air-defence operations in infrastructure-limited environments require architectures capable of functioning under constraints such as unreliable electrical power supply, sparse radar coverage, degraded communications networks, and geographically dispersed protected assets. These conditions are characteristic of many operational theatres across Sub-Saharan Africa, border stabilisation corridors, and humanitarian protection environments, where conventional fixed IADS cannot be deployed economically or sustainably [34]. As illustrated in Fig. 10, scalable protection strategies increasingly rely on distributed sensing nodes, mobile interception platforms, and resilient mesh-network command structures capable of maintaining operational continuity despite intermittent infrastructure availability, particularly for forward operating bases and civilian-infrastructure protection missions.



Fig. 10: Distributed air-defence architecture for infrastructure-limited operational theatres using mobile interceptors, sensor nodes, and resilient mesh-network command structures.

A. Solar-Powered Persistent Sensing Nodes

Solar-assisted sensing nodes provide long-duration surveillance capability in regions lacking grid-connected electrical infrastructure. Typical deployments integrate electro-optical surveillance towers, passive RF monitoring receivers, and acoustic detection arrays compact short-range radar modules. Such nodes enable continuous monitoring of border corridors, pipeline infrastructure, logistics supply routes, and forward operating base perimeters. Energy availability for persistent sensing operation may be approximated as:

$$E = \eta A I t$$

where:

- η represents panel efficiency
- A represents panel surface area
- I represents solar irradiance
- t represents exposure duration

Solar-assisted sensing architectures significantly reduce logistical dependency on generator fuel supply chains, improving operational sustainability in remote deployment environments.

B. Passive Detection Architectures

Passive detection frameworks provide covert surveillance capability without emitting electromagnetic radiation, thereby reducing vulnerability to anti-radiation targeting and electronic warfare interference. These architectures typically combine RF emission triangulation, acoustic signature detection, and EO/IR confirmation pipelines. Passive sensing layers are especially effective against communication-enabled UAV platforms operating at low altitude within cluttered urban and semi-urban environments. Their low power requirements make them well suited for integration into distributed perimeter defence grids supporting infrastructure protection missions.

C. Mobile Interceptor Platforms

Mobile interceptor platforms enable flexible engagement coverage across geographically dispersed operational sectors where fixed launcher installations are impractical. Representative deployment configurations include pickup-mounted SHORAD autocannon systems, trailer-mounted short-range missile launchers, tripod-mounted EO-guided interceptors, and vehicle-integrated directed-energy protection modules. Mobility improves survivability by enabling repositioning in response to evolving threat corridors and supports layered defence coverage for temporary operational sites and mobile humanitarian protection zones.

D. Resilient Mesh Communication Systems

Distributed air defence architectures require communication networks capable of maintaining connectivity under degraded infrastructure conditions. Mesh-networked sensing nodes allow decentralised information exchange between detection elements without reliance on centralised communication hubs. Network availability may be approximated as:

$$P_{network} = 1 - \prod_{i=1}^n (1 - P_{link,i})$$

where:

- $P_{network}$ represents overall network availability
- $P_{link,i}$ represents reliability of individual communication links

Such architectures improve operational resilience against communication disruption and enable scalable deployment across extended surveillance corridors typical of infrastructure-limited theatres [36], [37], [39].

XIII. EMERGING TECHNOLOGICAL DIRECTIONS

Future air-defence systems are expected to evolve toward adaptive, distributed, and autonomy-assisted interception architectures capable of operating effectively within contested electromagnetic environments and infrastructure-limited operational theatres. Advances in AI, resilient navigation systems, distributed sensing networks, and DE interception technologies are reshaping defensive airspace protection strategies across both conventional and asymmetric threat environments [36]–[39]. As illustrated in Fig. 11, these emerging capabilities are converging into integrated, network-enabled protection frameworks that combine intelligent decision-support systems, GNSS-resilient navigation, and multi-layer sensor fusion to enable scalable and mobile air-defence coverage across dispersed operational areas. These developments are particularly significant for emerging defence ecosystems seeking scalable protection solutions compatible with mobile deployment requirements and constrained infrastructure availability.

A. AI-Enabled Engagement Ranking and Decision Support

AI techniques increasingly support automated threat prioritisation by analysing multi-sensor observations, trajectory behaviour, and infrastructure proximity metrics to estimate engagement urgency levels. A simplified engagement ranking formulation may be expressed as:

$$S = w_1 d^{-1} + w_2 v + w_3 \dot{\lambda} + w_4 C$$

where:

- d represents distance to protected asset
- v represents target velocity
- $\dot{\lambda}$ represents line-of-sight angular rate
- C represents classification confidence score
- w_1, w_2, w_3, w_4 represent weighting coefficients

Such prioritisation pipelines enable rapid allocation of interception resources during multi-target engagement scenarios, including UAV swarm incursions and corridor-based reconnaissance threats.

AI-assisted engagement ranking also reduces operator cognitive workload and improves decision consistency within human-supervised command architectures, consistent with recent AI-enabled threat evaluation frameworks in distributed defence systems [29].

Adaptive, Distributed, and Autonomy-Assisted Protection for Contested and Infrastructure-Limited Environments



Fig. 11: Emerging AI-enabled distributed air-defence architecture integrating resilient navigation, multi-sensor fusion and DE interception for contested operational environments.

B. GNSS-Denied Navigation Architectures

Modern air defence systems must increasingly operate in environments where satellite navigation signals are degraded or unavailable due to jamming, spoofing, or terrain masking. As a result, interceptor platforms and sensing nodes increasingly rely on alternative navigation frameworks such as INS, Terrain-Referenced Navigation (TRN), visual odometry pipelines, and cooperative localisation within sensor networks. State propagation under inertial navigation may be expressed as:

$$x_{k+1} = Fx_k + Ga_k$$

where:

- x_k represents platform state vector
- F represents transition matrix
- G represents control matrix
- a_k represents measured acceleration

GNSS-independent navigation architectures are particularly important for distributed air defence deployments across remote border corridors and stabilisation theatres where persistent satellite navigation availability cannot be assumed.

C. Distributed Sensor Networks for Persistent Surveillance Coverage

Distributed sensing architectures integrating radar nodes, passive RF receivers, EO/IR towers and acoustic detection arrays significantly improve detection reliability against low-observable aerial threats. Sensor-network detection confidence may be approximated as:

$$P_D = 1 - \prod_{i=1}^n (1 - P_i)$$

where:

P_D represents overall detection probability

P_i represents detection probability of individual sensing nodes

Distributed sensor grids enable scalable protection across airfield perimeters, border surveillance corridors, logistics supply routes, energy transmission infrastructure, humanitarian protection zones. Such architectures form the sensing backbone of modular distributed air defence systems suitable for infrastructure-limited environments.

D. DE Technologies

DE interception platforms are expected to play an increasing role in counter-UAV defence due to their rapid response capability, reduced per-engagement cost, and precision targeting performance. High-energy laser systems enable silent interception operations, deep engagement magazines limited primarily by power availability, minimal collateral damage risk, and effectiveness against small UAV platforms. Mobile directed-energy protection units integrated with solar-assisted power systems represent a promising future capability for persistent perimeter defence deployments across remote operational theatres.

XIV. RESEARCH GAPS FOR DEVELOPING DEFENCE ECOSYSTEMS

Despite substantial advances in modern IADS, significant capability gaps remain across developing defence ecosystems where conventional radar-centric architectures are difficult to deploy at scale. These constraints arise primarily from infrastructure limitations, procurement cost barriers, communication-network fragility, and the growing prevalence of low-cost asymmetric aerial threats.

Addressing these gaps requires the development of modular, distributed and infrastructure-adaptive air defence architectures capable of supporting scalable protection coverage across geographically dispersed operational theatres. Key gaps include:

A. Limited Radar Coverage Continuity

Conventional air defence architectures rely heavily on fixed early-warning radar installations that require stable electrical infrastructure, hardened deployment sites, and continuous maintenance support. In many emerging defence environments, radar coverage continuity is constrained by terrain masking across forested and mountainous regions, sparse national surveillance networks, limited deployment density of tracking radars, and vulnerability of fixed radar nodes to precision targeting. As a result, low-altitude UAV platforms frequently exploit coverage gaps within national airspace surveillance grids. Future research is therefore required to develop hybrid sensing architectures integrating passive RF detection nodes, acoustic sensing arrays, EO/IR surveillance towers, and compact mobile radar platforms into distributed detection networks capable of improving coverage redundancy.

B. Constrained Electrical Power Infrastructure

Persistent operation of radar surveillance networks and interceptor launch platforms depends on reliable energy supply systems. However, infrastructure-limited operational theatres frequently experience intermittent grid availability, generator fuel supply constraints, and maintenance limitations for high-power radar installations. These conditions reduce operational availability of traditional IADS deployments. Research is therefore needed on energy-adaptive sensing architectures incorporating solar-powered surveillance nodes, low-power passive detection frameworks, mobile energy-assisted interceptor platforms, and hybrid energy-storage-supported detection towers. Such solutions enable persistent monitoring coverage across remote operational corridors.

C. Communications Network Fragility

Centralised command architectures depend on high-reliability communication backbones linking surveillance sensors, tracking radars, interceptor platforms and engagement coordination nodes. In many developing defence ecosystems, communication networks remain vulnerable to bandwidth limitations, terrain-induced signal obstruction, infrastructure disruption during conflict operations, and electronic warfare interference. These constraints degrade sensor-to-decision latency performance and reduce interception reliability. Future air defence architectures must therefore incorporate mesh-networked sensing nodes, decentralised engagement decision frameworks, redundant communication pathways, and latency-compensated guidance pipelines to maintain operational continuity across distributed deployment environments.

D. High Interceptor Procurement and Sustainment Costs

Missile-based interception systems remain among the most expensive components of layered air defence architectures. Acquisition and lifecycle sustainment costs often limit deployment density across extended operational sectors. Research is therefore needed to evaluate cost-effective alternatives including gun-based SHORAD interception platforms, DE terminal-layer interceptors, hybrid command-guided missile architectures, and distributed interceptor allocation strategies. Such approaches support scalable protection coverage without reliance on high-density missile inventories.

E. Limited Indigenous Air Defence Technology Integration Capacity

Many emerging defence ecosystems rely heavily on externally procured air defence platforms that may not be optimised for local terrain conditions, infrastructure constraints, or asymmetric threat environments. Limited domestic integration capability restricts sensor customisation flexibility, maintenance autonomy, upgrade pathways, and interoperability with national command networks. Future research should therefore prioritise development of modular open-architecture sensing frameworks, interoperable command-and-control interfaces, locally maintainable interceptor platforms, and scalable distributed deployment strategies. These capabilities improve long-term sustainability of national air defence architectures.

F. Protection Requirements for Dispersed Civilian Infrastructure

Conventional IADS architectures are primarily designed for protection of strategic military installations rather than geographically dispersed civilian infrastructure assets. However, the increasing availability of low-cost UAV platforms has expanded threat exposure across hospitals and emergency-response centres, refugee protection corridors, power transmission networks, airfields and logistics hubs, and transportation corridors. Research is therefore required to develop layered short-range protection architectures capable of supporting early warning and controlled interception within mixed civil–military operational environments. Such architectures represent a critical component of stabilisation and humanitarian protection operations across emerging security contexts.

G. Need for Modular Distributed Air Defence Architectures

The limitations identified above collectively motivate the development of modular distributed air defence system architectures capable of operating effectively within infrastructure-limited environments. Key research priorities include distributed sensor-fusion detection grids, mobile interceptor deployment frameworks, resilient mesh-network communication architectures, latency-aware engagement decision pipelines, and hybrid guidance interception strategies. The companion MDADS framework proposed in the subsequent paper addresses these requirements by introducing a scalable architecture optimised for infrastructure-constrained operational theatres and civilian infrastructure protection environments across Sub-Saharan Africa and comparable defence ecosystems.

XV. CONCLUSION

Modern air-defence systems are transitioning from centralised, radar-centric architectures to distributed, sensor-fusion-enabled protection frameworks capable of countering aircraft, missiles, UAVs, and loitering munitions across contested and infrastructure-limited environments. This review examined key system components, including surveillance sensors, fire-control and tracking methods, command-and-control architectures, interceptor guidance strategies, gun-based SHORAD platforms, and directed-energy technologies within layered defence structures. The study highlights the importance of multi-sensor integration, resilient communications, hybrid command frameworks, and AI-assisted engagement prioritisation for maintaining operational effectiveness where radar coverage, power supply, and communication infrastructure are limited. It further identifies cost-effective solutions, such as mobile interceptor platforms, passive sensing nodes, and solar-assisted surveillance systems as critical for scalable deployment in emerging defence ecosystems. Overall, the paper establishes a technical foundation for modular distributed air-defence architectures suitable for expeditionary operations and civilian-infrastructure protection in resource-constrained operational theatres.

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