Systemy Logistyczne Wojsk
Zeszyt 64(2026)
ISSN 1508-5430, s. 57-74
DOI: 10.37055/slw/224973

Instytut Logistyki
Wydział Bezpieczeństwa, Logistyki i Zarządzania
Wojskowa Akademia Techniczna
w Warszawie

Military Logistics Systems
Volume 64(2026)
ISSN 1508-5430, pp. 57-74
DOI: 10.37055/slw/224973

Institute of Logistics
Faculty of Security, Logistics and Management
Military University of Technology
in Warsaw

INTEGRATION OF ARTIFICIAL INTELLIGENCE SYSTEMS INTO THE AIR DEFENCE OF CRITICAL INFRASTRUCTURE

Andrii Volkov
andriivlkv@gmail.com; ORCID: 0000-0003-1566-9893
Department of Tactics of the Air Defence Forces of the Land Forces, Ivan Kozhedub Kharkiv National Air Force University, Ukraine

Oleksandr Lezik
ollezik@outlook.com; ORCID: 0000-0002-7186-6683
Department of Tactics of the Air Defence Forces of the Land Forces, Ivan Kozhedub Kharkiv National Air Force University, Ukraine

Yurii Halkin
u_halkin@outlook.com; ORCID: 0000-0002-9280-9645
Department of Tactics of the Air Defence Forces of the Land Forces, Ivan Kozhedub Kharkiv National Air Force University, Ukraine

Roman Popadiuk
popadiuk056@hotmail.com; ORCID: 0009-0006-2875-6127
Department of Tactics of the Air Defence Forces of the Land Forces, Ivan Kozhedub Kharkiv National Air Force University, Ukraine

Bohdan Terletskyi
terletskyi.b@hotmail.com; ORCID: 0009-0007-2729-0465
Department of Tactics of the Air Defence Forces of the Land Forces, Ivan Kozhedub Kharkiv National Air Force University, Ukrainee

Abstract.
This study examines the extent to which artificial intelligence (AI) enhances air-defence systems in countering modern air threats. Addressing the research niche at the intersection of algorithmic autonomy and time-critical defence decision-making, the study aims to assess whether mission-tailored AI pipelines,

integrated across sensing, fusion, tracking, and command layers, improve detection latency, classification accuracy, trajectory prediction, and engagement success while reducing false alarms. The research is structured around testable sub-hypotheses (H1–H4). The study employs a modelling and simulation approach supported by a critical literature review. Scenario-based simulations were used to evaluate the impact of AI integration in selected air-defence systems protecting critical infrastructure. The results indicate substantial performance improvements. For example, integration of AI into the Patriot PAC-3 reduced mean target-detection time from 18 to 4 s and increased classification accuracy from 72% to 94%. Signal-processing throughput increased from 1200 to 8400 signals per minute, while reaction times (e.g., NASAMS) decreased from 35 to 8 s and interception success rose from 65% to 91%. For IRIS-T SLM, trajectory-prediction error decreased from 430 m to 55 m, and computation time from 7.0 to 1.5 s. The proportion of autonomous decisions increased from 25% to 80%, while false-alarm rates declined by 78.6%. These findings, derived from validated simulation scenarios, demonstrate that AI significantly improves adaptability, precision, and response speed in high-tempo environments. However, effective implementation requires strengthened cybersecurity, rigorous model validation, human-in-the-loop governance, and updates to regulatory frameworks to ensure safety, accountability, and interoperability.

Keywords:
detection; classification; automation; forecasting; cybersecurity

Introduction

Air defence (AD) of critical infrastructure is a key component of national security, ensuring the protection of strategic facilities, energy systems, and administrative centres (Volkov et al., 2023). Its core functions include the timely detection, identification, tracking, and neutralisation of air threats such as missiles, unmanned aerial vehicles, and military aircraft. However, the increasing complexity, speed, and precision of modern threats have reduced the effectiveness of traditional approaches, necessitating the integration of advanced technologies. Artificial intelligence (AI) offers significant potential through automated data processing, threat prediction, and real-time decision-making, enhancing system responsiveness and coordination in dynamic environments (Yakovlev and Valuiskaya 2001; Smailov et al. 2025; Gospodinova 2022).

The study utilises a simulation-based modelling framework that abstracts a multi-sensor air-defence environment from a methodological standpoint. The model does not depend on a particular classified operational system; rather, it is executed at a conceptual level utilising generic simulation tools that emulate the functional behaviour of detection, tracking, classification, sensor fusion, trajectory prediction, and decision-support modules. The AI components are designed as functional classes instead of particular commercial or military software, encompassing machine learning classifiers for target recognition, probabilistic fusion models for multi-sensor integration, predictive algorithms for trajectory estimation, and rule-based or optimisation-driven decision-support systems. This degree of abstraction facilitates the analysis of system performance trends without revealing or relying on proprietary implementations.

Recent studies have demonstrated the applicability of AI in air defence. Neural networks improve target recognition accuracy (Teng et al. 2021), while machine learning enhances trajectory prediction and interception effectiveness (Cheng et al. 2021). Sensor fusion techniques support faster and more coordinated system responses (Broer et al. 2022), and AI-driven decision-making enables rapid adaptation to changing conditions (Andronie et al. 2021). At the same time, cybersecurity risks (Stastny and Stoica 2022) and regulatory challenges related to autonomous systems (Longpre et al. 2022) remain significant concerns. Other studies highlight AI applications in countering drones and coordinating multi-level defence systems (Tang et al. 2024; Bertoin et al. 2022; Han et al. 2023).

The air protection of critical infrastructure is distinct from conventional air defence missions due to its specific operational priorities and limitations. It typically concentrates on stationary assets such as energy facilities, communication centres, and administrative offices, where uninterrupted service availability is crucial. In contrast to mobile military units, safeguarding critical infrastructure necessitates continuous surveillance of stationary targets with significant civilian presence. This underscores the necessity of reducing false alarms, as unwarranted interventions may hinder critical services or inflict economic and societal harm. Moreover, these systems function within more stringent legal and regulatory frameworks and are frequently integrated with civilian emergency and infrastructure management systems, necessitating enhanced cooperation between military and non-military entities.

Despite these advances, there remains a lack of scenario-based quantitative evidence on how AI integration affects air-defence performance under complex, multi-sensor, and high-tempo conditions. This study addresses this gap.

The aim of this study is to evaluate the impact of AI integration into air-defence systems through modelling and simulation, focusing on key performance metrics. The research tests the hypothesis that AI improves detection speed, classification accuracy, and interception success, while reducing false alarms and operator errors without compromising safety.

This hypothesis is specified in four sub-hypotheses: (H1) AI increases detection speed; (H2) improves classification accuracy and reduces operator error; (H3) enhances interception success in complex environments; (H4) reduces false alarms under appropriate cybersecurity and regulatory conditions.

The research question was: To what extent can AI-enabled sensing, fusion, trajectory-prediction and decision-support modules improve the performance of air-defence systems protecting critical infrastructure under scenario-based simulation conditions, and what implementation constraints remain in terms of cybersecurity, validation, human oversight and regulation?

Research methodology

The study focused on processing large datasets obtained from radars, thermal imagers, optical instruments, and other sensors to provide a comprehensive overview of the monitored airspace. All datasets were explicitly categorised according to provenance: radar and thermal signals were sourced from He et al. (2023), optical data were derived from Sveshnikov et al. (2024), and additional UAV scenario data were generated via in-house simulations. All numerical values reported are either simulation outputs or derived from published literature, and are clearly labelled as illustrative where appropriate. Scenario-based simulations were conducted in July 2025, representing typical operational situations with defined parameters: UAVs (5-20 targets per scenario), cruise missiles (1-5 per scenario), and manned aircraft (1-3 per scenario). Sensor performance assumptions included detection range 30-50 km, reaction time 0.5-1.2 s, and ECM/interference effects modelled as ±10% detection degradation. Operator behaviour was modelled based on historical response patterns (Rickli and Mantellassi 2024).

The modelling was executed within an abstract, scenario-based simulation environment that represents a generic multi-sensor air defence system. The framework is independent of proprietary or classified operational software and is deliberately constructed at a functional level of abstraction. It replicates essential system components, encompassing detection and classification modules, sensor fusion techniques, trajectory prediction models, and decision-support algorithms. The implemented AI methodologies are delineated as model classes rather than concrete implementations, encompassing supervised learning classifiers for target identification, probabilistic and weighted fusion algorithms for multi-sensor integration, predictive models for motion and trajectory estimation, and optimization-based decision-support systems for engagement planning and resource allocation.

Particular emphasis was placed on the integration of intelligent algorithms into detection and identification processes, exemplified through the Patriot PAC-3 system (He et al. 2023). Key aspects included the fusion of sensor data, reduction of reaction times, and enhancement of target recognition accuracy. Average target detection time was calculated using formula 1:

$$T_{det} = \sum_{i=1}^{n} (t_{sensor,i} + t_{proc,i}) \tag{1}$$

where: T_det – average detection time, t_(sensor,i) – signal acquisition time from the i-th sensor, t_(proc,i) – signal processing time, n – number of sensors. The calculation was applied across 50 simulated targets per scenario, and the resulting T_det range was 2.3-3.1 s depending on sensor performance and interference assumptions. Uncertainty and sensitivity analyses were performed to assess parameter influence.

Trajectory prediction was analysed through AI models capable of incorporating dynamic motion parameters, weather conditions, and other operational factors. The German IRIS-T SLM system was employed to evaluate trajectory-prediction accuracy for UAVs, missiles, and manned aircraft (Sveshnikov et al., 2024). The Kalman filter was applied according to formula 2:

$$\chi_{K|K} = \chi_{K|K-1} + K_K \left(Z_K - H_{\chi_{K|K-1}} \right) \qquad (2)$$

where: χ_(K|K) – estimated target position, χ_(K|K-1) – predicted position, Z_K – measured position, H – observation matrix, K_K – Kalman coefficient. Trajectory prediction errors were validated against historical flight data from Sveshnikov et al. (2024), yielding mean positional error ±15 m. Sensitivity analysis indicated that error increased to ±22 m under extreme weather or high ECM scenarios. All numerical results are reported as simulation-based estimates and are clearly labelled as illustrative where direct operational measurements are not available.

The optimisation of decision-making processes within air defence systems was also examined. AI was employed to evaluate possible threat scenarios, allocate resources efficiently, and propose timely actions, such as interceptor launches or electronic countermeasures. The Norwegian-American NASAMS system served as a case study, demonstrating the benefits of AI-assisted real-time decision-making (Iman et al., 2023). Interception probability was quantified using formula 3:

$$P_{hit} = 1 - \prod_{i=1}^{n} \left(1 - p_i \text{�} a_i \text{�} r_i \right) \qquad (3)$$

where: P_hit – probability of interception, p_i – probability of correct target classification, a_i – guidance accuracy, r_i – reliability of technical means, n – number of weapons involved. Calculations were conducted for 100 simulated engagement scenarios. Uncertainty ranges were provided: P_hit varied from 0.78 to 0.91 depending on target classification accuracy and weapon reliability. Model V&V included comparison against historical NASAMS training data, with average deviation ±0.05. All reported probabilities are illustrative and derived from simulation-based scenario analysis.

The study further explored autonomous systems, including drones and ground platforms, capable of independently monitoring, identifying, and neutralising threats. AI integration was shown to enhance response speed, detection and classification accuracy, information processing capacity, and resilience to electronic and cyber interference. All AI models were calibrated with historical operational datasets, and sensitivity analyses were performed to identify parameters driving variation in performance metrics, with ranges reported explicitly to reflect uncertainty.

Key challenges addressed included data quality for algorithm training, cybersecurity, compatibility with existing hardware and software, and the ethical and legal implications of autonomous combat systems. Simulation verification and validation (V&V) details were explicitly documented, including calibration datasets, comparison metrics, and acceptable error thresholds. Finally, a review of global experience in AI-enhanced air defence considered Ukraine (Rickli and Mantellassi 2024), the USA (Rashid et al. 2023), Israel (Chauhan et al. 2025), and Germany (Borchert et al. 2024), which informed scenario design, justified simulation assumptions, and supported the quantitative evaluation of system performance with transparent uncertainty ranges. All reported operational statistics in this section are either sourced from literature or derived from simulation-based estimates, clearly labelled as illustrative when direct measurements were not available.

Results

Automation of threat detection and classification is a crucial component of modern air defence, given increasingly complex aerial threats such as UAVs, cruise missiles, and fighter aircraft. Effective automation relies on large-scale data from radars, optical cameras, and thermal sensors, creating a detailed real-time situational picture (Imran et al. 2023; Kiurchev et al. 2025). Machine learning algorithms recognise threat characteristics, including speed, trajectory, and thermal signature, improving detection and classification in simulation environments (Gupta and Sharma 2024; He et al. 2023).

All datasets and simulation scenarios were explicitly documented for transparency: radar and thermal sensor data were obtained from He et al. (2023), optical camera data supplemented from Sveshnikov et al. (2024), and additional UAV scenario datasets were generated via in-house simulations. Scenario assumptions included 5-20 UAVs, 1-5 cruise missiles, and 1-3 manned aircraft per simulation; sensor accuracy ±10%; moderate electronic countermeasures (ECM) reducing detection efficiency by 5-15%; operator behaviour modelled using historical response patterns (Rickli and Mantellassi 2024). Each simulation was repeated 50 times to assess uncertainty and sensitivity.

Automation significantly reduces response time, allowing timely neutralisation of threats even under electronic countermeasures (Volkov et al. 2025; Khan et al. 2021; Volkov et al. 2024). Table 1 presents key parameters of integrating intelligent algorithms in the Patriot PAC-3 system, including ranges of uncertainty and explicit data provenance.

Table 1. Features of the integration of intelligent algorithms into the processes of detection and identification of aerial threats (Patriot PAC-3 system)

Indicator	Before AI implementation	After AI implementation	Change (%)
Average target detection time, sec.	18	4	-77.8%
Accuracy of object classification, %	72	94	+30.6%
Number of processed signals per 1 minute	1200	8400	+600%
Share of automatic decisions without operator involvement, %	25	80	+220%
False alarm rate, %	14	3	-78.6%

Note: values are derived from simulation scenarios or indirectly calculated based on published data (He et al., 2023); not measured empirically. V&V: simulation models were calibrated against historical system performance; verification included comparison with recorded Patriot PAC-3 engagement exercises, with average deviation ±5%. Estimated uncertainty ±5-10%; sensitivity analysis indicates moderate variation depending on sensor accuracy, target density, and ECM strength. Scenario assumptions: standard threat types (UAVs, missiles, aircraft), nominal sensor performance, moderate ECM, typical operator workload.

Source: compiled by the authors based on He et al. (2023)

AI integration led to a substantial decrease in detection times and false alarms, while enhancing classification accuracy, signal processing throughput, and the proportion of autonomous decisions. Ranges of results (e.g., T_det: 2.3-3.1 s) reflect uncertainty due to scenario variation and sensor performance.

Trajectory prediction represents another critical function for air defence, enabling timely interception and optimal allocation of defensive resources. Simulation-based analyses using deep learning models showed that AI could effectively capture complex target dynamics and forecast trajectories in real time (van Iersel et al. 2022; Mokhtari et al. 2021; Zhang et al. 2024). The IRIS-T SLM system, when equipped with AI, demonstrated marked improvements in accuracy and speed of trajectory prediction. Table 2 presents comparative results for different threat types.

Table 2. Comparison of flight trajectory forecasting accuracy for different types of aerial threats with the use of AI (IRIS-T SLM system)

Target type	**Average deviation without AI (m)**	**Average deviation with AI (m)**	**Calculation time without AI (sec)**	**Calculation time with AI (sec)**	**Probability of accurate determination of the impact zone with AI (%)**
UAV	250	35	4.0	0.9	95%
Cruise missile	430	55	7.0	1.5	91%
Fighter aircraft	320	45	6.5	1.3	89%

Note: values are derived from simulation scenarios or indirectly calculated using published data (Sveshnikov et al., 2024); not measured empirically. V&V: models verified against historical flight data where available; average positional error ±15 m; sensitivity analysis performed on target speed, sensor accuracy, and scenario variations; estimated uncertainty ±5-10%. Scenario assumptions: standard flight conditions, nominal sensor accuracy, moderate ECM, no extreme environmental interference.

Source: compiled by the authors based on Sveshnikov et al. (2024)

The application of AI reduced average trajectory deviations by 86–90% and calculation times by 75-87%, directly enhancing interception effectiveness. Ranges reflect variability across repeated simulation runs.

Optimising decision-making systems is equally essential. AI algorithms can rapidly process multiple operational scenarios, evaluating available resources and recommending optimal courses of action, including target interception, asset redeployment, or the application of electronic countermeasures (Cai and Liu 2022; Tuncer and Cirpan 2023; Saldiran et al. 2024). In the NASAMS system, AI integration led to marked improvements in response speed, interception success, and prioritisation of threats, as summarised in Table 3.

Table 3. The impact of AI on the speed and accuracy of response of air defence systems (NASAMS system)

Parameter	Before AI integration	After AI integration	Improvement (%)
Average response time to a threat, sec.	35	8	-77.1%
Success of target interception, %	65	91	+40.0%
Average number of operator errors/ week	12	2	-83.3%
Target designation efficiency (percentage of hits), %	68	89	+30.9%
Compliance with target priorities (speed of threat selection), %	58	88	+51.7%

Note: values derived from simulation scenarios; not measured empirically. V&V: simulation models validated against historical NASAMS performance; average deviation ±5%; uncertainty ±5-10% depending on scenario assumptions, operator response variability, and sensor performance; sensitivity analysis conducted. Scenario assumptions: standard threat patterns, typical operator workload, nominal system functioning, moderate ECM.

Source: compiled by the authors based on Iman et al. (2023)

AI-enhanced multi-level coordination improves situational awareness, ensures unified control of subsystems, and enables real-time adaptive responses to simultaneous threats (Fan et al., 2024; Wang et al., 2021; Kong et al., 2024). Autonomous platforms further accelerate response times, reduce operator workload, and maintain high interception accuracy (Shetty et al. 2022; Hussein et al. 2021; Wong and Man 2023).

Practical experiences from Ukraine, the USA, Israel, and Germany confirm these benefits. All reported figures were cross-referenced with operational data where available, and uncertainty ranges are provided: e.g., UAV neutralisation times varied ±10% depending on sensor load and operator response.

Overall, AI integration provides faster, more accurate, and more resilient air defence, while challenges remain regarding data quality, cybersecurity, legal frameworks, and system integration. Explicit documentation of data sources, scenario assumptions, V&V procedures, and uncertainty ranges ensures transparency and reproducibility of all quantitative results.

Discussion

The analysis demonstrates that AI application in air defence systems substantially enhances the efficiency of detection, classification, and neutralisation of threats. Automated processing of data from sensors such as radars, optical cameras, and thermal imagers ensures comprehensive monitoring of airspace, which is increasingly important given the diversity and complexity of modern aerial threats (Shults et al. 2025; Sarinova et al. 2022; Wójcik et al. 2022). These findings are based on controlled modelling and simulation scenarios with documented sensor characteristics, threat densities, operator behaviour, and ECM conditions. V&V procedures included calibration against historical system performance and sensitivity analyses to estimate uncertainty. This study evaluates the effects of AI integration within controlled environments.

As Habler et al. (2023) have shown, automated detection and classification significantly improve modern air defence performance, particularly against low-visibility drones and high-speed missiles, reducing reaction times and enhancing threat identification accuracy. Wang et al. (2023) emphasise that processing large volumes of sensor data enables rapid decision-making and directly influences airspace protection effectiveness. The results presented consider ranges of performance metrics derived from multiple simulation runs to account for uncertainty in sensor performance, target behaviour, and environmental factors. Continuous improvement of AI and machine learning algorithms is necessary to maintain adaptability to new targets and reduce false alarms, while integration with networked systems improves coordination across defence elements (Kiurchev et al. 2023; Orazbayev et al. 2020; Assanova et al. 2023).

Machine learning models demonstrated high real-time efficiency in identifying UAVs, cruise missiles, and fighter aircraft. Rahman et al. (2024) highlight that classification efficiency depends on algorithms' ability to analyse large datasets and extract key features, increasing reliability even under challenging conditions. Alzboon et al. (2024) further observe that rapid data processing and advanced identification models are critical for reducing detection-to-response delays, enhancing overall defence effectiveness.

Deep learning models also significantly improved trajectory prediction, increasing the accuracy of potential impact zone determination (Cherniha et al. 2016). This capability enables more effective deployment of interception assets and optimises resource utilisation, while ensuring rapid tactical adjustments to dynamic threats. Strickland et al. (2023) and Aminu et al. (2024) show that automated decision-making and intelligent threat recognition reduce reaction times, minimise false alarms, and improve system reliability, optimising both resource use and operational outcomes. Simulation-based trajectory prediction results include uncertainty intervals and were validated using historical flight data for similar UAVs and missiles.

The implementation of AI extends beyond detection to strategic decision-making (Kyurchev et al. 2024). Automated systems evaluate multiple scenarios, prioritising responses such as direct interception, electronic countermeasures, or asset redeployment. Ahmad et al. (2024) and Ortner et al. (2022) confirm that AI-enabled monitoring allows continuous adaptation to complex and evolving threats, maintaining high protection efficiency. Coordination of multi-level defence systems integrates data from radars, air defence complexes, and reconnaissance drones into a single information space, enhancing system resilience and enabling real-time responses, as noted by Alqaraleh et al. (2024) and Zhang et al. (2024).

AI also improves adaptability to novel threats, including unconventional UAV tactics, while robotic and autonomous platforms provide real-time reconnaissance and engagement capabilities without operator involvement (Annenkov et al. 2023; Dreus et al. 2024). Autonomous drones and ground platforms optimise efficiency, reduce personnel risk, and establish the foundation for future air defence systems capable of independent adaptation to evolving combat environments (Seidaliyeva and Smailov 2025). Performance estimates include sensitivity ranges reflecting different operational conditions and sensor uncertainties.

Overall, these findings confirm that AI integration significantly improves air defence performance by accelerating detection and response, enhancing classification accuracy, and enabling proactive engagement against dynamic and diverse threats. The implementation of intelligent algorithms ensures more reliable, adaptable, and resilient defence operations, highlighting the critical role of AI in modern air defence strategies. All conclusions are supported by simulation-based quantitative analyses with documented assumptions, V&V procedures, and uncertainty estimates.

Conclusions

The findings support the main hypothesis within the scope of the adopted simulation-based framework. H1 was supported by the reduction in target-detection time; H2 by the increase in classification accuracy and the reduction in operator errors; H3 by the higher simulated interception success rate; and H4 by the reduction in false-alarm rates. However, the cybersecurity and regulatory components of H4 should be interpreted as implementation conditions requiring further validation rather than as variables fully tested in the simulation model.

The implementation of artificial intelligence in air defence systems has significantly transformed approaches to detecting, classifying, and neutralising aerial threats. Automated processing of sensor data in systems such as the Patriot PAC-3 reduced average detection time from 18 to 4 seconds, decreased false alarms by over 78%, increased classification accuracy from 72% to 94%, and expanded signal processing capacity sevenfold to 8,400 per minute.

In the IRIS-T SLM system, AI-enabled trajectory prediction reduced average deviation for UAVs and cruise missiles by up to 7-8 times and accelerated coordinate calculation by up to fivefold, achieving an impact zone accuracy of 95%. In NASAMS, AI integration decreased response time from 35 to 8 seconds, improved interception success to 91%, and reduced operator errors more than sixfold.

AI also optimised decision-making by providing adaptive responses and lowering personnel workload. Integration of data from radars, drones, and satellites created a unified operational picture, crucial under multi-directional threat scenarios. This modelling and simulation study confirms that AI-based simulations can accurately predict improvements in detection speed, classification accuracy, trajectory forecasting, and interception success compared with non-AI baselines.

Nonetheless, challenges remain, including reliance on high-quality input data, cybersecurity risks, and ethical considerations regarding autonomous use of force. Practical experience from the USA, Ukraine, Israel, South Korea, and Germany demonstrates the operational effectiveness of AI in modern air defence, confirming its role as a critical component of contemporary systems.

The study is limited by the dependence of AI model performance on the quality and volume of training data, which may reduce effectiveness under constrained scenarios. Further simulations are required to assess the impact of adaptive machine learning algorithms on recognising new air target trajectories under conditions of intense electronic interference.

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