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ANALYSIS OF DEVELOPMENT TRENDS AND PROSPECTS FOR THE IMPROVEMENT OF MODERN RADAR SYSTEMS

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Abstract. This article analyzes the principal development trends and prospects for improving modern radar systems from the perspectives of antenna architecture, radio-frequency electronics, digital signal processing, distributed sensing, artificial intelligence, spectrum efficiency, reliability, and lifecycle engineering. The study uses a structured qualitative review of authoritative institutional sources, peer-reviewed publications, and relevant scientific materials from Uzbekistan. The evidence indicates that future radar capability will depend less on a single breakthrough component than on the integration of gallium-nitride radio-frequency electronics, high-speed data conversion, scalable digital processing, adaptive resource management, artificial-intelligence-assisted signal interpretation, distributed sensor cooperation, and predictive maintenance. Recent research also points toward metacognitive radar networks and integrated sensing-and-communications concepts, although these remain at different levels of technological maturity. The article emphasizes that higher digitization increases both flexibility and computational, thermal, calibration, cybersecurity, and verification requirements.

Keywords: radar systems; phased array; active electronically scanned array; digital beamforming; gallium nitride; cognitive radar; distributed radar; artificial intelligence; spectrum sharing; reliability; predictive maintenance; Uzbekistan.

Annotatsiya. Ushbu maqolada antenna arxitekturasi, radiochastotali elektronika, raqamli signalni qayta ishlash, taqsimlangan sensorlar, sun'iy intellekt, spektr samaradorligi, ishonchliligi va hayot aylanishi muhandisligi nuqtai nazaridan zamonaviy radar tizimlarini takomillashtirishning asosiy rivojlanish tendentsiyalari va istiqbollari tahlil qilinadi. Tadqiqotda O'zbekistondan olingan nufuzli institutsional manbalar, ekspertlar tomonidan ko'rib chiqilgan nashrlar va tegishli ilmiy materiallarning strukturaviy sifatli sharhi qo'llaniladi. Dalillar shuni ko'rsatadiki, kelajakdagi radar imkoniyatlari bitta yutuqli komponentga emas, balki galliy-nitrid radiochastotali elektronika, yuqori tezlikdagi ma'lumotlarni konvertatsiya qilish, masshtablanadigan raqamli ishlov berish, moslashuvchan resurslarni boshqarish, sun'iy intellekt yordamida signallarni talqin qilish, taqsimlangan sensorlar hamkorligi va bashoratli texnik xizmat ko'rsatishning integratsiyasiga bog'liq bo'ladi. So'nggi tadqiqotlar shuningdek, metakognitiv radar tarmoqlari va integratsiyalashgan sensorlar

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va aloqa konsepsiyalariga garchi ular texnologik yetuklikning turli darajalarida bo'lsa ham ishora qiladi,. Maqolada yuqori raqamlashtirish ham moslashuvchanlikni, ham hisoblash, issiqlik, kalibrlash, kiberxavfsizlik va tekshirish talablarini oshirishi ta'kidlangan.

Kalit so'zlar: radar tizimlari; bosqichli massiv; faol elektron skanerlangan massiv; raqamli nurlanish; galliy nitridi; kognitiv radar; taqsimlangan radar; sun'iy intellekt; spektr almashinuvi; ishonchlilik; bashoratli texnik xizmat ko'rsatish; O'zbekiston.

Аннотация. В данной статье анализируются основные тенденции развития и перспективы совершенствования современных радиолокационных систем с точки зрения архитектуры антенн, радиочастотной электроники, цифровой обработки сигналов, распределенного зондирования, искусственного интеллекта, эффективности использования спектра, надежности и проектирования жизненного цикла. В исследовании использован структурированный качественный обзор авторитетных институциональных источников, рецензируемых публикаций и соответствующих научных материалов из Узбекистана. Полученные данные свидетельствуют о том, что будущие возможности радиолокации будут зависеть не столько от одного прорывного компонента, сколько от интеграции радиочастотной электроники на основе нитрида галлия, высокоскоростного преобразования данных, масштабируемой цифровой обработки, адаптивного управления ресурсами, интерпретации сигналов с помощью искусственного интеллекта, распределенного взаимодействия датчиков и прогнозирующего технического обслуживания. Недавние исследования также указывают на метакогнитивные радиолокационные сети и интегрированные концепции зондирования и связи, хотя они остаются на разных уровнях технологической зрелости. В статье подчеркивается, что более высокая степень цифровизации повышает как гибкость, так и вычислительные, тепловые, калибровочные, кибербезопасные и верификационные требования.

Ключевые слова: радиолокационные системы; фазированная антенная решетка; активная электронно-сканируемая антенная решетка; цифровое формирование луча; нитрид галлия; когнитивный радар; распределенный радар; искусственный интеллект; совместное использование спектра; надежность; прогнозирующее техническое обслуживание; Узбекистан.

INTRODUCTION

Radar has evolved from a specialized ranging technology into a family of multifunction sensing systems used in civil aviation, meteorology, remote sensing, transportation, space observation, maritime safety, scientific measurement, and defense. The fundamental task remains the transmission, reception, and interpretation of electromagnetic energy, but the architecture that performs this task has changed profoundly. Modern systems increasingly distribute sensing, conversion, processing, control, and decision-support functions across large numbers of solid-state and digital components.

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The phased-array transition is one of the most important historical developments. MIT Lincoln Laboratory documents phased-array research extending from the late 1950s through decades of work on radiating elements, phase shifters, solid-state transmit-and-receive modules, monolithic microwave integrated circuits, calibration, beamforming, and system testing [1]. Later analysis by Herd and Conway describes a further transition toward highly digitized phased-array architectures in which commercial processor development and high-volume microwave manufacturing enable greater flexibility and lower lifecycle cost [2]. This historical trajectory provides a useful basis for understanding current radar modernization.

Contemporary radar design is being shaped by several simultaneous pressures: detection of smaller and more diverse objects, operation in dense electromagnetic environments, requirements for multiple functions on a common aperture, growing data rates, the need for rapid reconfiguration, higher expectations for availability, and tighter lifecycle-cost constraints. These pressures have accelerated development of active electronically scanned arrays, gallium-nitride radio-frequency devices, digital beamforming, adaptive signal processing, software-defined radar, cognitive resource management, distributed sensing, and artificial-intelligence-assisted interpretation [3-6].

The objective of this article is to identify the most significant development trends in modern radar systems, assess their engineering significance, and formulate realistic prospects for further improvement. Particular attention is given to the relationship between hardware evolution and software-defined capability, because increasing digitization transfers many functions from fixed radio-frequency hardware into configurable signal-processing and resource-management layers. The study also examines relevant research capacity in Uzbekistan. The analysis is technological and systems-engineering in nature and deliberately excludes tactical employment, operational vulnerabilities, electronic-attack procedures, or methods for defeating radar systems.

LITERATURE REVIEW

The literature shows that radar modernization has proceeded through overlapping architectural generations rather than a single linear replacement cycle. Early electronically steered arrays improved scan agility by controlling the phase of signals across antenna elements. Active electronically scanned arrays subsequently distributed amplification and control across multiple transmit-and-receive modules, improving flexibility, graceful degradation, multifunction operation, and beam agility. IEEE literature identifies active electronically scanned array technology, together with gallium-nitride devices and monolithic microwave integrated circuits, as a major direction in modern radar engineering [3].

Digitization represents a second major transition. In analog or partially digital arrays, beam formation occurs primarily in the radio-frequency or intermediate-frequency domain. In digital arrays, a larger number of receiving channels are digitized separately, enabling adaptive digital beamforming before final beam formation. This architecture can improve interference suppression, sidelobe control, multi-beam operation, calibration, and software reconfigurability, but it also increases data throughput,

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processing load, synchronization requirements, and power consumption [4]. MIT Lincoln Laboratory characterizes high levels of digitization as a defining feature of next-generation phased arrays [2].

Radio-frequency semiconductor technology is another enabling factor. Gallium nitride is attractive for high-power and high-frequency electronics because of its material properties and ability to support high power density. Modern phased-array development increasingly combines gallium-nitride components with compact packaging and tile architectures. The engineering challenge is not only transistor performance: thermal management, packaging density, yield, calibration, cost, and long-term reliability determine whether component-level advantages become system-level advantages [2,7].

Cognitive radar extends adaptivity from individual algorithms toward a closed perception-action cycle. A widely cited IEEE overview explains that cognitive radar emerged through the combination of cybernetics, waveform diversity, and knowledge-aided signal processing and is intended to maintain performance in dynamically changing environments [5]. More recent work moves toward metacognitive radar, in which an outer learning and control process monitors the performance of the cognitive radar itself. A 2025 IEEE article identifies reinforcement learning, spectrum sharing, networked cognition, and game-theoretic coordination as emerging research directions [6]. These approaches are promising but remain constrained by training data, verification, computational requirements, explainability, and the risk of poor adaptation under conditions not represented during development.

Distributed and collaborative sensing is a parallel trend. Instead of requiring one radar to maximize every performance dimension, multiple geographically or functionally separated sensors can contribute complementary observations to a common information picture. Recent research on multifunction air-defense radar identifies distributed collaborative detection, fully digital active electronically scanned arrays, adaptive resource management, integrated multichannel transmit-and-receive modules, and intelligent radar as important emerging technologies [8]. Distributed sensing can improve spatial diversity and coverage, but it places greater demands on synchronization, communications, data association, calibration, network resilience, and fusion algorithms.

Another long-term trend is convergence between radar and communications. A 2023 IEEE Signal Processing Magazine review traces seventy years of separate development followed by growing integration into integrated sensing-and-communications concepts. Two broad technological trends are emphasized: increasing frequencies and bandwidths and expanding antenna arrays [9]. Shared apertures, waveforms, spectrum, and processing resources could reduce hardware duplication and improve spectrum utilization, but practical deployment requires careful management of conflicting sensing and communications objectives.

Artificial intelligence is increasingly applied to radar classification, image interpretation, anomaly detection, resource management, and maintenance. The most mature value is likely to arise where machine learning augments rather than replaces established estimation and detection methods.

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A 2026 review of fifty years of synthetic-aperture-radar automatic target recognition surveyed approximately 260 research contributions and concluded that progress depends strongly on high-quality large-scale datasets, fair benchmarks, and safe research ecosystems [10]. This conclusion is relevant beyond synthetic-aperture radar: data quality and validation are central constraints on artificial-intelligence-enabled radar.

Uzbekistan possesses an institutional research base relevant to these trends. The national scientific-attestation system maintains specialization 05.04.02, covering radiotechnics, radionavigation, radiolocation and television systems and devices, with active research at the Tashkent University of Information Technologies and other institutions [11]. Recent Uzbek doctoral work includes models and algorithms for improving ultra-high-frequency radio-monitoring efficiency and cognitive spectrum management [12,13]. Domestic publications also address radar-system reliability, diagnostics, maintenance planning and digital monitoring [14,15], while 2026 research on radar interferometry discusses synthetic-aperture radar and millimeter-scale deformation monitoring [16]. These activities do not constitute a complete domestic radar industry, but they demonstrate a scientific base in radio-frequency systems, signal processing, spectrum management, reliability and radar remote sensing.

METHODOLOGY

The study employed a structured qualitative review and technology-trend synthesis. Sources were selected from four categories: (1) authoritative research institutions with long-term radar-development programs; (2) peer-reviewed IEEE and comparable scientific publications on phased arrays, digital beamforming, cognitive radar, distributed sensing and integrated sensing; (3) recent studies that identify future radar research directions; and (4) official or scientific sources demonstrating relevant research capacity in Uzbekistan. Preference was given to sources with identifiable authors, publication venues, technical scope, and explicit dates.

The evidence was organized into seven analytical dimensions: antenna and radio-frequency architecture; digitization and beamforming; signal processing and artificial intelligence; distributed and networked sensing; spectrum and multifunction integration; reliability and lifecycle support; and national scientific capacity. Each trend was assessed according to its expected contribution, technological maturity, principal engineering constraints, and likely role in future radar architecture.

The article does not attempt to rank individual radar products or compare classified performance parameters. Numerical values that depend strongly on a specific design, frequency band, aperture, waveform, or operational environment were excluded unless they served a broad scientific purpose. This prevents misleading comparison between systems designed for different missions. The focus is therefore on reproducible engineering trends rather than tactical capability claims.

A distinction was also made between mature trends and exploratory concepts. Active electronically scanned arrays, digital signal processing, solid-state transmit-and-receive modules, and software-controlled resource management are established technologies. Cognitive and metacognitive

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radar, highly distributed cooperative sensing, integrated sensing-and-communications, and some advanced artificial-intelligence functions are developing at different maturity levels. Quantum radar was treated only as a research topic rather than as an established modernization path because the open literature does not support placing it at the same maturity level as digital phased arrays [8].

RESULTS AND DISCUSSION

The review identifies a clear architectural transition from hardware-defined radar toward digitally programmable sensing platforms. The defining change is not simply electronic scanning. Modern radar increasingly moves analog-to-digital conversion closer to the antenna elements and transfers beam formation, filtering, resource allocation, calibration, and portions of detection and classification into software-controlled processing. This increases functional flexibility and allows one aperture to support multiple sensing tasks, but it also changes the dominant engineering bottlenecks from mechanical motion and analog hardware toward computation, thermal management, synchronization, software assurance, and data movement.

Table 1 summarizes the principal development trends, their benefits, and the constraints that must be addressed before further capability can be realized.

Table 1. Major development trends and improvement prospects in modern radar systems

Technology trend	Expected contribution	Main engineering constraints	Development outlook
Active electronically scanned arrays and GaN RF electronics	Fast electronic steering, multifunction operation, solid-state reliability, higher power density and modularity.	Thermal management, packaging density, calibration, cost, device yield and lifecycle reliability.	Mature core technology; continued improvement through GaN, integration and lower-cost manufacturing [2,3,7].
Digital beamforming and highly digitized arrays	Multiple simultaneous beams, adaptive nulling, flexible sidelobe control, software reconfiguration and improved calibration.	Very high data rates, converter performance, clock synchronization, processing power and energy consumption.	One of the strongest near- and medium-term modernization directions [2,4].
Cognitive and metacognitive radar	Adaptive waveform/resource selection and closed-loop optimization in changing environments.	Training/knowledge quality, verification, computational burden, explainability and robustness outside learned conditions.	High research potential; transition from theory toward increasingly practical demonstrations [5,6].
Distributed	Spatial diversity,	Time synchronization,	Growing importance as

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collaborative sensing	complementary observations, scalable coverage and shared situational information.	communications, calibration, data association, fusion and network resilience.	radar becomes a networked sensor rather than an isolated platform [8].
Integrated sensing and communications	Shared spectrum, aperture and hardware resources; improved spectrum efficiency.	Competing performance objectives, waveform design, regulation, coexistence and system complexity.	Strong long-term research trend driven by convergence of radar and communications [9].
Artificial-intelligence-assisted processing	Improved classification, image interpretation, anomaly detection, resource management and maintenance support.	Dataset bias, limited labeled data, explainability, generalization, cybersecurity and validation.	Best prospects in hybrid architectures combining model-based processing with machine learning [10].
Predictive maintenance and digital diagnostics	Higher availability, earlier fault detection, optimized maintenance intervals and lower lifecycle cost.	Need for high-quality condition data, health models, sensor instrumentation and validated prognostics.	Increasingly important as radar architectures become more modular and software-intensive [14,15].

The first major conclusion from the table is that the active electronically scanned array is becoming a platform for further innovation rather than an endpoint. The next step is deeper digitization. Digital beamforming allows the same physical aperture to form and manage several beams or adaptive spatial responses through software. This provides a foundation for multifunction operation, but the price is a sharp increase in channel count and internal data movement. Therefore, future performance depends as much on converters, timing distribution, processors, memory architecture and cooling as on antenna gain.

The second conclusion is that gallium nitride should be understood as a system enabler rather than a stand-alone performance solution. Higher power density can improve transmit-module capability and reduce some size constraints, but heat must still be removed and dense arrays must remain calibratable and reliable. The most successful architectures will therefore combine semiconductor advances with thermal design, heterogeneous integration, packaging, built-in test, and manufacturing methods that control lifecycle cost [7].

Third, artificial intelligence and cognitive processing are changing radar from a fixed sequence of processing operations toward adaptive sensing. However, the literature does not justify replacing established radar estimation and detection theory with opaque machine-learning models. A more credible development path is hybrid: physics-based and statistical signal processing provides

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predictable baseline behavior, while machine learning assists classification, resource allocation, anomaly detection or model selection. The approximately 260 studies reviewed in the 2026 synthetic-aperture-radar automatic-target-recognition survey demonstrate the scale of artificial-intelligence research, but the authors still identify dataset quality and fair benchmarking as fundamental unresolved needs [10].

Fourth, radar is becoming increasingly network-centric. Distributed sensors can observe a scene from different geometries and frequency bands, creating opportunities for cooperative detection and more robust information fusion. Yet distributed sensing moves complexity from the individual sensor into the network. Time synchronization, metadata consistency, communications latency, sensor registration, track association and fusion quality become system-level performance parameters. Thus, future radar engineering must increasingly integrate radio-frequency design with networking, distributed computing and data architecture.

Fifth, spectrum pressure will encourage multifunction and integrated sensing approaches. Radar and communications historically developed as separate electromagnetic systems, but the growth of bandwidth, array size and digital processing is creating common technological foundations [9]. The long-term prospect is not necessarily one universal waveform, but increasingly coordinated use of antennas, spectrum and processing resources. This direction is particularly relevant where spectrum is congested and where the economic or physical cost of multiple separate apertures is high.

Reliability is a sixth major development axis. Modern solid-state arrays can tolerate individual module failures better than architectures built around a small number of high-power components, but the total number of electronic and software elements is much larger. This creates a need for built-in diagnostics, health monitoring, automated fault localization and predictive maintenance. Uzbek research on radar maintenance emphasizes mean time between failures, mean time to repair, availability, diagnostics and monitoring as core evaluation criteria [14,15]. Such lifecycle engineering should be considered during design rather than added after deployment.

For Uzbekistan, the most realistic improvement strategy is capacity-oriented. The country already has formal doctoral specialization in radiotechnics, radionavigation and radiolocation, and active work in ultra-high-frequency monitoring and cognitive spectrum management [11-13]. These areas overlap directly with future radar needs in spectrum awareness, digital signal processing, adaptive algorithms and radio-frequency measurement. Research on radar interferometry additionally demonstrates competence in phase-sensitive radar processing and synthetic-aperture methods [16]. Building on these capabilities could support laboratories for digital beamforming, phased-array calibration, radio-frequency electronics, radar signal datasets, reliability diagnostics and simulation.

A staged national research approach would be scientifically preferable to attempting complete high-performance radar development in a single step. First-stage work can focus on software-defined radar test beds, signal-processing algorithms, calibration, spectrum monitoring and digital diagnostics using non-sensitive experimental systems. The second stage can integrate small phased arrays,

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multichannel conversion and real-time beamforming. A later stage can address distributed sensing and artificial-intelligence-assisted resource management. This sequence develops human capital and verification methods alongside hardware.

The analysis also shows that future radar improvement must be measured with multidimensional criteria. Detection performance alone is insufficient. Relevant engineering indicators include calibration stability, beamforming accuracy, processing latency, energy efficiency, thermal margin, availability, maintainability, software updateability, spectrum efficiency, interoperability, data quality, cybersecurity, and lifecycle cost. A system that gains sensitivity but becomes difficult to calibrate, cool, verify or maintain may not represent a net improvement.

CONCLUSION AND RECOMMENDATIONS

Modern radar systems are undergoing a transition from specialized hardware-defined sensors to highly digitized, software-configurable and increasingly networked sensing platforms. Active electronically scanned arrays and solid-state radio-frequency electronics provide the physical foundation, while digital beamforming, adaptive processing, high-performance computing and software-defined resource management provide much of the emerging functional flexibility. Gallium-nitride technology, advanced packaging and improved thermal engineering will continue to raise the capability of transmit-and-receive modules, but system-level integration will remain decisive.

Cognitive radar, metacognitive control, artificial intelligence and distributed sensing represent important future directions, yet they should be evaluated according to technological maturity and verifiability. Artificial intelligence is most credible when used to augment well-understood signal-processing chains rather than replace them without transparent validation. Similarly, distributed radar can provide spatial diversity and shared information, but only when synchronization, networking, calibration and fusion are engineered as integral parts of the sensing system.

The convergence of radar and communications suggests a longer-term move toward coordinated sensing, communications and spectrum management. At the same time, growing system complexity makes reliability engineering, predictive diagnostics, cybersecurity and lifecycle management increasingly important. Future radar excellence will therefore depend on multidisciplinary integration across microwave electronics, antennas, converters, digital hardware, algorithms, software engineering, data science, networking and maintenance engineering.

For Uzbekistan, the existing 05.04.02 scientific specialization and current research in radiomonitoring, cognitive spectrum management, radar reliability and interferometric radar provide a useful academic base. It is recommended to strengthen experimental laboratories for multichannel radio-frequency measurement, software-defined radar, digital beamforming and phased-array calibration; develop representative radar-signal datasets for academic research; expand work on reliability and predictive diagnostics; and connect radar research with national programs in artificial intelligence, microelectronics and advanced communications. International scientific cooperation and

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open, non-sensitive test platforms can accelerate competence without requiring access to classified systems.

Overall, the most promising model for radar modernization is evolutionary integration rather than dependence on a single disruptive technology. The future radar will be more digital, more adaptive, more distributed, more software-defined and more data-intensive. Its success, however, will be determined by whether these capabilities can be made reliable, explainable, energy-efficient, maintainable and economically sustainable.

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