

THE USE OF INNOVATIVE UAVS AND SLAM-LIDAR TECHNOLOGIES FOR MONITORING AT NUCLEAR POWER PLANTS

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Abstract. The article is devoted to the analysis of the current state, practical possibilities and prospects of using unmanned aerial vehicles in combination with SLAM and LiDAR technologies for monitoring nuclear power facilities. The purpose of the article is a comprehensive analysis of the current state and prospects of using unmanned aerial vehicles in combination with SLAM and LiDAR technologies for monitoring nuclear power facilities. The work uses methods of analytical review of scientific and industry sources, comparative analysis of technological solutions, generalization of statistical data, systematization of practical cases, as well as logical and structural analysis of trends in the development of unmanned and navigation technologies. The results shows for the first time that the combination of unmanned aerial vehicles with SLAM and LiDAR technologies allows to significantly improve the monitoring of nuclear power facilities by ensuring accurate spatial localization, construction of metrically correct three-dimensional models and stable navigation in conditions of complex geometry, limited lighting and lack of satellite navigation signals. In particular, the integration of active laser sensing with algorithms of simultaneous localization and mapping creates the prerequisites for the transition from fragmentary visual inspections to systematic, reproducible and quantitatively controlled spatial analysis of the state of technological premises and structures. Future directions of technology development are also shown and systematized, in particular, increasing the autonomy of platforms, intellectualization of data processing, integration of multi-sensor complexes and the transition to distributed robotic systems. In practical terms, this creates the prerequisites for active technology transfer to the nuclear energy industry, when companies will be able not only to adapt ready-made solutions, but also to form their own specialized products for inspection, post-accident monitoring and digital modeling of facilities. Thus, the work forms a conceptual basis for combining scientific developments, market trends and applied needs of nuclear infrastructure.

Keywords: SLAM-LiDAR, unmanned aerial vehicles, nuclear power plants, technology transfer, autonomous monitoring.

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Introduction

Today, unmanned platforms are no longer perceived as something “additional” – rather as a working tool for inspection and monitoring, which is rapidly scalable in various industries. For example, according to the FAA, as of November 2025, there were 837,513 registered UAVs, of which 453,635 were commercial, and the number of certified remote pilots reached 481,760, which directly indicates the maturity of the market and the growth of the professional segment [6]. In general, unmanned aircraft systems are relatively new participants in the airspace, but they demonstrate steady growth and diversification of application scenarios (infrastructure monitoring, emergency and rescue operations, etc.), and this, in fact, creates a fairly strong “ecosystem base” for the use of drones in critical infrastructure [7]. If we talk specifically about nuclear power plants, the picture is as follows: the technology is already used and has real cases, but its spread “within the nuclear sector” is naturally restrained by safety requirements, regulatory procedures and the need for proven operating scenarios. For example, the UK report on UAVs in nuclear decommissioning collected twenty examples of drone use, and in most cases these are serial platforms for regular visual inspections or the involvement of contractors for photo/data collection; the effect is described in quite practical terms - increased safety, reduced costs and reduced work time compared to traditional methods, in particular work at height with scaffolding. In this context, it is important to emphasize that there are many technologies for monitoring, but not all of them are equally well “adapted” to the conditions of nuclear power plants.

Against the background of other technologies, the combination of SLAM-LiDAR technologies in the context of nuclear power plants looks like one of the best adapted technologies: it allows not only to collect data, but also to localize the platform and build a spatially consistent 3D map where typical limitations for visual systems begin, and this is what opens up the prospect of moving from one-off inspections to systematic, regular monitoring.

The issue of using unmanned aerial vehicles and SLAM-LiDAR technologies for monitoring nuclear power facilities is quite widely presented in modern scientific literature. The paper uses the scientific works of J.E.A. Bermudez, L. Kang, H.-L. Chi [1], M. Bloesch, J. Czarnowski, R. Clark, S. Leutenegger, A.J. Davison [2], C. Campos, R. Elvira, J.J.G. Rodríguez, J.M. Montiel, J.D. Tardós [3], D.T. Connor et al. [4], World Nuclear News materials [5], FAA statistical reports [6][7], C. Forster, L. Carlone, F. Dellaert, D. Scaramuzza [8], C. Forster, Z. Zhang, M. Gassner, M. Werlberger, D. Scaramuzza [9], analytical report Global State of Drones [10], C. Kerl, J. Sturm, D. Cremers [11], J. Levinson et al. [12], M. Meilland, C. Barat, A. Comport [13], R. Newcombe [14], O.O. Popov [15], T. Qin, P. Li, S. Shen [16], A. Sachenko, V. Kochan, V. Kharchenko, M. Yastrebenetsky, H. Fesenko, M. Yanovsky [17], GOV.UK materials [18][21], J.E. Smart [19], S. Thrun et al. [20], C. Urmson et al. [22].

If we highlight the works that are more devoted to the practical application of UAVs at nuclear power plants and in the post-accident environment, it is advisable to rely on the studies of J.E.A. Bermudez, L. Kang, H.-L. Chi [1], D.T. Connor et al. [4], World Nuclear News materials [5], the Sellafield case [18], the GOV.UK report on nuclear decommissioning [21], as well as the works of J.E. Smart [19] and A. Sachenko, V. Kochan, V. Kharchenko et al. [17], which consider the issues of automated inspection, radiation mapping, organization of drone fleets, network interaction and post-accident monitoring of nuclear facilities.

If we focus on the technological basis of SLAM and LiDAR, the most relevant works are those of M. Bloesch et al. [2], C. Campos et al. [3], C. Forster et al. [8,9], T. Qin, P. Li, S. Shen [16], C. Kerl, J. Sturm, D. Cremers [11], M. Meilland, C. Barat, A. Comport [13], R. Newcombe [14], as well as the classic works on autonomous navigation and laser sensing by S. Thrun et al. [20], C. Urmson et al. [22], J. Levinson et al. [12], which have developed methodological

approaches to building dense three-dimensional maps, integrating inertial measurements, and ensuring stable localization in complex environments.

A separate group consists of overview, statistical and forecast materials presented in the FAA reports [6,7] and Global State of Drones [10], which allow us to assess the scale of UAV distribution, market structure, growth rates of the commercial segment and regulatory restrictions that directly affect the possibilities of implementing innovative technologies in critical infrastructure.

The purpose of the article is a comprehensive analysis of the current state and prospects for the use of unmanned aerial vehicles in combination with SLAM and LiDAR technologies for monitoring nuclear power facilities. In accordance with the stated goal, the article provides for the solution of the following three tasks: 1) to carry out a general review of the current practice of using unmanned aerial vehicles in the field of inspection and monitoring of nuclear power plants; 2) to analyze the features of LiDAR and SLAM technologies, their technical advantages and limitations; 3) to outline the main directions of future development of unmanned and SLAM-LiDAR technologies, taking into account the trends of autonomization.

Results

In the practice of nuclear power plants, UAVs most often go where it is either “long and expensive” or simply dangerous for a person: visual inspections of high and hard-to-reach surfaces, operational survey of the technical condition of structures, perimeter inspection, and emergency response support. According to J.E.A. Bermudez, L. Kang, H.-L. Chi, even such a specific task as shell inspection can be transferred to semi-automatic or autonomous mode: through flights around cylindrical objects with control over points of interest and trajectory parameters (radius, height, pitch), which provides reproducibility of the procedure and reduces dependence on “manual” piloting [1]. Looking at the sector more broadly, a UK review of nuclear decommissioning shows that in practice, serial platforms are often used (either by their own operators or through contractors) for regular inspections and data collection, and the key effect is described there quite pragmatically: safer, faster and cheaper than traditional methods, such as working at height with scaffolding [21]. Functionally, UAVs at nuclear facilities are not just a “camera in the air”, but a whole range of roles: from real-time situational awareness to elements of the safeguards system and post-accident monitoring. For example, J.E. Smart describes approaches where drones with 360° panoramic cameras can form a virtual perimeter and maintain entry/exit control on the site, and regular flights along the fence allow for recording changes in the state of structures with subsequent automated image processing [19]. A. Sachenko et al. propose a concept of a post-accident monitoring system, where there are drones-relays, drones-observers and drones-sensors, and the logic of the operation is built as a managed network (Master-Slave) to ensure communication with measuring modules and minimize energy consumption in crisis conditions [17].

Table 1 – Advantages of using UAVs at nuclear power plants

Advantage	Practical implementation	Typical tasks
Improved personnel safety	Reduced need to work in hazardous or elevated areas; lower exposure and injury risk	inspections; surveys; emergency response [21]
Reduced work time	Rapid deployment; fast collection of photos/videos/data without scaffolding or complex preparation	routine inspections; surface monitoring; structural assessments [21]
Cost reduction	Lower labor intensity; less auxiliary	scheduled surveys; support

	infrastructure (scaffolding, lifts); use of commercial platforms	for decommissioning projects [21]
Repeatability and standardization of procedures	Autonomous/semi-autonomous flight paths (e.g. orbiting targets, altitude layers) ensure consistent results over time	containment inspection; routine object flyovers [1]
Enhanced physical security and situational awareness	Video feed/panoramic monitoring; "virtual perimeter"; traffic flow control	perimeter monitoring; access control; event logging [19]
Operation in post-accident conditions	Drone network deployed as a wireless "extension" for data transmission; support for sensor and module connectivity	post-accident monitoring; data relay; incident site control [17]

Note: compiled on the basis of a generalization of materials [1, 17, 19, 21]

If we talk about real cases, then one of the most illustrative examples is the RISER system (Remote Intelligence Survey Equipment for Radiation), which is described in materials about work at the British site Sellafield: there, a drone in combination with radiation mapping software was used to survey heavily contaminated areas without the presence of personnel "inside" the hazardous environment [18]. The essence of the approach looks quite convincing: a compact device, autonomous navigation with collision avoidance, data collection and visualization of the radiation field in the form of a spatial (actually 3D) model, which makes it possible to plan further cleaning and dismantling work more reasonably [18].

Another striking case is the plans and actual use of drones for radiation mapping at the Fukushima Daiichi NPP site: the World Nuclear News report describes that the RISER system was being prepared for use to measure ionizing radiation levels near damaged reactors, with the emphasis being on autonomous navigation in environments without GNSS and on integrating the platform with a mapping software module [5]. And here, in our opinion, it is important to note a practical conclusion: the "nuclear" request is most often not about flights for the sake of flights, but about the "platform + sensor + map" connection, where the final result is not a video, but a solution (where it is dangerous, where the contamination is localized, how to plan access and dismantling) [5].

The technology of simultaneous localization and mapping (SLAM) in general terms consists in the fact that a mobile platform (for example, a drone or a ground robot) simultaneously estimates its own position in space and forms a digital model of the environment. In simpler terms, the system "learns to understand where it is" and at the same time "remembers what the space around it looks like". As noted by C. Forster et al. [8], as well as T. Qin, P. Li, S. Shen [16], the combination of visual and inertial measurements allows achieving high accuracy in estimating the position and orientation of the platform even in real time, which is critically important for autonomous navigation. At the same time, as C. Campos et al. believe, modern libraries such as ORB-SLAM3 already allow working with different sensor configurations (visual, visual-inertial, multi-map), which makes SLAM a universal tool for mobile robotics [3].

However, in industrial environments of nuclear power plants, purely visual SLAM solutions have objective limitations.

LiDAR, unlike passive optics, directly measures the distance to objects using laser radiation, forming a three-dimensional point cloud regardless of ambient lighting. According to S. Thrun et al. and C. Urmson et al., it was LiDAR that became the key sensor in early and modern autonomous transport systems, providing stable localization and map building in

difficult conditions [20, 22]. Experience, summarized by J. Levinson et al., shows that the development of solid-state LiDAR devices has led to a reduction in size, weight and power consumption while simultaneously increasing the accuracy and range of measurements, which makes them suitable for integration into mobile platforms with limited payload capacity, in particular drones and compact robots [12].

In combination, SLAM and LiDAR form a technological basis for building dense, metrically correct 3D maps and stable navigation without dependence on GNSS, which is especially important for the interiors of nuclear power plants. For example, direct point cloud registration methods and integration with inertial measurements allow to compensate for motion distortions, increase the accuracy of trajectory estimation and maintain map relevance in real time [8,9]. In practical terms, this means the possibility of forming digital twins of premises, planning safe trajectories of movement and repetitive inspection routes, as well as comparing data over time to detect changes or degradation of structures [12, 20]. Technological features are shown in Table 2.

Table 2 – Technological features of SLAM-LiDAR and their impact on nuclear power plant monitoring

Technological feature	How it improves monitoring at NPPs
Simultaneous localization and mapping (SLAM)	Provides accurate positioning of the drone/robot and spatial referencing of measurements, enabling route repetition and time-based data comparison [16]
Active LiDAR depth sensing	Operates independently of lighting; performs reliably in dark, dusty, or metal-rich environments [22]
Dense 3D map generation	Enables the creation of digital twins of rooms and structures; supports detailed analysis of geometry and zone accessibility [13]
Integration with inertial sensors	Compensates for motion distortions; improves trajectory accuracy and navigation stability [8,9]
Operation without GNSS	Allows autonomous navigation in indoor areas such as reactor compartments, galleries, and technical corridors [12]
Scalability and automation	Enables the shift from one-time inspections to regular, standardized monitoring [3]

Note: summarized from [3, 8, 9, 12, 13, 14, 16, 20, 22].

At present, drone systems are undergoing rapid advancement driven by innovative technological developments. Among the most significant improvements is the integration of event-based cameras with minimal latency. These sensors enable near-instantaneous detection of obstacles and moving objects, allowing unmanned aerial vehicles to safely operate in complex environments, including dense industrial infrastructure, pipeline networks, low-visibility conditions, as well as open industrial facilities and natural landscapes.

Another major advancement is the implementation of propulsion systems with gimbal-mounted motors, which markedly enhance aerial maneuverability. By enabling thrust vectoring in arbitrary directions, such systems support smooth, snake-like flight trajectories with high precision of control. This capability is essential not only for accurate agricultural operations, such as targeted spraying and crop inspection, but also for reliable navigation within the highly constrained and structurally complex environments of nuclear power plants, including flights between structural elements, within confined building spaces, and in proximity to reactor units.

In summary, SLAM-LiDAR is not just another sensor approach, but a holistic technological platform for autonomous data collection, spatial reference, and analysis in complex industrial environments.

If we look at the further development of SLAM-LiDAR and unmanned platforms in the context of nuclear power plants, the first obvious direction is to increase the autonomy of the systems and reduce dependence on the operator. In particular, as C. Forster et al. and T. Qin, P. Li, S. Shen believe, the integration of inertial measurement modules with more stable state optimization algorithms allows us to gradually move from “semi-autonomous” scenarios to fully autonomous navigation in complex environments [8, 16]. In practical terms, this means the development of the following functions:

- automatic trajectory planning taking into account space constraints and dangerous zones;
- adaptive obstacle avoidance in a dynamic environment;
- independent return of the platform to the base or charging area without operator participation.

Such capabilities are especially important for post-accident scenarios, where the presence of personnel may be limited or even undesirable [17].

The second direction is associated with increasing the “intelligence” of data processing, i.e., the transition from a simple geometric map to semantically rich digital models. For example, as noted by M. Bloesch et al. and C. Campos et al., modern approaches to SLAM already integrate elements of machine learning and optimization of compact representations of the scene, which allows not only to build a map, but also to interpret its content – to highlight objects, surfaces, potentially dangerous zones [2,3].

The third important vector of development is the expansion of sensory integration and increased specialization for nuclear tasks. According to O.O. Popov, the combination of UAVs with intelligent modules for analyzing radiation signals and elements of artificial intelligence for autonomous decision-making, optimization of routes taking into account the radiation situation and forecasting the development of the situation is promising [15]. In the same vein, J.E. Smart and A. Sachenko et al. emphasize the feasibility of developing network architectures of drones (repeaters, sensors, observers), which allow scaling the monitoring system to large industrial sites and ensuring resistance to failures of individual elements [17,19]. In fact, we are talking about the transition from “one drone” to a distributed robotic system.

In parallel, according to the results of global industry surveys, the role of software solutions and service models is increasing, while regulatory authorities remain key drivers or limiters of the market [10]. In this sense, nuclear power, as one of the most regulated industries, will likely introduce SLAM-LiDAR gradually, but with high requirements for reliability, certification and integration into existing safety systems [21].

Conclusions

Thus, the use of unmanned platforms at nuclear facilities creates conditions for the transition to a safer and more rational organization of inspection and control work. Remote execution of operations reduces the need for personnel to be in hazardous areas, accelerates the acquisition of necessary information, optimizes maintenance costs and ensures the stability of results during multiple surveys.

The effectiveness of such solutions is determined by the set of technological properties of SLAM-LiDAR, which allow the system to independently navigate in space and form a detailed digital representation of the environment. Active laser scanning ensures the stability of measurements regardless of lighting conditions, and the combination with inertial data increases the accuracy of the trajectory and spatial reference of information. The construction of dense three-dimensional models opens up the possibility of analytical assessment of the state of objects, work in closed rooms without satellite navigation and scaling solutions for regular automated control.

Further development of these approaches is expected in the direction of increasing the level of autonomy, complexity of intelligent data processing algorithms, expansion of sensor integration and active implementation of technologies in industrial practice.

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