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# KEY PRINCIPLES OF TECHNOLOGY TRANSFER OF A SLAM-ORIENTED UAV PLATFORM FOR LIDAR MONITORING IN AGRICULTURAL SYSTEMS AND RADIATION CONTAMINATION ZONES

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***Abstract.*** *The article is devoted to the study of the possibilities of transferring SLAM-oriented platform technologies using LIDAR monitoring to the agricultural sector and the sphere of limited physical access associated with radiation. The purpose of the article is a comprehensive analysis of the engineering principles of building a universal SLAM-oriented unmanned aerial vehicle platform for LIDAR monitoring with an emphasis on the possibility of its effective application in agricultural systems and areas of increased danger. To achieve the goal, general scientific methods of cognition were used in the course of the study, and the conclusions were based on the results of a critical analysis of the world's current scientific literature in this area. The results of the study showed that LIDAR monitoring is a high-precision spatial sensing technology that forms detailed three-dimensional models of the environment and provides autonomous navigation in conditions of limited visibility and the absence of GNSS. The study analyzed the key features of LIDAR technology as a basic tool for spatial monitoring of unmanned platforms. It is shown that in agricultural systems it is used for autonomous navigation in forests, precision agriculture and obstacle detection. In areas of radiation contamination and other hazardous environments, LIDAR platforms provide remote mapping, emergency rescue operations and autonomous inspection of infrastructure. The study of the features of SLAM technology made it possible to determine its role as the core of autonomous navigation and mapping in conditions of limited or absent external navigation infrastructure. The practical significance of this study lies in the identification of key rules for technology transfer to any industry, which allows to significantly improve the state of monitoring of any production and social processes in the world without risks.*

***Keywords:*** *SLAM, LIDAR, UAV, monitoring, technology transfer.*

## Introduction

In modern autonomous robotics research, the key problem remains ensuring stable localization and spatial orientation of unmanned platforms in environments with problematic satellite signals. Navigation reliability is significantly reduced in conditions of dynamic interference, vibrations, dustiness, and unstable sensor measurements [3], which is characteristic of both natural landscapes and man-made objects. At the same time, the use of LIDAR sensors allows for highly accurate formation of three-dimensional geometry of the environment regardless of lighting and weather conditions, which justifies their use as a basic source of spatial information [11].

Modern scientific research in the field of autonomous navigation of unmanned platforms forms a multi-vector scientific discourse. The works of J.Zhang and S, Singh [11], H.Wang et al. [10], T.Shan and B.Englot [8] laid the methodological foundations of LIDAR technologies, geometric feature extraction and optimization of computational efficiency of real-time algorithms. These studies form the theoretical basis for building high-precision SLAM systems capable of working with large volumes of point clouds with limited computing resources. A separate area of research is devoted to multisensor integration and increasing the stability of navigation solutions in difficult operating conditions. The works of P.Chen et al. [1], Y.Li et al. [4], A.Liang et al. [5]. focus on the combination of LIDAR, visual sensors, inertial modules and satellite navigation in single optimization schemes. The key in these approaches is to ensure the adaptability of algorithms to changes in the quality of sensor data, reduce error drift and increase the continuity of localization in spatially heterogeneous environments.

An important group is made up of applied research focused on real scenarios for the use of autonomous systems. The works of I. Ouattara and A. Visala [7] consider UAV navigation in an agricultural environment with GNSS degradation, which demonstrates the effectiveness of LIDAR odometry in natural conditions. R. Milijaš and co-authors [6] perform a comparative analysis of various SLAM solutions for UAV control, emphasizing the trade-offs between accuracy, computational costs and stability. The studies of A. Kravchuk et al. [3] focus on the problems of autonomous navigation in GPS-denied environments, which is critically important for emergency and man-made hazardous areas.

The development of practical scenarios for the use of autonomous platforms in difficult operating conditions is especially relevant. In particular, I. Ouattara and A. Visala demonstrate the effectiveness of LIDAR technologies for UAV navigation in young forest stands under conditions of GNSS degradation, which is a typical example of an agricultural environment with high structural complexity. In industrial and infrastructure facilities, the emphasis is on multisensor integration of LIDAR, IMU and RTK to ensure continuous localization during the inspection of long structures, even with partial loss of satellite signal [5]. For dangerous and hard-to-reach areas, in particular emergency or high-risk areas, autonomous mapping systems such as Hovermap [2] are used, which provide remote acquisition of 3D models without the involvement of personnel.

However, the results of R. Milijaš et al., T. Shan and B. Englot [6], as well as P. Chen et al. [1] indicate the presence of fundamental limitations in terms of computational complexity, energy consumption and universality of SLAM algorithms when transferring them between different environments. Solutions optimized for specific types of scenes often require significant adaptation when changing geometry, feature density or dynamics of objects, which confirms the relevance of the problem of portability of navigation technologies. In this context, the formation of a universal SLAM-oriented UAV platform for LIDAR monitoring is considered as an engineering approach to unifying architecture, algorithms and sensor integration in order to ensure scalability of solutions between agricultural systems, industrial facilities and accident relief zones [1,3].

***The purpose of the article*** is a comprehensive analysis of the engineering principles of building a universal SLAM-oriented unmanned aerial vehicle platform for LIDAR monitoring with an emphasis on the possibility of its effective application in agricultural systems and areas of increased danger. To achieve the set goal, the ***following tasks*** are expected to be performed: 1. Analyze the features of LIDAR technology as a basic tool for spatial monitoring and navigation of UAVs; 2. Investigate the features of SLAM technology and modern algorithmic approaches to LIDAR odometry and mapping; 3. Evaluate practical scenarios for using LIDAR- and SLAM-oriented platforms in agricultural systems and formulate the principles of transferring technological solutions between the agricultural sector, industrial facilities and accident relief zones.

## Research Results

LIDAR (Light Detection and Ranging) is a highly accurate active sensor technology for remote sensing, the principle of which is based on the emission of a laser pulse, its reflection from environmental objects and measuring the time it takes for the signal to return to the receiver. Based on this time, the distance to each reflected point is calculated, which allows you to form a detailed spatial model of the environment [1, 2].

The result of the system is the formation of a point cloud, which provides:

- millimeter measurement accuracy [3];
- independence from lighting, which allows you to work both day and night [11];
- resistance to difficult weather conditions, smoke and the absence of a GPS signal [3].

In combination with SLAM algorithms, LIDAR allows for autonomous platform localization in the complete or partial absence of external navigation infrastructure.

In the agricultural sector, in particular in forestry, LIDAR monitoring is considered a basic technology for automating complex spatial operations and increasing the autonomy of unmanned aerial vehicles [7]. In particular, as shown in the study by Ouattara I., Visala A, in young forests or dense stands, the satellite signal often degrades or disappears completely. LIDAR allows UAVs to perform localization and map construction, using tree trunks as stable geometric features for navigation [7]. This approach provides stable orientation of the device without dependence on GNSS.

LIDAR information allows for high-precision positioning of the drone relative to individual plants or their elements. The works of I. Ouattara and A. Visala show the possibility of using UAVs for selective spraying of chemicals (repellents) directly onto the tops of young pine trees to protect them from damage by animals [7]. Such systems provide accurate detection of tree crowns and other obstacles, which allows implementing collision avoidance algorithms during low-altitude flight. This is critically important for monitoring agricultural land and performing technological operations in complex terrain.

So we can summarize that in agricultural systems, LIDAR monitoring provides both navigational stability, geometric accuracy and the ability to automate high-precision agro-technological operations.

Regarding the use of LIDAR monitoring in areas of radiation contamination and hazardous environments, there are practically no scientific papers describing the use of such technology today, however, in similar environments (for example, firefighting), the technology is described in sufficient detail.

First of all, the technology is used to organize emergency rescue and inspection operations. LIDAR systems are critically important in scenarios where external conditions change unpredictably (disasters, industrial accidents). High accuracy and autonomous navigation allow remote surveying without the direct presence of personnel [3].

Autonomous mapping of hazardous objects is another common area of technology use. For example, platforms such as Hovermap [2] provide fully autonomous three-dimensional mapping of mines, warehouses and facilities with limited access. Such solutions allow obtaining high-precision 3D models of the environment without human involvement, which is fundamentally important in areas of increased radiation hazard.

Another important area of technology use is in GPS-denied spaces. Thanks to the use of SLAM, LIDAR drones are able to work effectively in closed rooms, tunnels, under rubble or in shielded environments where satellite navigation is unavailable [3].

A universal SLAM-oriented unmanned aerial vehicle (UAV) platform is an integrated hardware and software system for autonomous flight missions based on the implementation of Simultaneous Localization and Mapping (SLAM) - simultaneous localization and 3D mapping of the environment. Such a platform is capable of operating without a constant satellite navigation signal (GNSS) and provides independent orientation in complex environments based on data from onboard sensors (LIDAR, IMU, etc.) using appropriate algorithms [3].

The purpose of the universal SLAM platform is to ensure maximum autonomy, reliability and modularity for performing complex flight tasks in various conditions.

This platform includes a number of key functional blocks that together form a set of capabilities for autonomous operation, which are shown in Table 1.

Table 1 – Component architecture of the SLAM platform

| Component | Description |
|---|---|
| Sensor module | LIDAR sensors provide a highly accurate 3D representation of the environment. They form the basis for implementing SLAM algorithms and generate a point cloud that serves as the foundation for localization, mapping, and obstacle detection [11] |
| Inertial measurement units (IMU) | deliver angular velocity and acceleration estimates, making it possible to compensate for moments when LIDAR data temporarily weakens (during rapid maneuvers, etc.) |
| Optical cameras (used for image integration) | in some platform variations, they are used for additional environmental feature recognition or sensor data filtering |
| Processing unit | the data processing center that runs SLAM algorithms, estimates the vehicle's state in real time, builds the map, and makes flight path decisions. High-performance processors or graphic accelerators make it possible to process large volumes of LIDAR data in real time |
| Flight control module | this module is integrated with navigation algorithms and the vehicle's stabilization system [11]. It performs control based on the platform's state and SLAM data, ensuring smooth and safe flight trajectories |
| Autonomous route planning system | includes trajectory generation algorithms, obstacle avoidance, reactive response to environmental changes, and adaptive real-time flight control [11] |

*Note: systematized by the author*

The main advantages of using such technology, which actually describe the functionality, include:

1) Autonomous localization in GPS-denied conditions. A universal SLAM platform is able to independently estimate its position in space without relying on GNSS. This is critically important for working in dense vegetation, tunnels, industrial complexes, under canopies and in areas where the satellite signal is weak or absent [3]

2) Real parallel map construction and positioning. SLAM algorithms allow you to dynamically create a three-dimensional model of the environment simultaneously with assessing the state of the platform. This allows not only to navigate, but also provides a spatial understanding of the geometry of the environment for further navigation solutions.

3) Adaptive navigation in complex environments. The universal platform is able to effectively detect obstacles (trees, walls, supports, technical objects), build dynamic bypass trajectories and avoid collisions in real time.

4) High accuracy and reliability. The combination of LIDAR and IMU achieves high positioning accuracy and minimizes the accumulation of errors (drift) over time,

which is critically important for long-term flight missions.

5) Modularity and wide functional expansion. PLATFORM is able to integrate additional sensor modules (cameras, multi-sensor systems, spectral sensors) for specialized monitoring tasks (geodesy, agricultural monitoring, etc.).

It can be understood that the use of such technologies is multifunctional, and they can be applied in various fields if the engineering principles of transferring solutions between industries are followed. Direct technology transfer between different industries is based on the ability to universalize hardware and software components, adapt algorithms to different physical environments, and ensure navigation stability under uncertainty. In the studies of Kravchuk et al. [3], Zhang & Singh [11], Shan & Englot [8], Liang et al. [5], Ouattara & Visala [7], Chen et al. [1]. a set of engineering principles has been formed that ensure effective cross-industry integration of SLAM platforms and LIDAR monitoring. Let's consider them (Fig. 1.)

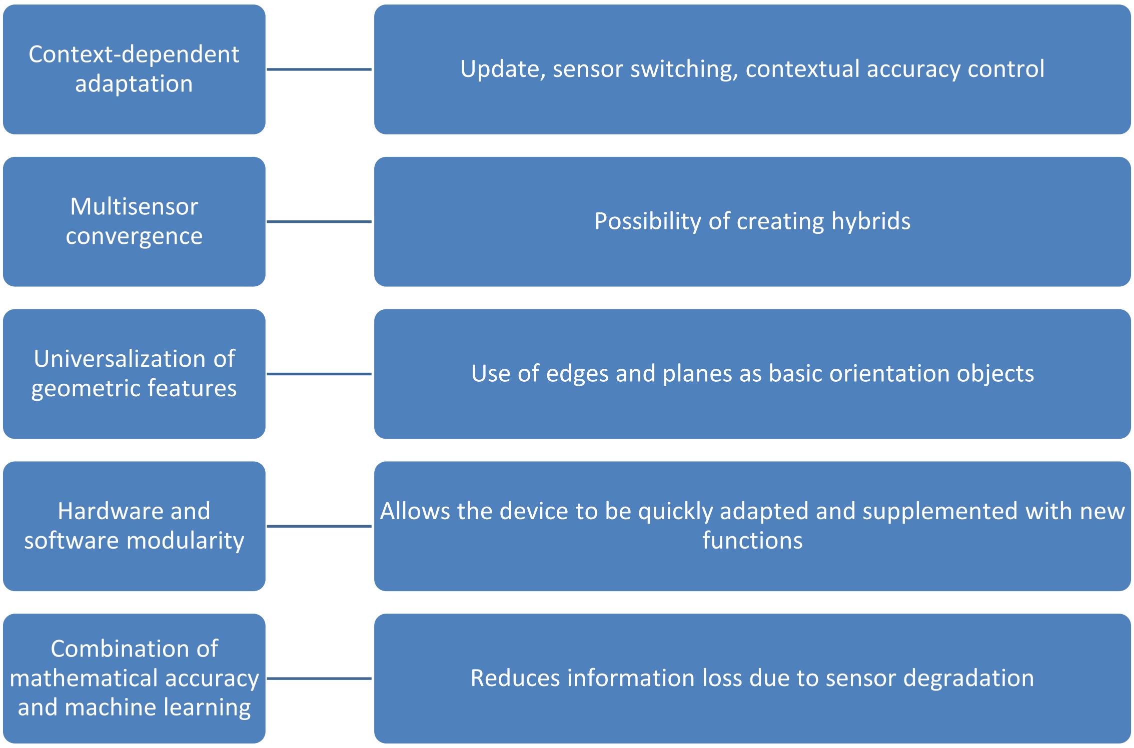

**Figure 1 - Principles of transferring LIDAR technology to different areas**

*Note: developed by the author*

The principle of context-dependent adaptation (Context-Dependency). SLAM algorithms and navigation models demonstrate high efficiency only in environments for which they are optimized. When transferring from laboratory or urban conditions to forests, industrial facilities or emergency zones, the influence of noise, occlusions, smoke, unstable geometry and GNSS degradation increases [3]. The transfer is implemented through dynamic reconfiguration of SLAM parameters: 1) adaptation of the update rate, sensor weights and filtering thresholds depending on the level of environmental noise; 2) adaptive sensor switching: in open space, GNSS/RTK dominates, in closed or shielded areas – LIDAR and IMU [5], 3) contextual control of accuracy and resources: in the agricultural sector, lower map detail is allowed, in the emergency zone – maximum accuracy at the expense of increased computational costs. Thus, the same platform functions in different industries by algorithmically adapting to the context of operation.

The principle of multisensor convergence provides the possibility of creating hybrids, since no sensor is universal. LIDAR provides high geometric accuracy and independence from lighting [11], IMU provides high-frequency dynamics of movement, GNSS – absolute fixation, and radars or cameras – additional information in specific conditions. Chen et al. [1] emphasize the need to integrate LIDAR and visual sensors to increase the robustness of SLAM. The transfer can be implemented using tightly-coupled integration: all measurements are included in a single optimization problem that minimizes drift [5]; LIDAR compensates for the weakness of cameras in the dark; radar enhances reliability in smoke or fog [5]; the system automatically redistributes trust between sensors depending on their reliability. In agricultural systems, this allows for stable operation among vegetation [7], and in emergency zones - to maintain navigation with complete degradation of GNSS [3].

The principle of universalization of geometric features. Instead of using specific environment markers, universal geometric primitives are used - edges and planes. This approach is embedded in the LOAM and LeGO-LOAM algorithms [8,11]. The implementation of the principle is due to: 1) the selection of edge and planar points from the point cloud to reduce the computational load; 2) invariance to the type of environment: edges exist in the forest (tree trunks), in industrial facilities (beams, columns), and in destruction zones; 3) semantic filtering: neural network models allow you to filter out moving or irrelevant objects [1]. Due to this, the same feature logic works in different industries without significant changes.

The principle of modularity of hardware and software. LIDAR modules, IMUs, computing units and payloads can vary depending on the task. At the same time, they can be optimized for different resources: for example, for small-sized platforms, lightweight algorithms (LeGO-LOAM) are used, which reduce computational costs [8].

The principle of combining mathematical accuracy and machine learning. The use of this principle is important, since in conditions of sensor data degradation, data compensation using intelligent scenarios and formulas is important [8]. Compliance with this principle is important for unpredictable scenarios, especially in conditions of operation in an emergency environment.

Today, drone technology is being improved through innovative solutions. Key innovations include the use of low-latency event cameras. Such cameras provide ultra-fast detection of obstacles and dynamic objects, which allows drones to avoid collisions in difficult environments, in particular among technological structures, pipelines or in conditions of limited visibility, as well as during flights on open industrial sites or in natural ecosystems. Another important innovation is a power plant with gimbal-mounted engines, which can significantly increase the maneuverability of aircraft. Directing the air flow in any direction ensures smooth, serpentine maneuvers with high control accuracy, which is critical for both precise spraying or crop inspection, and for navigation in complex industrial areas of nuclear power plants, including flights between engineering structures, inside building volumes or near reactor compartments.

Thanks to the combination of high-speed sensor systems and controlled thrust vectors, drones are able to perform tasks with high spatial accuracy, which opens up opportunities for precision agricultural monitoring, technical diagnostics of critical infrastructure, operational damage assessment, as well as the delivery of sensors and surveillance equipment to areas that are dangerous or inaccessible to personnel during emergencies at nuclear power plants.

## Conclusions

So, LIDAR sensors provide the formation of a highly accurate three-dimensional geometric model of the environment. This results in independence from the level of illumination and increased maneuverability regardless of the presence of various obstacles. However, the high performance of LIDAR data is accompanied by significant computational costs, which requires increased power supply, and at the same time optimization of data processing algorithms that are equipped in UAVs. The effectiveness of SLAM largely depends on various factors: first, the stability of geometric features (environment), second, the correctness of sensor data processing, third, the ability of algorithms to work with errors and process them. As a result, adaptive algorithmic solutions are used in practice, as well as hybrid approaches that combine geometric methods with intelligent data analysis models to increase stability in dynamic and unpredictable environments.

The evaluation of practical scenarios for the application of LIDAR and SLAM-oriented platforms in the agricultural sector and hazardous areas has made it possible to formulate a set of principles, the observance of which will facilitate the transfer of technology: adaptability of algorithms, multisensor integration, universalization of geometric features, modularity of hardware and software architecture and a balance between accuracy and resource efficiency. The use of these approaches allows, as a result, to scale the work, as well as reduce the costs of adaptation and transfer of technologies.

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