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PRIORITY AREAS FOR THE APPLICATION OF UAV WITH MULTISENSOR SYSTEMS FOR MONITORING

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Abstract. *The paper presents a comprehensive analysis of the use of multisensor systems (LiDAR, RGB, TIR, MS) for monitoring spontaneous combustion of coal mining waste using UAVs. It highlights the advantages of 3D modeling, thermal imaging, and multispectral monitoring, including the application of machine learning for the assessment of thermal anomalies and risk prediction. The study demonstrates the potential of implementing these technologies in Ukraine for environmental monitoring and 3D mapping of mine waste dumps, which are complex geotechnical systems subject to anthropogenic impact.*

Keywords: *monitoring of mine dumps, UAV, spontaneous combustion of spoil tips, geotechnical system.*

Introduction

Ukraine by the Russian Federation in early 2022, there has been a significant and gradual advancement in the field of unmanned aerial vehicles (UAVs), particularly in systems equipped with multisensor complexes.

As of early 2025, various optical technologies integrated into UAVs have seen widespread application for mapping terrain or designated areas.

Currently, depending on the specific tasks, UAVs employ the following types of cameras:

–**Visible spectrum (RGB) cameras** – used for video recording, photography, real-time broadcasting, inspections, surveillance, and promotional filming;

–Multispectral cameras – used for agromonitoring (NDVI, NDRE), detection of plant diseases, soil condition assessment, and moisture analysis;

–**Thermal imagers (infrared cameras)** – used for locating people and animals, night surveillance, temperature monitoring of buildings, power lines, and equipment;

–**Near-infrared (NIR) cameras** – applied for biomass analysis, moisture evaluation, and remote monitoring of tailings storage facilities and soils;

–**LiDAR (Light Detection and Ranging)** – used in geodesy, archaeology, and engineering surveys; they enable the creation of 3D models of terrain, structures, and vegetation.

Consider the specifics of using UAVs equipped with such systems to monitor complex geotechnical systems exposed to anthropogenic impact, using terricones (spoil tips) as an example.

Terricones – byproducts of coal mining – pose a serious environmental threat due to their tendency to spontaneous combustion, a process accompanied by the release of toxic gases and prolonged smoldering.

Traditional methods of monitoring such sites are generally costly, hazardous to personnel, and limited in operational efficiency. In this context, UAVs offer new opportunities for effective, contactless monitoring with high spatial and spectral precision.

According to recent studies, the use of multispectral and thermal imaging via UAVs enables the detection of hidden thermal anomalies, a decrease in vegetation biomass as an indicator of underground heating, and the ability to regularly assess the stability of terricones.

In Ukraine, where issues of civil safety are particularly acute, one of the most critical areas of research has become the monitoring of geomechanical systems affected by anthropogenic impact. In particular, the study of terricone conditions remains especially relevant in the eastern regions, where the integration of such approaches into environmental monitoring systems clearly enhances the safety of research activities.

This work provides a comprehensive review of modern approaches to the problem of monitoring spontaneous combustion of coal mining waste using UAVs.

We examine and analyze the most effective technical solutions in order to outline the prospects for their adaptation to domestic conditions and the development of new capabilities – particularly using artificial intelligence (AI). This enables the identification of parameters for thermal combustion zones within coal waste. When a UAV can autonomously monitor designated areas based on predefined parameters, it significantly reduces the risk of human error and ensures consistent and high-quality monitoring. The AI-based machine learning process in UAVs can be expanded to recognize thermal combustion zones, vegetation color, and biomass density on the slopes of coal waste heaps – thereby enabling the simultaneous execution of multiple monitoring tasks.

Literature review

Currently, the key areas of application include the following: monitoring of landslides and soil stability, assessment of working environment conditions, detection of underground coal fires, support of drilling and blasting operations, and inspection of waste dumps.

In this context, several core elements of monitoring practices are considered.

For instance, in paper [1], an important technical aspect of such operations is discussed, focusing on the variety of sensors (RGB cameras, multispectral, and thermal imaging). The study outlines methods of sensor data processing as well as varying levels of flight autonomy – from manual control to pre-programmed flight paths.

On the other hand, all components must be integrated into a unified system. Thus, the authors of paper [2] describe an efficient prototype system that combines sensors and analytics for monitoring spontaneous combustion of coal mining waste. The system improves monitoring performance, increases defect detection accuracy via UAVs, reduces response time, and provides recommendations for future industrial-scale implementations.

Taking into account the fact that such systems can evolve, a flexible structure is obtained, i.e., the one that can adapt to changing external conditions.

Paper [3] presents a different, yet also innovative, approach for detecting and spatial-thermal modeling of spontaneous combustion in a coal waste dump at the Antaibao mine (China). This method combines multi-angle UAV-based thermal infrared imaging with batch image pre-processing, filtering of false high-temperature readings, and 3D reconstruction of the surface temperature field. Such a method enables more accurate localization of the combustion zones and enhances the efficiency of fire suppression efforts.

Conference proceedings [4] explore the feasibility of using UAVs for thermal imaging of waste rock dumps to enable timely detection of self-heating centers and prevent spontaneous combustion. The authors criticize traditional monitoring methods as inefficient, labor-intensive, and hazardous. They justify the advantages of remote sensing and thermal imaging, particularly when integrated into UAV platforms. The work presents examples of recommended drone models and describes software solutions for image processing. It demonstrates that this technology allows for rapid and highly accurate monitoring of the thermal state of waste heaps, offering considerable environmental and social benefits.

Another approach is outlined in [5], where the authors propose an automated system for monitoring radiation levels and toxic gas emissions from coal waste dumps, adapted for use in combat zones. The system's concept involves UAV reconnaissance combined with a wireless sensor network for real-time data transmission. The authors detail the technical implementation of the platform, including sensor types, communication architecture, and signal processing algorithms.

The study presents the results of field test trials demonstrating the system's effectiveness in detecting anomalous levels of radiation and gases. It also discusses the potential for scaling the system to other hazardous sites.

At the same time, improvements in image processing continue. Paper [6] introduces a novel method for 3D thermal mapping of slow-burning coal deposits. It combines oblique-angle UAV-based thermal imaging with batch image processing (including temperature scale normalization and contrast enhancement) in a four-stage workflow: flight planning, data collection, preprocessing, and 3D modeling through photogrammetry and SIFT triangulation. This method enables accurate reconstruction of the temperature field in three dimensions and has been successfully applied at the Maoergou open pit (China), where high-temperature zones were identified to support fire suppression operations.

It should be noted that a separate research direction has emerged around assessing the effectiveness of monitoring systems using various predictive models.

For example, study [7] demonstrates the efficiency of using UAVs equipped with multisensor cameras (RGB, multispectral, and thermal) for evaluating above-ground biomass of alfalfa (Medicagosativa L.) on a reclaimed coal waste dump in Shanxi Province, China. The analysis was conducted using different regression models (RF, GBDT, KNN, SVR) and their stacking combinations.

At the same time, RGB imagery alone provided nearly the same level of accuracy, allowing for significant cost reduction. A negative correlation was identified between soil temperature and biomass, indicating the potential of using biomass as an indicator of subsurface spontaneous combustion of waste material. The results confirm the potential of UAVs for monitoring vegetation recovery and developing land management strategies for such areas [1].

Article [11] presents a comprehensive systematic review of UAV applications in the monitoring of mining waste, which are technogenic objects by nature. Therefore, the monitoring approach focuses on multisensor capabilities and analytical methods. The author reviews 64 sources published between 2010 and 2023, highlighting the main application areas: environmental monitoring, 3D terrain modeling, and safety assessment – with LiDAR, structure-from-motion (SfM) photogrammetry, and thermal imaging being the dominant techniques.

It is noted that UAVs enable fast and safe collection of high-precision DEM/DSM, detailed orthophotos, and thermal maps, which facilitate the detection of erosion, deformations, and early identification of spontaneous combustion on waste piles. Of particular interest is the integration of thermal imaging (thermal anomalies) with geoinformation models, as well as the use of AI methods (SA-DNN) for automatic detection of contamination or disturbances (e.g., copper distribution), significantly expanding UAV capabilities from passive monitoring to active risk prediction. In conclusion, the article reinforces the understanding that UAVs represent a flexible, safe, and efficient solution for multi-faceted management of mine waste dumps, requiring further development of auto-validated data processing and implementation standards.

Study [12] demonstrates the high potential of UAVs equipped with RGB cameras for early detection of potential spontaneous combustion in coal waste piles through the assessment of above-ground biomass (AGB) of alfalfa. The authors applied multi-structural analysis of spectral indices and textural features derived from UAV imagery and developed stepwise linear regression models, enabling reliable correlation with high temperatures in deeper soil layers. Unlike direct TIR methods, which only capture surface temperature, alfalfa AGB proved to be more sensitive to hidden heating in early stages when the surface remains stable. This approach allows for rapid, safe, and cost-effective large-scale monitoring of reclaimed dumps, positioning UAV-RGB as an effective tool for environmental early warning, especially in hard-to-reach areas where traditional methods are risky or expensive.

Methodology

The conducted analysis showed that mapping methods for complex geotechnical systems, especially coal mining waste, using UAVs equipped with optical instruments (LiDAR, RGB, TIR, MS) are continuously evolving. This enables obtaining high-resolution images from various angles in both visible and infrared spectra, as well as multispectral data.

Such methods open new possibilities for the rapid detection of spontaneous-combustion zones, monitoring of thermal anomalies, and assessment of the spatial dynamics of technogenic objects. Combining thermal imaging data with 3D modeling allows the creation of accurate digital thermal models of waste piles, significantly enhancing the efficiency of environmental monitoring and technogenic safety while protecting environmental personnel from direct presence at hazardous sites.

(Table 1) shows the advantages and limitations of using additional optical sensors on UAVs for monitoring the thermal state of coal mining waste.

Table 1. Application of optical device technology in UAVs

Technology (applied in UAV)	Capabilities *advantages*/*limitation*
LiDAR – a UAV-applied remote sensing technology that uses laser pulses to create high-precision three-dimensional models of some terrain or objects.	***Advantages:*** ▪ High accuracy – provides precise digital elevation models (DEM) even in hard-to-reach or densely vegetated areas. ▪ Ability to scan through tree canopies – LiDAR can penetrate foliage and deliver accurate data on the ground surface. ▪ Autonomy and mobility – UAVs equipped with LiDAR can cover large areas with minimal operator effort. ▪ Data collection speed – significantly faster than traditional ground-based topographic surveys. ***Limitations:*** ▪ High cost – both of the LiDAR itself and the UAV capable of carrying it. ▪ Heavy equipment weight – requires drones with increased payload capacity. ▪ Necessity to process large volumes of data – requires specialized software.
RGB – use of RGB cameras on UAVs is one of the most common methods for remote monitoring. An RGB camera is a standard digital camera that captures images in three spectral bands: Red, Green, and Blue.	***Advantages:*** ▪ Affordability – cameras are cheaper than multispectral or LiDAR systems. ▪ High resolution – allows capturing detailed images of the surface. ▪ Ease of processing – images can be easily processed using common software (e.g., Agisoft Metashape, Pix4D). ▪ Flexibility of use – can be used for both photography and video recording. ***Limitations:*** ▪ Cannot see beyond the visible spectrum – not suitable for detailed spectral analysis (e.g., plant health assessment using NDVI). ▪ Do not provide height information independently – need to be combined with photogrammetry for elevation data. ▪ Dependence on lighting and weather conditions – fog, rain, or strong sunlight can reduce image quality.
TIR – use of Thermal Infrared (TIR) in UAVs is not only possible but also highly effective in many fields where detecting thermal anomalies or monitoring temperature processes is necessary. It enables "seeing" what is invisible to ordinary RGB cameras.	***Advantages:*** ▪ Detection of thermal objects in darkness or poor visibility (fog, smoke). ▪ Remote diagnostics of objects without the need for direct contact. ▪ Rapid response to emergency situations: fires, leaks, overheating. ***Limitations:*** ▪ High cost – cameras range from several thousand to tens of thousands of USD. ▪ Lower resolution compared to RGB cameras. ▪ Sensitivity to weather conditions – strong wind, rain, and sunlight glare can affect accuracy.

Technology (applied in UAV)	Capabilities advantages/limitation
	▪ Requires calibration and expertise in data interpretation – thermal images are not always straightforward for inexperienced operators.
MS – use of MS (Multispectral) cameras on UAVs is widely applied in the agricultural sector, ecology, land monitoring, hydrology, forestry, and other knowledge-intensive fields.	***Advantages:*** ▪ Assessment of plant health even before visual symptoms appear. ▪ Optimization of fertilizer, water, and pesticide application (field zoning). ▪ Automated data processing using specialized software (Pix4Dfields, DroneDeploy, Agisoft, QGIS). ▪ Cost reduction through a targeted approach. ***Limitations:*** ▪ Cost is higher than RGB cameras (ranging from USD2,000 to over USD10,000). ▪ Requires calibration panels (reflectance panels) for accuracy. ▪ Needs understanding of spectral indices and agronomic processes. ▪ Dependent on weather conditions (sunlight, clouds may affect data quality).

Moreover, the effectiveness of all systems can be enhanced through their integration with machine learning algorithms. This opens up prospects for automated classification of areas based on risk levels, which can serve as a foundation for timely intervention and minimization of environmental impacts.

Results

A visual-comparative demonstration of the main types of UAV imaging of coal mining waste using RGB, TIR, MS, and LiDAR is shown in (Table 2).

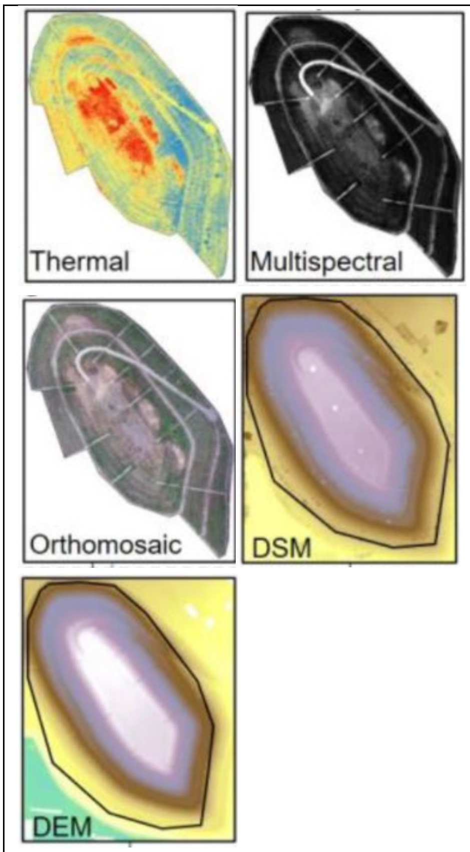
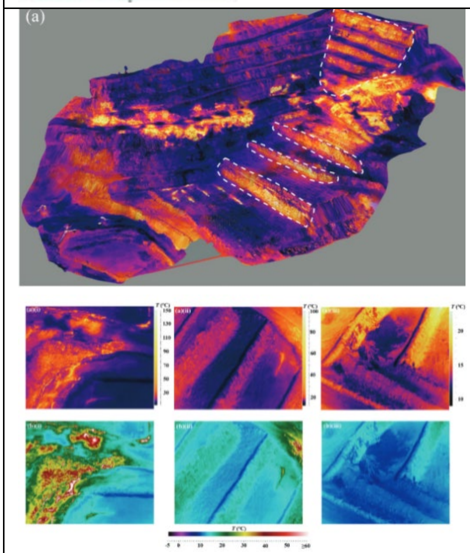
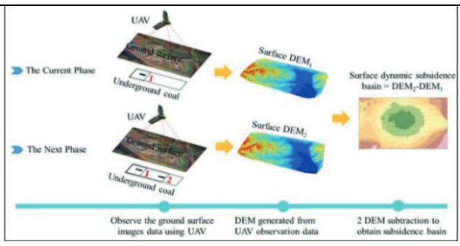
Based on the data from Table 1, it can be stated that China is currently the undisputed leader in the use and modification of UAVs for fire monitoring.

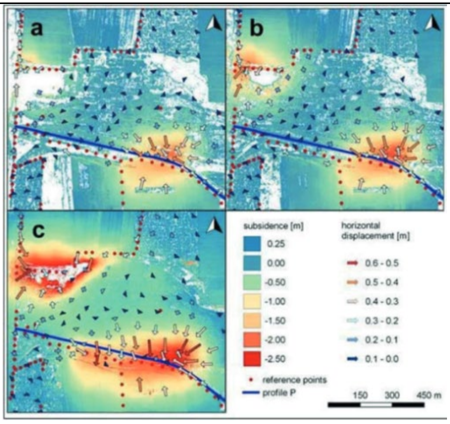
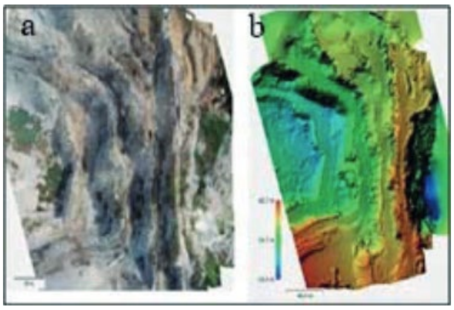
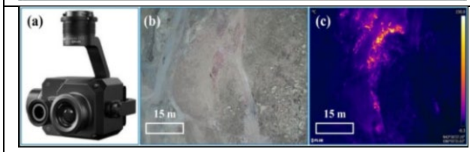
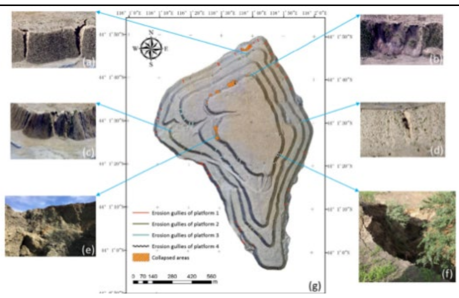
The top five also include Ukraine, the USA, India, and Germany. Poland and several other countries are actively developing in this area.

The analysis of countries by the level of UAV application can be presented in the form of a ranking table (see Table 3).

This is related to the fact that China is the largest manufacturer of unmanned systems in the world and also the largest coal producer globally.

Table 2. General overview of surface mapping of coal mining waste based on UAV imaging using additional optical sensors

	Results of study [7]: Considering the economic efficiency of RGB images, they are the most common type of data in mining areas. For this purpose, the study examined four combinations: Combination I (RGB), Combination II (RGB + MS), Combination III (RGB + TIR), and Combination IV (RGB + MS + TIR), to investigate the impact of integrating UAV image features on the accuracy of AGB alfalfa estimation. The study also compared the effectiveness of different machine learning models (RFR, GBDT, SVR, KNN, and stacking). The workflow of this study is illustrated in the figure.
	In study [6], a thermal infrared 3D model of coal mining waste was created using UAV data, based on raw thermal images. The views include perspectives from the southeast and the south. Although the 3D model was successfully constructed, identical colors do not necessarily indicate the same temperature. White dashed lines mark false high-temperature zones influenced by sunlight. The proposed method for 3D visualization of thermal surfaces of coal fires using thermal infrared sensing data from UAVs involves four main stages: route planning, data collection, preprocessing of thermal infrared data, and 3D visualization.
	In source [1], thermal displacement zones of coal mining waste were identified using photogrammetry with UAVs at the Pikary site. The sketch of the UAV photogrammetry technology is presented for monitoring surface subsidence caused by coal mining. This approach enables capturing clear images of the defined thermal zone of the combustion core from different angles and determining the burning ranges of the hotspot.

	
	In study [8], the flexibility of UAV thermography for monitoring surface temperature anomalies caused by underground coal fires is demonstrated. The authors compared UAV Land Surface Temperature (LST) data with ground measurements, identified the influence of survey scale on the accuracy of thermal images, and showed that under optimal conditions (flight altitude, sensor resolution), UAVs can reproduce temperature profiles with an error margin of ±1–2 °C. This confirms their suitability for prompt detection and mapping of prolonged underground fire zones, especially in hard-to-reach areas where traditional methods are less effective.
	In study [9], the effectiveness of a flexible approach using drones, satellite imagery, and field measurements is demonstrated for assessing soil degradation and erosion at an open pit mine dump in China after five years of natural reclamation. The authors combined satellite vegetation data from GF-1 with precise 3D terrain models obtained through UAV photogrammetry, along with soil physical properties from field samples, to identify the most erosion-prone areas. Using a geographic detector, they found that slope aspect and vegetation cover were key factors in degradation. Based on this, adaptive measures were proposed: restoring natural landforms, reinforcing slopes, and planting pioneer species to stabilize the soil. This integrated approach shows how UAV monitoring combined with geoinformation analysis can provide accurate, rapid, and adaptive management of land reclamation after mining activities.

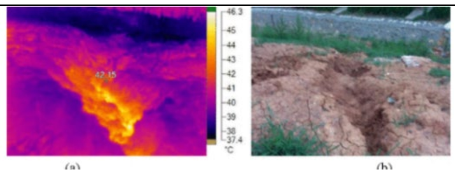
	In paper [10], a comprehensive approach to detecting and extinguishing spontaneous combustion in coal mining waste heaps is presented, specifically utilizing UAV thermography. The authors conducted thermal mapping of the surface with drones to identify shallow hot spots, supplemented by intensive drilling to detect deeper fires (at depths of 3–5 meters), demonstrating that these areas are interconnected through the "stack effect." After accurately locating the fire centers, they applied multiphase foam injection and fracture filling, significantly increasing the stability of the mine dump. The process was completed with reclamation involving the application of a soil cover and revegetation. Integrating UAVs into this workflow allowed for timely and precise fire localization, prevented catastrophic damage, optimized remediation costs, and established a repeatable protocol for effective environmental management of such sites.

Table 3. Use of UAV technology by countries around the world

Rank	Country	Main advantage
1	China	Wide-scale application and innovations in the design and modernization of UAVs.
2	Ukraine	Primarily designed for military purposes in the war against Russia, but in Ukraine's post-war economic recovery, there is widespread use of UAVs in the mining sector – especially for monitoring coal mining waste fires. Development of specialized UAV technologies tailored to specific tasks in the mining industry.
2	The USA	Complex multisensor solutions. The focus is on UAV technological advancement, requiring multi-stage testing and implementation.
3	India	There is a high demand due to active waste fires. However, UAVs are not yet widely used on a large scale (so far).
4	Germany	Systematic ecological approach. UAVs are not widely used yet.
5	Poland	Eco-focused biomass monitoring. UAV applications are still sporadic.

It has thousands of active and closed mines where underground fires often occur, which are difficult to detect by traditional methods. Therefore, UAVs are actively used there for monitoring coal waste combustion, due to the large volumes of coal and high risk of spontaneous combustion, combined with the state policy strategy for environmental control.

Ukraine should also be noted. Since the beginning of the full-scale Russian invasion, Ukraine, together with partners (the EU, the USA, and the UK), started developing its own UAVs. As of 2025, the production potential is estimated at 10 million UAVs per year (≈800,000 per month) [13].

The main advantage of Ukrainian UAVs is their technological sophistication – developed from scratch and designed as multifunctional drones for specific tasks.

It is forecasted that after the war, the use of UAVs in Ukraine will take new forms. This is primarily due to the transition of military technologies and systems with very rapid aging cycles into civilian use. Especially during wartime, these systems age quickly but hold great potential in civilian life. By moving from restricted-access areas into open ones, this transition allows training of specialists with materials developed in not decades, but within 1-3 years.

Thus, rapid growth is expected in the industrial sectors, particularly mining, for several reasons:

- The war provided unique experience in the mass application of UAVs.

- It created a powerful generation of drone operators with high technical skills. These specialists can work in industry, including mining enterprises, after the war.

- Mass production of UAVs will make them accessible to civilian enterprises and reduce their cost by 30–50%.

The cost of optical devices for UAV systems in Ukraine at the present time is shown in (Table 4).

Table 4. Approximate cost of optical devices for UAVs as of 2025

Sensor	Price range (USD)
LiDAR (basic)	2 000 – 5 000
LiDAR (mid-range)	10 000 – 50 000
LiDAR (high-resolution)	50 000 – 200 000
Multispectral (MS)	5 000 – 15 000 (up to 25 000)
Thermal imager (TIR)	200 – 10 000

Conclusions.

Summing up, it can be said that the use of UAVs equipped with multisensor systems and machine learning has the potential to become a key tool for comprehensive monitoring of environmentally hazardous waste dumps and spontaneous combustion zones in mining waste. In the future, this will enable safe and rapid detection of active or potentially dangerous technogenic objects within geomechanical systems, such as combustion hotspots. It will help prevent uncontrolled underground fires that damage the environment, threaten human life, and cause infrastructure destruction.

Currently, there are no open-source UAV monitoring systems comparable to conventional operational ones. This is due to the fact that such systems are underdeveloped and highly commercialized. Their main users are military forces, government agencies, and large corporations, which means there is not yet a sufficiently competitive environment for broader development.

For Ukraine, currently facing challenges due to Russian aggression, this presents a unique opportunity to become a global leader in the development and implementation of such UAV-based monitoring systems. By reducing reliance on dangerous and costly fieldwork, and integrating UAV data with GIS systems and artificial intelligence, Ukraine can create a national registry of hazardous waste dumps for continuous monitoring. This will not only improve the environmental condition of mining regions but also enable the country to adopt a modern approach to sustainable resource management in the coal sector.

Post-war, Ukraine will have a unique advantage – a large fleet of UAVs, skilled operators, and existing local production of drones and sensors. This will allow for widespread use of UAVs in automated monitoring of waste dumps even at medium and small mines. This emerging market could become a key driver of Ukraine's postwar economic growth

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