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ADVANCED DRONE-BASED MONITORING OF AGRICULTURAL, FORESTRY, AND AQUATIC ECOSYSTEMS: TECHNICAL FRAMEWORK

Maria Gutu*, ORCID: 0000-0002-2820-393X,
Lilia Rotaru, ORCID: 0000-0002-6578-418X,
Victoria Alexei, ORCID: 0000-0003-4560-3131,
Maxim Kapusteanski, ORCID: 0009-0004-5009-6503

Technical University of Moldova, 168 Stefan cel Mare Blvd., Chisinau, Republic of Moldova
* Corresponding author: Maria Gutu, *maria.gutu@iis.utm.md*

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Abstract. The rapid advancement of drone technology has significantly transformed environmental monitoring, enhancing capabilities for observing and managing agricultural, forestry, and aquatic ecosystems. This paper presents a comprehensive technical framework for implementing advanced drone-based systems into ecosystem monitoring, focusing on integrating high-resolution sensors, data processing, and artificial intelligence-based analytics. The framework incorporates modern technologies, including drones from Da-Jiang Innovations or First-Person View drones equipped with metric cameras for aerial photogrammetry. These can be further enhanced with multispectral and Light Detection and Ranging sensors to acquire real-time data, enabling more effective analysis. Furthermore, the Proxmox Virtual Environment is the core of the system's architecture, increasing effective virtualisation and deployment. Core data processing technologies include Python scripts, Quantum Geographic Information System, and Pix4D software for photogrammetric reconstruction, as well as Elasticsearch for database management, acquisition, and storage. The Kibana platform ensures interactive data visualisation and supports evidence-based decision-making. The service-oriented structure and system modularity enable the rapid integration of new analytical tools that are adaptable to diverse ecological contexts. Validation in operational environments confirms the framework's ability to address challenges in ecosystem management, particularly in remote areas. This integrated approach contributes to more sustainable and adaptive ecosystem monitoring and management practices.

Keywords: *drone-based monitoring, ecosystem management, real-time data processing, ai-driven analytics, precision agriculture.*

Rezumat. Evoluția accelerată a tehnologiei dronelor a transformat semnificativ procesul de monitorizare a mediului, extinzând capacitățile de observare și gestionare a ecosistemelor agricole, forestiere și acvatice. Lucrarea prezintă un cadru tehnico-științific complex pentru implementarea sistemelor avansate de monitorizare ecologică bazate pe drone, cu accent pe integrarea senzorilor multispectrali și a tehnologiei de detectare și măsurare a distanței prin lumină, precum și a analiticii avansate asistate de inteligență artificială. Arhitectura este fundamentată pe mediul virtual Proxmox, care permite virtualizarea scalabilă și implementarea modulară a componentelor. Fluxurile de achiziție și procesare a datelor utilizează scripturi automatizate în Python, sistemul geografic de informații Quantum pentru analiză geospațială, Pix4D pentru reconstrucție fotogrammetrică și Elasticsearch pentru stocare și indexare performantă. Platforma Kibana asigură vizualizarea interactivă a datelor și sprijină procesul decizional bazat pe dovezi. Structura orientată pe servicii și modularitatea sistemului permit integrarea rapidă a noilor instrumente analitice, adaptabile diverselor contexte ecologice. Validarea experimentală în medii operaționale confirmă eficiența metodologiei propuse în depășirea constrângerilor geografice, promovând astfel o guvernanță ecologică sustenabilă și adaptativă, bazată pe tehnologii de teledetecție de generație nouă.

Cuvinte-cheie: *monitorizare bazată pe drone, managementul ecosistemelor, procesarea datelor în timp real, analize bazate pe inteligență artificială, agricultură de precizie.*

1. Introduction

The swift advancements in drone technology have dramatically reshaped the field of environmental monitoring, offering innovative solutions for efficiently managing agricultural, forestry, and aquatic ecosystems. Unmanned Aerial Vehicle (UAV) imagery has become a crucial data source for Geographic Information Systems (GIS), providing high-resolution visual data that is essential for spatial analysis and informed environmental decision-making [1]. Equipped with advanced sensors and real-time data processing capabilities, drone systems have become essential instruments for better resource management and improved ecosystem care practices. The increasing preference for UAVs can be attributed to their affordability, ease of use, and ability to minimise fieldwork. Their efficiency in rapidly collecting photogrammetric data, combined with the high accuracy and detail of the resulting analyses, has made them a preferred option in environmental studies [2].

The foundation of the digital photogrammetry technique lies in image processing and analysis, enabling the generation of precise data [3,4]. Integrating low-cost UAVs with digital cameras provides a viable and cost-effective alternative for documenting surface structures and generating 3D models from collected data [4,5]. High-resolution drone imagery enables the creation of detailed terrain maps, which are valuable in urban planning, land-use management, and environmental monitoring. These maps, derived from UAV data, deliver accurate and comprehensive representations of various landscapes, enabling informed decision-making [6].

GIS-integrated drone technology is a notable application in disaster management and emergency response. UAVs equipped with thermal cameras can detect and monitor wildfires or other natural disasters, providing real-time data that is crucial for timely intervention. Additionally, drones can assess post-disaster damage and pinpoint areas that require immediate attention. The integration of GIS enables the analysis of this data, the production of maps that illustrate the extent of damage, and the pinpointing of critical areas for emergency response efforts [1,6].

UAV-supported remote sensing techniques have been effectively employed across several environmental domains. Notable examples include forest monitoring [7–10], agricultural assessments [11–13], and studies of aquatic ecosystems [14–16]. UAV technology presents a time- and cost-efficient framework, enhancing data resolution and offering new perspectives on observed objects and phenomena. This approach is especially advantageous for monitoring settings such as remote or complex underwater habitats, where conventional techniques may be insufficient.

This paper outlines a comprehensive technical architecture for a drone-based monitoring system, highlighting the incorporation of advanced sensors and artificial intelligence (AI) algorithms for effective data analysis. The proposed system utilises drones manufactured by Da-Jiang Innovations (DJI) and First-Person View (FPV) drones equipped with multispectral cameras to collect and process data in real-time, ensuring an accurate and detailed visualisation of the monitored ecosystems. The primary objective of this framework is to enhance environmental monitoring techniques and provide effective approaches for sustainable resource management.

The primary objective of this project is to develop an adaptable system for overseeing and controlling agricultural lands, forests, and water environments using drones and advanced data processing technologies. This study focuses on establishing UAV-based data acquisition protocols alongside GIS-based image processing guidelines to enhance the monitoring and management of these ecosystems. Specifically, the research addresses critical applications across three environmental domains: the agricultural, forestry, and aquatic systems.

For the agricultural system, the guidelines are customised to assist with various monitoring tasks, such as spraying field crops [17] and overseeing irrigation practices, while evaluating crop conditions during different growth stages, including winter wheat seeding. Identifying and diagnosing diseased areas is a crucial process for preventing plant disease outbreaks and safeguarding both public health and the economy [6,18]. In the forestry system, the project aims to facilitate the monitoring of deforestation, landslides, and other natural disasters that threaten forested areas. Lastly, for the aquatic system, the guidelines are geared towards monitoring the health of lakes and rivers, providing insights into water quality and detecting ecological disturbances.

Through the implementation of this comprehensive monitoring solution, the project pursues the following key goals:

1. Real-time monitoring of crop and forest health and water quality using multispectral sensors and high-resolution cameras. This feature facilitates interventions and well-informed resource management decisions.
2. Data processing and analysis using AI to detect and mitigate ecological issues, such as soil degradation, illegal deforestation, and water pollution. AI-driven analysis enhances the precision and speed of data interpretation, providing actionable insights to effectively prevent and manage environmental challenges.
3. Integration and management of real-time data through a scalable and efficient platform. The proposed system utilises Proxmox Virtual Environment for virtualisation alongside open-source software solutions for data storage and visualisation. This approach ensures that the platform is flexible, easily adaptable, and capable of handling large volumes of data while maintaining high performance and reliability.

The project is designed to create a robust framework that leverages UAV technology and GIS-based data processing to optimise the monitoring and management of various ecosystems. By advancing the capabilities of environmental monitoring, this research aims to support sustainable practices and promote the efficient use of natural resources.

2. Materials and Methods

2.1. Platform Architecture

The technical architecture of the proposed monitoring and management system (Figure 1) is founded on a Service-Oriented Architecture, which ensures the modularity and scalability necessary for integrating emerging technologies. The system utilises Docker containers to deploy and manage individual services, including data storage and processing, within the Proxmox Virtual Environment. This virtualisation infrastructure facilitates efficient resource allocation and the streamlined execution of services.

The platform is designed to exhibit a high degree of flexibility, facilitating the seamless integration of new functionalities as the needs of its users evolve. This flexibility is demonstrated through the ease with which additional features, such as advanced image analysis algorithms or the incorporation of external data sources, can be added to enhance the system's capabilities. The architecture's modular design ensures that these integrations do not disrupt existing functionalities but complement and expand the system's operational scope.

This adaptability is particularly beneficial in addressing the diverse requirements of various end-users, including researchers, decision-makers, and agricultural managers. Each of these groups has distinct needs for data analysis, monitoring, and reporting, and the platform's design allows it to provide tailored solutions accordingly. The platform can facilitate detailed and customizable analyses for researchers, supporting scientific investigations and data-driven discoveries. Conversely, decision-makers may benefit from real-time data processing and visualisation capabilities, enabling informed and timely decisions that are critical in dynamic environments. Agricultural managers can leverage the platform to precisely monitor plantations and aquatic surfaces, utilising the insights generated to optimise resource management and improve productivity.

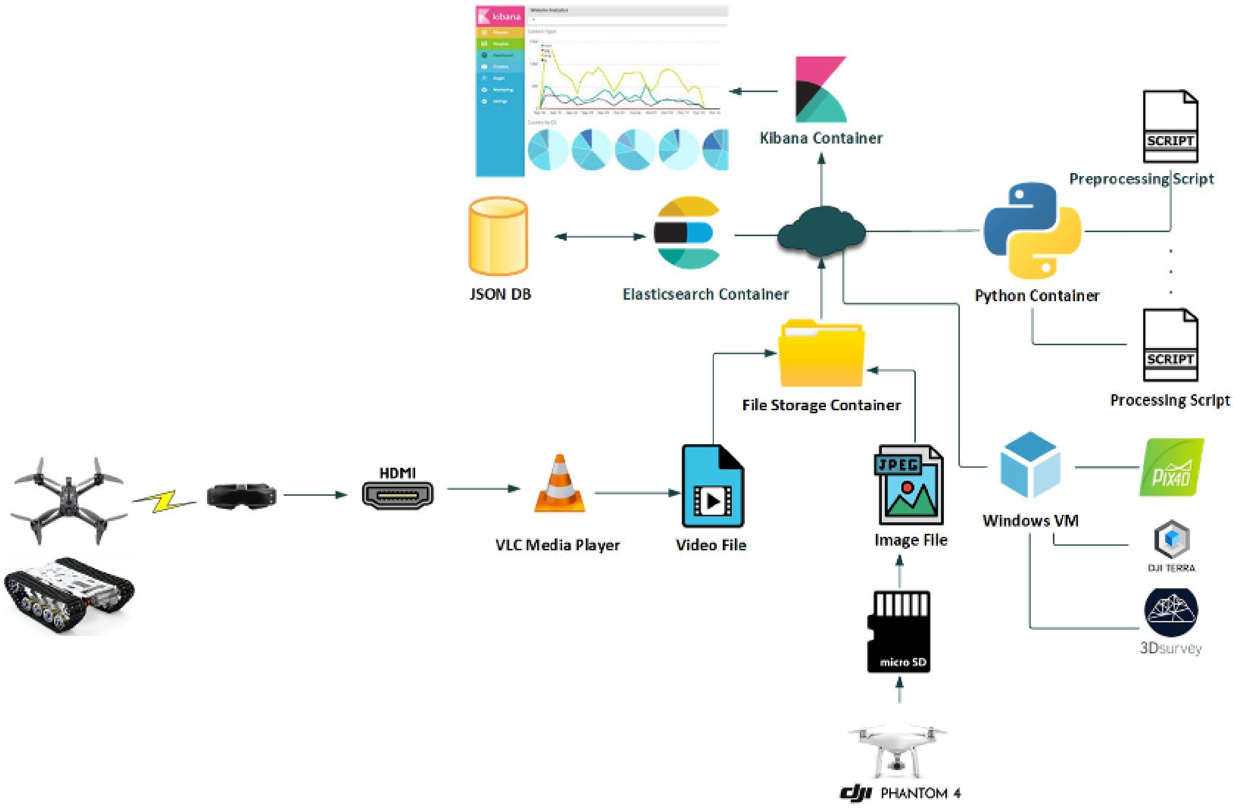

Figure 1. Architecture of the monitoring and management platform for plantations and aquatic surfaces.

The platform is versatile and robust because it supports a wide range of use cases. It is capable of meeting both current monitoring needs and anticipating future requirements, ensuring long-term utility and relevance across various fields of application. The system's inherent flexibility promotes innovation and the integration of cutting-edge technologies, ensuring that the platform remains responsive to the continuously evolving landscape of user demands and technological advancements [19].

The system is designed using the open-source Proxmox Virtual Environment, which optimises the management and utilisation of hardware resources. Proxmox is a powerful and flexible virtualisation platform that facilitates the deployment, operation, and oversight of both virtual machines and containers. This capability ensures a highly robust, efficient, and scalable infrastructure that meets the demands of modern virtualised environments.

The system's hardware configuration is based on multiple Lenovo ThinkCentre mini PCs, specifically models M700, M73, and M710Q. These devices have been upgraded with more powerful Intel i3 and i5 processors to boost performance. Additionally, the storage capacity has been significantly enhanced by integrating solid-state drives and hard disk drives, providing a balance between speed and storage capacity.

These mini PCs are integrated into a cluster environment, which allows them to function as a cohesive unit managed through a single, centralised web interface. This configuration simulates the operational framework of a traditional data centre. The system ensures streamlined management, optimised resource allocation, and enhanced reliability by leveraging the cluster capabilities. This infrastructure provides a comprehensive and scalable solution, ideally suited for efficient and centralised hardware resource management scenarios.

Within this architectural framework, services are strategically developed and deployed using either containers or virtual machines, selected based on criteria such as resource efficiency and software compatibility requirements. Containers, known for their lightweight design and reduced overhead, are generally the preferred method for deploying services when optimal resource utilisation is essential. Their efficiency arises from sharing the host operating system's kernel, which reduces the duplication of system resources and accelerates the deployment and scalability of applications.

Nonetheless, virtual machines are employed when specific platform services require an operating system different from Linux, which containers predominantly support. Virtual machines offer the flexibility to run a completely isolated operating system, complete with its kernel, thereby accommodating software environments and dependencies that are not natively compatible with the Linux-based container ecosystem. This dual deployment strategy ensures that the platform remains versatile and capable of supporting a broad spectrum of software environments, from container-optimised applications to services that demand a more traditional virtualised infrastructure.

Moreover, the architecture facilitates the seamless integration of additional hardware components or external workstations. This adaptability is enabled through robust connectivity options, supporting communication and data exchange over local networks or the Internet. Such integration capabilities enhance the system's extensibility, allowing both internal and external resources, including specialised software applications and web-based services, to be efficiently incorporated into the platform. By enabling smooth communication between disparate hardware and software components, the architecture ensures that the system can expand and evolve to meet diverse operational demands, fostering an adaptable and future-proof environment.

Considering the diverse requirements and the dynamic conditions during system design and development, a microservice-based architectural approach was selected as the foundational framework. This architectural paradigm, rooted in Service-Oriented Architecture (SOA) principles, effectively organises software components into a collection of independent and self-contained services. Each microservice performs a specific function and operates autonomously. Therefore, all services within the system communicate seamlessly using standardised protocols, such as HTTP, SOAP (Simple Object Access Protocol), or REST (Representational State Transfer).

A Service-Oriented Architecture framework ensures that each microservice has well-defined interfaces, such as HTTP APIs or messaging systems, that facilitate smooth communication and data exchange between services. This decoupling of services is a crucial feature, as it significantly reduces the direct dependencies that often complicate software systems. Consequently, this modular design enables the modification, enhancement, or updating of individual services without compromising the overall system's functionality or performance.

Moreover, this microservice-based approach provides substantial flexibility in addressing varying performance and usage demands. Since each service operates independently, scaling can be performed per service, ensuring efficient resource utilisation. For instance, services experiencing high loads can be scaled to accommodate increased demand, while other services that require fewer resources can remain unaffected. This scalability ensures the system remains robust and responsive, even under fluctuating workloads or expanding functionalities.

Adopting a microservice architecture also enhances the system's ability to adapt to evolving requirements. As new features or services become necessary, they can be integrated seamlessly into the existing architecture without necessitating a comprehensive redesign. This capacity to incorporate changes efficiently is particularly advantageous in environments subject to rapid technological advancements or shifting user needs, ensuring that the system remains relevant and future-proof. Overall, the microservice-based design promotes maintainability, scalability, and continuous system improvement, making it a highly effective and sustainable architectural choice.

2.2. Technologies Used

The proposed monitoring platform is designed to integrate a diverse array of technologies, providing comprehensive support for data collection, processing, and visualisation. The foundational infrastructure is built upon the Proxmox Virtual Environment, an open-source platform that delivers a robust and efficient solution for container virtualisation and the optimal management of hardware resources. Proxmox’s virtualisation capabilities are instrumental in efficiently handling multiple workloads, enabling the seamless deployment and management of virtual machines and containers on a unified platform.

By leveraging the Proxmox Virtual Environment, the monitoring platform effectively optimises the performance of servers and Lenovo ThinkCentre mini-PCs, which serve as key hardware components. The integration of these hardware resources is streamlined, with Proxmox ensuring efficient resource allocation and load balancing, thereby enhancing the overall system's performance and reliability. This optimization extends to data storage and analysis processes, where Proxmox's advanced features facilitate the efficient management and processing of large datasets, reducing latency and improving throughput.

Furthermore, the architecture's inherent scalability is a significant advantage. As the platform's data processing and analysis requirements grow, the Proxmox Virtual Environment allows for the seamless addition of new resources, such as servers or containers, without compromising system stability or performance. This scalability is crucial for adapting to growing data volumes and evolving monitoring requirements, offering a future-proof solution that accommodates advancements in data analysis technologies.

The performance and scalability benefits of this architecture are illustrated in Figure 2, which depicts how Proxmox's efficient virtualisation framework enhances the platform's capacity to handle complex and data-intensive operations. By integrating these technologies, the platform meets current operational demands and remains adaptable to future developments, ensuring long-term sustainability and effectiveness in diverse monitoring applications.

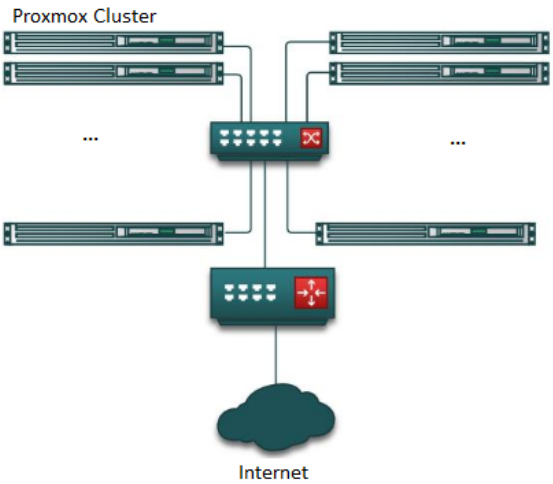

Figure 2. Universal development and deployment infrastructure.

For data collection, the proposed monitoring platform utilises advanced unmanned aerial vehicles, specifically DJI and FPV drones [20, 21], equipped with high-precision metric cameras and state-of-the-art multispectral sensors. These sophisticated sensing devices can capture high-resolution images and generate extensive datasets, providing detailed and accurate visual representations of the monitored ecosystems. Integrating metric cameras ensures that spatial data is collected with high accuracy. At the same time, multispectral sensors enable the acquisition of spectral information essential for analysing vegetation health, water quality, and other ecological indicators.

The drones are engineered to transmit collected data in real-time, thereby facilitating immediate analysis and rapid response in dynamic monitoring situations. For scenarios where instantaneous data analysis is not required, the drones are also equipped to store captured information on SD cards, enabling subsequent data processing at a more convenient time. This dual capability ensures the system is flexible and can be adapted to various monitoring scenarios, from emergency response and rapid environmental assessment to more comprehensive and in-depth post-mission analyses.

Once the images and datasets have been acquired, they are subjected to rigorous analysis using Geographic Information System (GIS) software, such as QGIS and Pix4D. These advanced geospatial tools are crucial for interpreting the collected data, as they support the creation of accurate and detailed maps and models of the monitored ecosystems. QGIS, an open-source GIS application, facilitates the analysis and visualisation of spatial data through various geoprocessing tools [6], while Pix4D specialises in photogrammetry and 3D mapping, enabling precise modelling and measurement of environmental features.

Integrating drone-based data acquisition with GIS technologies significantly enhances the overall efficiency and precision of the monitoring process. The platform can generate high-quality geospatial information that informs and improves decision-making processes by leveraging these advanced analytical tools. This integration is valuable for real-time environmental management, allowing stakeholders to respond quickly and effectively to changing conditions. Moreover, combining high-resolution data collection and sophisticated GIS analysis contributes to a more holistic understanding of ecosystem dynamics, supporting immediate interventions and long-term environmental monitoring and management strategies.

2.3. Platform Functionality

The data processing framework embedded within the proposed monitoring platform is designed to be highly robust and capable of managing and analysing the complex, high-volume information collected from diverse ecosystems, such as forests, agricultural landscapes, and aquatic environments. This framework employs state-of-the-art software solutions and sophisticated algorithms to ensure that data is efficiently processed, securely stored, and effectively visualised, all aimed at facilitating proactive and informed ecosystem management.

At the core of the data processing pipeline are Python scripts, which are strategically deployed within dedicated containers to optimise performance and scalability. These scripts harness advanced artificial intelligence and machine learning algorithms to analyse the high-resolution images and comprehensive datasets that drones capture. The primary objective of these algorithms is to automate the detection and classification of various environmental anomalies, including critical issues such as deforestation, soil erosion, forest fires, water pollution, and other forms of ecological disturbance. The framework's capability to conduct real-time analysis ensures that significant environmental threats are rapidly identified, enabling swift intervention and enhancing the responsiveness of monitoring operations.

Regarding data management, the platform employs a sophisticated multi-layered storage and retrieval system that ensures both the security and efficiency of data handling. Raw data, which includes live video streams and high-resolution image files collected by drones, is initially stored in a secure File Storage Container. This setup provides a scalable and organised repository for large volumes of unprocessed data, facilitating efficient data access and retrieval for subsequent analysis. After data processing, the refined and analysed datasets are transferred into a JSON-based database managed by Elasticsearch.

Elasticsearch is a high-performance, scalable database system that supports rapid data querying and is essential for conducting in-depth data analysis. Implementing Elasticsearch streamlines data retrieval and enhances the system's ability to recognise complex patterns and environmental trends. This capability is especially crucial for effective ecosystem monitoring and management. Furthermore, Elasticsearch's integration with the platform enables the deployment of advanced, machine learning-driven mechanisms that monitor infrastructure for potential anomalies [22]. These mechanisms can automatically generate alerts, notifying managers or administrators when environmental or infrastructural issues are detected, ensuring that timely and informed decisions are made. This integration supports efficient and accurate environmental monitoring, empowering stakeholders to make data-driven decisions and implement rapid response measures to mitigate ecological threats.

The data processing workflow within the proposed monitoring platform is structured into two primary stages: image pre-processing and advanced analysis. During the image pre-processing phase, raw data captured by drones and sensors is converted into formats optimised for integration and compatibility, such as GeoJSON. This conversion step ensures that the data are standardised and seamlessly interact with the broader monitoring system. By establishing a uniform and optimised data structure, this phase lays a critical foundation for the detailed and complex analysis that follows.

In the subsequent stage, advanced machine learning algorithms are employed to conduct in-depth analyses and generate comprehensive maps of the monitored ecosystems. These algorithms process pre-formatted data to produce high-resolution, geospatially accurate maps that visually delineate areas at risk of ecological degradation. These detailed maps serve as an essential resource for researchers and policymakers, visually representing environmental vulnerabilities and enabling targeted intervention strategies for ecological preservation and sustainable management.

PostgreSQL is integrated as the primary relational database management system to further augment the platform's analytical capabilities. PostgreSQL's robust architecture allows it to efficiently handle complex queries and manage extensive datasets, organising the data to facilitate seamless access, refinement, and analysis. This integration is particularly valuable for supporting high-precision data analysis tasks, as it provides a stable and efficient foundation for managing the large volumes of information generated by the monitoring activities.

Data visualisation constitutes a vital component of the overall data processing framework and is accomplished using Kibana, an open-source analytics and visualisation tool. Kibana enables the creation of dynamic and interactive dashboards that allow stakeholders to explore and interpret data patterns through intuitive graphical representations. These dashboards highlight critical findings and trends, making it easier for environmental managers, researchers, and decision-makers to gain actionable insights and engage in data-driven decision-making. By offering a user-friendly interface, Kibana enables stakeholders to make informed decisions regarding resource allocation, environmental protection, and ecosystem management.

Additionally, the platform extends its data processing and analysis capabilities through a dedicated Windows Virtual Machine. This virtual environment hosts specialised software tools, such as DJI Terra and 3DSurvey, for photogrammetric analysis and generating three-dimensional models from drone imagery. Integrating these tools is crucial for conducting detailed structural assessments of ecosystems and creating advanced topographical maps. The addition of this 3D modelling capability significantly enhances the platform's analytical potential, allowing for a more nuanced understanding of ecosystem structures and landscape changes, which is indispensable for advanced environmental studies and management efforts [4].

Overall, the data processing system is characterised by a modular design, further strengthened by a containerised architecture. This approach ensures that the platform is both scalable and adaptable, enabling it to evolve in response to the changing needs of research and monitoring initiatives. By combining state-of-the-art artificial intelligence algorithms, efficient data storage solutions, and intuitive visualisation tools, a comprehensive and highly effective framework for modern environmental monitoring is provided. This integration of advanced technology ensures that the platform can deliver accurate, timely, and actionable insights, making it a powerful tool for addressing complex environmental challenges and promoting sustainable resource management.

3. Results

Comprehensive empirical results are currently unavailable, as the research remains in the development and local testing phase. Nevertheless, preliminary observations have highlighted the proposed platform’s significant potential for enhancing environmental monitoring and management practices. Integrating advanced technologies, including drone-based data collection and artificial intelligence-driven data processing, presents a promising framework that could substantially improve real-time ecosystem analysis and facilitate more effective environmental interventions.

Initial testing efforts have primarily focused on evaluating the functionality and interoperability of the platform's integrated hardware and software components. The system’s modular architecture, which leverages Docker containers for efficient resource management within the Proxmox Virtual Environment, has demonstrated noteworthy flexibility and adaptability. These preliminary tests have validated the seamless operation of individual components, such as Python-based data processing scripts and the Elasticsearch database utilised for high-performance data storage and retrieval. Specifically, the Python scripts are responsible for executing machine learning algorithms designed to analyse and interpret drone-captured imagery, while Elasticsearch ensures that processed data is organised and accessible for subsequent analysis and decision-making.

Further assessments have examined the platform's capacity to manage diverse data formats and support rapid data retrieval, which is critical for applicability in real-world environmental monitoring scenarios. The system’s ability to process and store data efficiently is crucial for generating timely insights, especially in dynamic ecological contexts where prompt responses are necessary. Additionally, the performance of data visualisation tools, such as Kibana, has been preliminarily evaluated. Early results suggest that Kibana’s intuitive and interactive dashboards effectively translate processed data into graphical insights, making complex environmental information more accessible to researchers and decision-makers. The platform’s visualisation capabilities have shown promise in identifying and highlighting potential ecological risks, which could be instrumental in guiding informed management strategies.

Moreover, the deployment of machine learning algorithms for anomaly detection is undergoing rigorous validation. These algorithms are designed to identify environmental disturbances, such as deforestation, soil erosion, or water contamination, and their accuracy and efficiency are being closely monitored. Early testing indicates that these algorithms have the potential to automate the detection process effectively, enabling proactive responses to environmental threats. However, further validation is necessary to ensure these machine-learning models perform reliably across various ecological conditions.

As the project advances, comprehensive validation in various environmental settings will be crucial to fully assess the platform’s scalability and overall effectiveness. The research aims to produce detailed, high-resolution maps and generate actionable insights to inform sustainable resource management practices. Future testing phases will be crucial to evaluate the platform’s impact across various ecosystems, spanning from terrestrial to aquatic environments. The research will assess the system's capacity to deliver real-world benefits and contribute meaningfully to global environmental conservation and management efforts through extensive field trials. The ongoing development and testing are expected to yield a robust and adaptable monitoring solution that addresses complex environmental challenges.

4. Discussion

The development and initial deployment of the proposed UAV-integrated environmental monitoring platform underscore a paradigm shift in ecosystem observation methodologies, facilitated by the convergence of edge sensing, containerised data processing, and geospatial intelligence. Rather than merely automating existing workflows, the system redefines the spatial and temporal resolution at which ecological phenomena can be captured, interpreted, and acted upon. This advancement is particularly pertinent in the context of increasingly volatile environmental conditions, where real-time, high-fidelity data are essential for evidence-based intervention [9].

A salient observation from the preliminary phase pertains to the system's architectural agility. The microservice-driven deployment model, underpinned by the Proxmox virtualisation layer and Docker containerisation, enables the dynamic orchestration of analytic services. Such decoupling of functionalities enhances system resilience and facilitates rapid, iterative development, a crucial feature in ecological domains characterised by unpredictable and heterogeneous data influxes. Moreover, this design promotes cross-disciplinary extensibility, allowing the platform to incorporate emerging technologies (e.g., edge AI, semantic geospatial reasoning) without necessitating structural overhauls.

The application of machine learning models to drone-derived datasets reflects a broader movement toward predictive environmental analytics [17]. Thus, it also exposes foundational challenges related to model generalizability and data representativeness. While the initial anomaly detection outcomes suggest promise, particularly in identifying biophysical stressors such as vegetation chlorosis or aquatic turbidity gradients, these models remain constrained by the limited scope of training data and the absence of longitudinal environmental baselines. A rigorous validation campaign involving multi-seasonal, multi-ecosystem deployments is required to mitigate overfitting and establish model robustness across ecological gradients.

From a human-systems integration perspective, the visualisation layer, anchored by Kibana dashboards, functions not only as an interpretive interface but also as a cognitive scaffold for decision-makers. The ability to synthesise volumetric spatial-temporal data into actionable insights represents a key advantage of the system [4]. However, the epistemological implications of relying on algorithmically filtered representations must be acknowledged. Future development cycles should prioritise transparency and explainability in the AI modules to foster trust and accountability in high-stakes ecological decision-making.

Another dimension warranting attention is operational sustainability. While the mini-PC cluster approach provides an energy-efficient and cost-effective computing backbone for localised deployments, its efficacy in field conditions subject to environmental stressors (e.g., humidity, temperature extremes, network intermittency) remains to be empirically evaluated. Additionally, the current reliance on Windows-based photogrammetric suites introduces heterogeneity in the software ecosystem, which could complicate long-term maintainability and integration [5, 7]. Migrating critical photogrammetric functionalities to containerised, platform-agnostic services would enhance systemic coherence and reduce operational friction.

Finally, the platform’s capacity for synergistic integration with external environmental data sources (e.g., satellite imagery, IoT sensor networks, citizen science inputs) opens compelling avenues for hybrid data fusion and multiscale modelling. These capabilities would enable the system to transcend its current diagnostic function and evolve into a forecasting and simulation tool, supporting anticipatory governance of environmental resources.

Therefore, the proposed architecture lays a foundational framework for next-generation environmental monitoring—one that is modular, scalable, and poised for intelligence augmentation. The implications extend beyond technical efficacy to questions of ecological epistemology, technological sovereignty, and the ethics of automated environmental stewardship. Advancing this system from a functional prototype to a broadly deployable monitoring infrastructure will require not only technological refinements but also a sustained commitment to interdisciplinary co-design, empirical validation, and critical reflection.

5. Conclusions

The proposed monitoring and management system enables the comprehensive assessment of forests, agricultural lands, and aquatic ecosystems. It provides an effective environmental monitoring and exploration structure by integrating advanced technology and software elements. The system features are divided into services stored in containers, each designed for a particular purpose, such as storing data, conducting analysis, or processing information. This architecture ensures the efficient use of resources, thereby improving the overall management of different ecosystems.

Central to the platform’s functionality is its capability to handle high volumes of data collected by drones and other monitoring devices. The data flow begins with ingesting raw images and sensor readings, which are then pre-processed and stored in a structured format. Using dedicated containers for tasks such as Python-based data processing and Elasticsearch for data management allows for the rapid and efficient handling of complex datasets. The processed data are subsequently analysed using machine learning algorithms, which detect patterns and anomalies, providing valuable insights for environmental monitoring.

Moreover, integrating visualisation tools like Kibana enables users to interact with the processed data through intuitive and customizable dashboards. These visualisations support data-driven decision-making by highlighting critical areas, such as regions susceptible to ecological disturbances or needing immediate intervention. The platform’s modular design ensures that additional functionalities, such as new data analysis techniques or external data integrations, can be easily incorporated without disrupting the existing system.

Therefore, the platform’s structured and scalable data management and analysis approach enhances its effectiveness in monitoring complex ecosystems. The platform is a valuable tool for researchers, policymakers, and environmental managers dedicated to sustainable ecosystem management, providing real-time insights and a high degree of adaptability.

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Submission of manuscripts: jes@meridian.utm.md