

A FRAMEWORK FOR WIND TURBINE STRUCTURAL DAMAGE DETECTION VIA UAV IMAGING AND ARTIFICIAL INTELLIGENCE

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Abstract: *The purpose of this study is to present a methodological framework for wind turbine damage detection using unmanned aerial vehicles supported by artificial intelligence techniques. Traditional inspection procedures are often costly, time-consuming, and contribute significantly to the operational and maintenance share of the Levelized Cost of Energy. The investigation includes an overview of the most common wind turbine structural designs, typical damage mechanisms, and power control strategies required to maintain voltage and frequency stability. Particular attention is given to the role of cyclic condition monitoring as a key factor in ensuring high efficiency and reliability of wind power systems. The proposed approach combines UAV-based visual inspection with AI-assisted damage identification, enabling safer and more effective assessment of turbine technical condition. Safety principles for conducting UAV operations in close proximity to wind turbine infrastructure are also discussed. The results confirm that integrating autonomous aerial inspection with intelligent detection methods may significantly improve maintenance strategies and support the development of more sustainable energy systems.*

Keywords: Wind turbine, Damage detection, Unmanned aerial vehicles (UAV), Artificial intelligence

1. Introduction

In recent decades, issues related to environmental protection, sustainable development, and global warming have become central topics in social, political, and scientific debates worldwide. One of the key challenges addressed in these discussions is the global dependence on conventional energy sources, particularly fossil fuels, and the question of how future energy systems should evolve.

Along with industrial growth and technological progress, global electricity consumption has steadily increased (Luty et al., 2023). For many years, the primary response to this growing demand was a significant expansion in the use of non-renewable energy sources (Fouquet, 2009). At the same time, modern societies have become increasingly aware of sustainability concerns and the responsibility to protect the natural environment. As a result, efforts are being made to meet energy needs by improving the efficiency of existing generation technologies and shifting toward renewable energy resources.

Among renewable energy technologies, wind power has emerged as one of the most important and dynamically developing solutions. Wind energy can supply electricity not only for small households but also for large-scale industrial applications (Du et al., 2020). Currently, wind energy represents the second-largest share among renewable sources, accounting for 13.2% of the total contribution. The largest share is provided by solid biofuels (41.4%), while hydropower ranks third with 11.9% (Eurostat, 2023).

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A major factor determining the competitiveness of any electricity generation technology is the Levelized Cost of Energy (LCoE). A substantial portion of LCoE is associated with Operation and Maintenance (O&M). In the case of wind turbines, O&M costs may account for up to 25% of the total energy cost (Shafiee et al., 2021; Shihavuddin et al., 2019). Regular technical inspections play a crucial role in preventing failures and maintaining turbine performance (Liu & Ishihara, 2015; Kulsinskas et al., 2021). Additionally, reducing turbine downtime is directly linked to economic efficiency, as each day out of service may generate losses ranging from 800 to 1600 US dollars (Katsaprakakis et al., 2021).

In recent years, increasing attention has been given to modern inspection approaches aimed at improving the efficiency of wind turbine condition assessment while reducing operational costs and risks to maintenance personnel. One of the most promising directions involves the application of unmanned aerial vehicles (UAVs), which enable rapid acquisition of high-resolution visual data from difficult-to-access turbine components. Furthermore, artificial intelligence and machine learning techniques provide tools for supporting the automated identification and classification of typical defects such as cracks, erosion, or delamination.

Therefore, the integration of UAV-based inspection with AI-assisted damage detection constitutes a relevant methodological pathway for wind turbine maintenance practices. This paper focuses on outlining such an inspection framework and discussing key operational and safety aspects of implementing UAV and AI technologies in wind energy systems. The main contribution of this work is the proposed inspection procedure and workflow, rather than a performance evaluation or final damage detection results.

2. Methodology

Inspection of wind turbines using aerial systems has become a standard practice in the wind energy maintenance market, driven by the demand for safer, faster and more cost-efficient condition monitoring (CM) solutions. The proposed methodology aligns with current industrial procedures for visual inspection and automated damage analysis, integrating unmanned aerial vehicles (UAVs) with artificial intelligence (AI)-supported identification tools.

Industrial-grade UAV platforms equipped with high-resolution imaging sensors are widely used in commercial inspection services due to their ability to capture detailed visual data in challenging environments. In this framework, a professional multi-rotor system with RGB imaging and optical zoom is treated as a reference configuration. For example, platforms such as DJI Matrice M300, DJI Matrice 350 RTK or DJI Matrice 30T, paired with a high-zoom camera (e.g., Zenmuse-series), represent typical solutions adopted in the market for turbine inspection tasks. These systems offer extended flight endurance, high wind resistance, and long-range operation suitable for wind turbine sites, while optical zoom enables detailed observation of structural elements from a safe distance.

The first step of the methodology involves acquiring photo and video material during an on-site inspection. This is consistent with prevailing practices among professional UAV service providers, who focus on capturing comprehensive visual coverage of critical turbine components. The inspection scope in this methodology emphasizes wind turbine blades, as blade damage typically accounts for a large proportion of maintenance costs and operational risks. Both aerodynamic sides of the blade—the suction side and the pressure side – are included, with particular attention given to the leading edge and trailing edge. When feasible and cost-effective, additional visual assessment of the nacelle and tower may be integrated into the inspection flight plan.

After visual data acquisition, the collected material is transferred to a digital processing environment. In current market practices, data annotation and preprocessing serve as a foundation for developing AI models capable of supporting automated damage detection and classification. Following this trend, the proposed workflow integrates expert-supported annotation with iterative AI model development. Initial interpretation of selected samples may be performed by an engineer experienced in wind turbine operation, and the annotated dataset is subsequently used for training an AI-based model. Iterative refinement of model parameters and evaluation cycles continues until an appropriate level of reliability is achieved for the intended inspection scope, in line with strategies reported in recent literature.

The above methodology schematic representation was presented in Fig. 1.



Fig. 1: Workflow of the proposed UAV-based inspection and YOLOv8-assisted damage detection framework for wind turbine blade condition assessment.

It should be emphasized that the presented research represents an initial stage of ongoing work. At this phase, preliminary analyses were conducted, and a first proof-of-concept implementation of an AI-based detection model was developed using the YOLOv8 architecture. YOLO (You Only Look Once) belongs to the family of one-stage object detection algorithms, where localization and classification are performed simultaneously in a single forward pass. The preliminary detection capability of the model is demonstrated in Fig. 2, which presents example UAV inspection images with bounding boxes highlighting damage candidate regions. These include typical surface defect patterns such as erosion marks, cracks, and discoloration. Although the current results should be treated as exploratory, they confirm the feasibility of integrating UAV inspection workflows with modern deep-learning detection frameworks. Future work will focus on expanding the dataset and performing systematic quantitative validation under operational conditions.

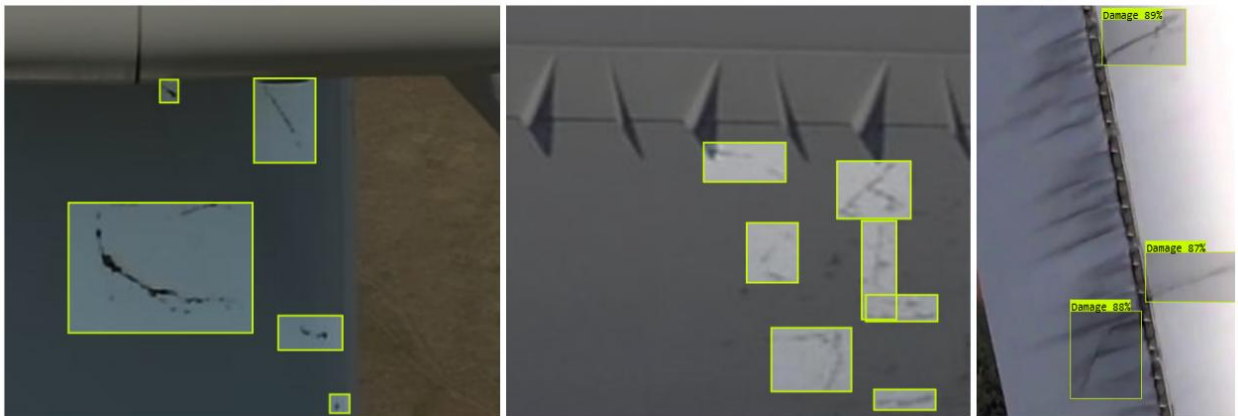


Fig. 2: Preliminary detection results of the YOLOv8 damage model applied to UAV images.

The methodology also highlights the importance of large and diverse datasets, a recognized challenge in both academic research and industrial deployment. Market actors and research initiatives have begun to address this limitation by sharing inspection datasets and benchmarks; such collaborative actions may contribute to accelerating the development of robust AI-assisted inspection tools.

3 Conclusions

The application of unmanned aerial vehicles (UAVs) in wind turbine inspection represents a significant advancement in operation and maintenance strategies. Compared to traditional inspection methods, such as rope-access techniques, UAV-based visual assessment substantially improves safety by reducing the need for personnel to work in hazardous conditions and at great heights. Moreover, this technology is already widely accessible and enables inspections to be performed not only more safely, but also faster and at lower cost.

It has been estimated that UAV inspections can generate savings of up to 40% in comparison with conventional rope-based procedures (Stout & Thompson, 2019). As operation and maintenance costs account for a considerable share of the Levelized Cost of Energy (LCoE), the adoption of aerial inspection methods can contribute directly to improving the economic competitiveness of wind energy systems.

Furthermore, the integration of condition monitoring processes with artificial intelligence algorithms offers additional potential for cost reduction and efficiency improvement. Although the development of AI-supported damage detection models requires substantial initial investment, particularly related to building and annotating large datasets, such tools may significantly enhance the automation and reliability of defect identification. In the long term, this may reduce inspection effort, minimize turbine downtime, and support predictive maintenance approaches.

Overall, the proposed framework combining UAV imaging with AI-assisted damage detection provides a promising pathway toward more sustainable and effective wind turbine maintenance. Continued research and industrial collaboration, especially in the area of shared datasets and model benchmarking, will be essential for the broader deployment of autonomous inspection technologies and for further reductions in LCoE, making wind-generated electricity even more attractive within future energy systems.

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References

- Du, Y., Zhou, S., Jing, X., Peng, Y., Wu, H., & Kwok, N. (2020). Damage detection techniques for wind turbine blades: A review. *Mech. Syst. Signal Process.*, 141, pp. 106445
- Eurostat. (2023). Sustainable development in the European Union — Monitoring report on progress towards the SDGs in an EU context. In *Publications Office of the European Union*. Publications Office of the European Union, Luxembourg.
- Fouquet, R. (2009). A brief history of energy, in Evans, J., end Hunt, L., C., eds., *International Handbook of the Economics of Energy*, . Edward Elgar Publications, Cheltenham, United Kingdom, pp. 1-20.
- Katsaprakakis, D. Al, Papadakis, N., & Ntintakis, I. (2021). A comprehensive analysis of wind turbine blade damage. *Energies*, 14(18), pp. 5974
- Kulsinskas, A., Durdevic, P., & Ortiz-Arroyo, D. (2021). Internal wind turbine blade inspections using uavs: Analysis and design issues. *Energies*, 14(2), pp. 0294
- Liu, Y., & Ishihara, T. (2015). Fatigue Failure Accident of Wind Turbine Tower in Taikoyama Wind Farm, in Anbrun, J., Mann, J., end, Muskulus, M., eds., *Proc. 2015 EWEA Scientific Proceedings*, European Win Energy Assosiation, pp. 121-125.
- Luty, L., Ziolo, M., Knapik, W., Bąk, I., & Kukuła, K. (2023). Energy Security in Light of Sustainable Development -Goals. *Energies*, 16(3), pp. 1390.
- Shafiee, M., Zhou, Z., Mei, L., Dinmohammadi, F., Karama, J., & Flynn, D. (2021). Unmanned aerial drones for inspection of offshore wind turbines: A mission-critical failure analysis. *Robotics*, 10(1), pp. 0026
- Shihavuddin, A., Chen, X., Fedorov, V., Christensen, A. N., Andre, N., Riis, B., Branner, K., Dahl, A. B., & Paulsen, R. R. (2019). Wind Turbine Surface Damage Detection by Deep Learning Aided Drone Inspection Analysis. *Energies* 12(4), pp. 0676.
- Stout, C., & Thompson, D. (2019). UAV Approaches to Wind Turbine Inspection Reducing Reliance on Rope-Access. Offshore Renewable Energy Catapult (OREC), Mar. 2019. Accessed: Feb. 02, 2023. [Online]. Available: <https://cms.ore.catapult.org.uk/wp-content/uploads/2019/03/Cyberhawks-Approach-to-UAV-Inspection-Craig-Stout-ORE-Catapult.pdf>