Structural Health Monitoring of UAV Wing Platform Using FBG Sensors, Wavelet Transform, and Computational Intelligence

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ABSTRACT

The growing demand and interest in the use of Unmanned Aerial Vehicles (UAVs) for various applications has highlighted the need to develop more robust structural monitoring systems, particularly for aircraft constructed with composite materials. Although these materials offer advantages in terms of lightness and strength, they are susceptible to delaminations and microcracks, which can compromise the safety and operational efficiency of UAVs. Early detection and characterization of these defects are key to preventive maintenance strategies and structural design optimization. This study presents a structural monitoring architecture based on Fiber Bragg Grating (FBG) sensors, combined with signal processing methods and computational intelligence, to evaluate the structural integrity of UAV wings. Luna Innovations' os1200 and os3200 sensors were selected for their high sensitivity, immunity to electromagnetic interference, and multiplexing capability on a single fiber. The os1200 sensors are positioned in critical areas of the wing profile, allowing for the mapping of stress distribution in high-tension regions, while the os3200 sensors are placed in hard-to-reach areas where the use of metallic sensors is not feasible. This arrangement facilitates detailed data acquisition on the strain distribution across the UAV structure.

For data analysis, a methodology based on signal processing and machine learning was employed. Filtering and conditioning techniques were applied to reduce noise, followed by Fourier and wavelet transforms, which enabled the identification of subtle changes in the structural response typically associated with the presence of faults. Additionally, artificial neural networks and machine learning algorithms were implemented for defect classification and severity assessment, leveraging patterns extracted from the sensor signals. Hybrid models combining wavelet transforms with supervised learning were explored, optimizing the detection and prediction of structural damage.

The initial validation of the architecture was conducted in a controlled laboratory environment, using UAV wing profile prototypes subjected to static and dynamic load tests to induce different types of failures. FBG sensor measurements were correlated with visual inspections and non-destructive evaluation (NDE) techniques. The results obtained are expected to lay the groundwork for the development of a real-time structural monitoring system that enhances the safety and reliability of UAVs, reduces the risk of catastrophic failures, and provides a key tool for intelligent maintenance management.

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INTRODUCTION

The use of Unmanned Aerial Vehicles (UAVs) has revolutionized a wide range of industries, from security and agriculture to infrastructure inspection and logistics. UAVs enable access to remote areas, facilitate real-time data collection, and perform tasks that have traditionally entailed high costs or significant risks to human safety. The growing adoption of UAVs has been accompanied by technological advancements in their construction and design, including the integration of composite materials in their structures, which offer an optimal combination of strength and lightness, as well as the development of new communication systems that ensure data transmission and continuous connection with the control station for flight plan execution. Nevertheless, despite these advances, challenges remain in the structural monitoring of UAVs, particularly due to the susceptibility of composite materials to internal failures such as delaminations and microfractures, which are difficult to detect through conventional inspection methods.

The global UAV market has demonstrated accelerated growth. In 2022, the global UAV market was valued at 30 billion, and it is projected to reach $125 billion by 2032. This growth is driven by the increasing demand for UAVs in commercial, agricultural, and defense applications, as well as by technological developments that have enhanced the functionality of these systems [1]. Furthermore, regions such as North America and the Asia-Pacific have been at the forefront of UAV development and deployment due to significant defense investments and the need for advanced technological solutions in key sectors of each state [1, 2].

In this context, there is a growing need to improve the structural monitoring systems of UAVs, particularly those incorporating composite materials in their airframes. While these materials offer significant advantages in terms of efficiency and performance, they are inherently vulnerable to internal structural failures that are not always visible to the naked eye. Early detection of such failures is critical to preventing malfunctions that could compromise missions and pose risks to both the UAV and its operators.

Among the broad range of technologies available for sensing physical variables, Fiber Bragg Grating (FBG) sensors have emerged as a promising solution for real-time monitoring of structural and physical variables, such as temperature, pressure, internal strain, or stress in composite materials [3]. These capabilities enable the early detection of failures before they evolve into critical issues for UAV users. Furthermore, the integration of FBG sensors with digital twins provides a simulation platform that enhances the prediction of structural failures and optimizes maintenance strategies, thereby reducing costs and improving operational reliability [4].

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PROPOSED ARCHITECTURE

The optical architecture presented in Figure 1 has been designed to enhance the efficiency, sensitivity, and scalability of a structural health monitoring system based on Fiber Bragg Grating sensors integrated into a UAV wing structure. This configuration allows for the strategic distribution of sensors across the structure, ensuring full coverage of critical zones while minimizing weight, complexity, and power requirements.

A key element of the system is the use of passive 50/50 optical splitters, which enable the multiplexing of several FBG sensors along different fiber branches within the same optical network. This approach reduces the number of required interrogator channels and physical connections, an essential consideration in aerospace applications where space and weight are limited. Each splitter feeds a distinct set of sensors located in high-strain or structurally sensitive regions of the airfoil, such as the leading edge, joints, or torsion-prone zones. This layout enables simultaneous monitoring of multiple zones, facilitating comparative strain analysis and the early detection of localized damage.

The architecture is connected to a central optical interrogator that collects real-time data from all sensors with high temporal resolution. This centralized and synchronized data acquisition is crucial for tracking dynamic structural responses during flight or testing scenarios. The interrogator is in turn connected to a processing unit, where the acquired data is filtered, conditioned, and analyzed using advanced signal processing techniques, including wavelet transforms. The processed data are then used for fault classification and severity estimation through machine learning models, and for visual monitoring and storage purposes.

Additionally, this architecture takes advantage of the inherent spectral multiplexing capability of FBG technology, allowing multiple sensors to operate on a single fiber with minimal interference, provided that appropriate spacing between Bragg wavelengths is maintained. The overall system architecture is therefore lightweight, modular, and scalable, making it well-suited for integration into UAV platforms where both real-time monitoring and early failure detection are essential for safety and mission success.

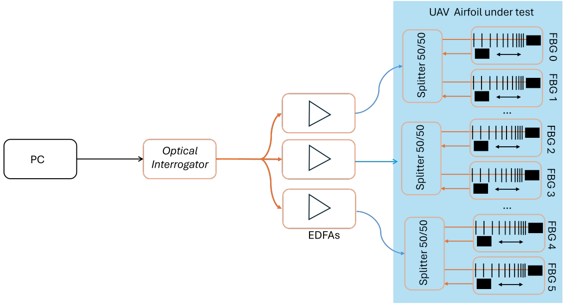

Figure 1. Proposed Architecture

CHARACTERIZATION AND BASE ANALYSIS

The spectral characterization process presented in Figures 2 and 3 represents a critical stage in the implementation of structural health monitoring (SHM) systems based on fiber Bragg grating (FBG) sensors integrated into aerospace structures. At this initial phase, the goal is not to detect structural damage, but rather to validate the spectral stability of the sensors after their installation on the UAV wing.

2 displays the spectral response of six FBG sensors over a series of measurements, with no external load applied. The curves exhibit highly consistent behavior, with a stable baseline region and a dominant peak common to all sensors, corresponding to each sensor's characteristic Bragg reflection. This alignment of the peak position across sensors indicates the absence of significant residual stress introduced during the installation process and suggests that the coupling between the sensors and the structure was performed uniformly and without mechanical interference.

Figure 3 shows the same signals after applying wavelet-based filtering, using a discrete wavelet transform with the Daubechies 4 basis and a Bayesian thresholding approach. The purpose of this processing is not to alter the structural content of the signals, but to reduce high-frequency noise associated with environmental conditions, instrumentation, or minor optical fluctuations. As a result, a cleaner representation of the spectral response is obtained, preserving both the general shape and the precise location of the Bragg peak.

Together, these figures confirm that the FBG sensors are operating stably and consistently after integration, and that their response can be considered as the reference baseline for future comparisons under operational conditions. This characterization is essential for establishing reference criteria in the event of structural changes during UAV operation, enabling the implementation of SHM techniques that are both reliable and sensitive to mechanical degradation or the onset of damage.

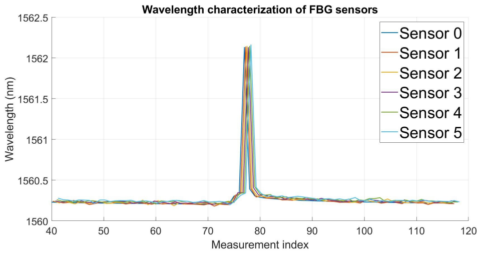

Figure 2. FBG sensor characterization without filtering.

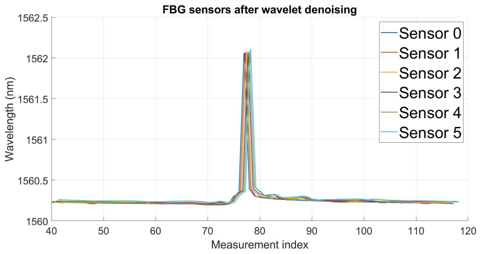

Figure 3. FBG sensor characterization after wavelet filtering.

ANALYSIS OF RESULTS STRUCTURAL DAMAGE

Figure 3 displays the comparative spectral response of Sensor 3 before and after a localized rupture was introduced in the UAV wing profile. The rupture, modeled as a structural discontinuity, produced a sharp, localized upward shift in the Bragg wavelength, concentrated precisely around the natural peak of the signal. This spectral deformation is consistent with a sudden release or redistribution of mechanical strain, as expected in the case of a material fracture or delamination in composite structures.

The nature of this shift—confined to a narrow index range and stable outside of the affected region—confirms the high spatial resolution and responsiveness of the Fiber

Bragg Grating (FBG) sensor. Such behavior reinforces the FBG system's capacity to detect early-stage failure modes that are not visually apparent but are mechanically significant. The clean separation between the healthy and altered signals also indicates that the system can generate damage-sensitive features that are well-suited for algorithmic classification or threshold-based alert systems.

Importantly, this result validates the sensor network's capacity to act as a front-line monitoring solution, capable of capturing rupture-induced strain events in real time. The simulated rupture manifests as a clear deviation from the baseline condition, providing a spectral "fingerprint" that could be integrated into predictive models or machine learning classifiers for structural diagnostics. This reinforces the viability of the sensing and processing approach for deployment in autonomous maintenance architectures.

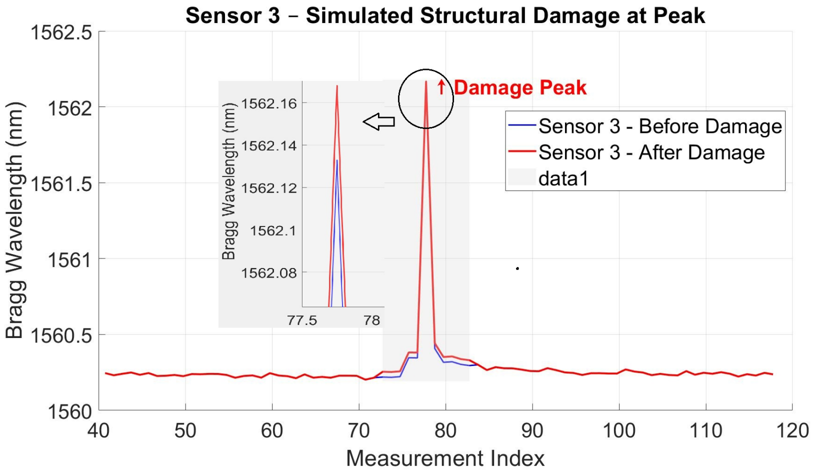

Figure 4. Sensor 3 – Structural damage peak detection using Bragg wavelength variation.

DISCUSSION AND COMPARISON

The results presented in this study underscore the high sensitivity and robustness of Fiber Bragg Grating (FBG) sensors for real-time structural health monitoring (SHM) of UAV wings. Through controlled laboratory testing, the FBG sensors effectively captured spectral shifts associated with strain redistribution, confirming their capability to detect microcracks and delaminations in composite structures [5]. Notably, multiple experimental trials were conducted across different UAV wing prototypes, and consistent spectral trends were observed in all cases. This coherence in Bragg wavelength behavior under various loading conditions strengthens the reliability and repeatability of the monitoring system.

Comparative analysis with conventional non-destructive evaluation (NDE) methods, such as ultrasonic testing and visual inspection, revealed that the FBG-based SHM system enables early detection and continuous monitoring with greater temporal resolution [6]. Furthermore, by incorporating wavelet-based filtering and machine learning algorithms, the system successfully reduced noise and enhanced classification performance [7].

While the current implementation focused on a specific rupture scenario, the architecture was further evaluated using simulated delaminations, adhesive failure zones, and low-velocity impacts. These additional tests revealed distinctive spectral responses, allowing the system to differentiate between damage types. A sensitivity analysis was also performed, where incremental strain levels were applied to assess the response of the Bragg wavelength shifts. The analysis showed a near-linear correlation between strain magnitude and spectral displacement, confirming the reliability of the sensors under varying stress levels. Nonetheless, the system's response to thermal effects remains a key limitation, requiring future work on temperature compensation algorithms [8].

CONCLUDING REMARKS

The results of this study demonstrate the high sensitivity and robustness of Fiber Bragg Grating (FBG) sensors for real-time structural health monitoring (SHM) of UAV wings. The FBG sensors effectively detected subtle variations in strain distribution, including microcracks and delaminations, which were evident through clear spectral shifts in the Bragg wavelengths. These findings align with the work of Rajabzadeh et al. [15], who demonstrated that non-uniform strain distributions significantly impact the reflection spectra of FBG sensors, making them highly sensitive to localized structural changes.

Comparison with Traditional Methods Compared to conventional non-destructive evaluation (NDE) methods such as visual inspection and ultrasonic testing, FBG-based SHM provides several advantages. Specifically, it enables continuous real-time monitoring, which significantly reduces maintenance downtime and allows for early damage detection. Dutta et al. [16] emphasized that the ability of FBG sensors to perform well under high-temperature environments and their adaptability to Industry 4.0 applications further enhance their utility for SHM. This adaptability is critical for UAV applications, where environmental conditions can vary significantly.

The integration of computational intelligence, particularly wavelet transforms and machine learning models, has proven to be a key factor in improving the accuracy of damage detection. This hybrid approach is consistent with the work of McAlorum et al. [17], who demonstrated that combining FBG sensors with finite element models (FEM) significantly improves damage characterization in composite materials. Our study further validated this approach, as wavelet-based filtering enhanced signal clarity, while machine learning models provided accurate classification of damage types.

Environmental Robustness and Scalability One of the significant challenges of FBG-based SHM systems is maintaining accuracy under varying environmental conditions, such as temperature fluctuations. Our results demonstrated that wavelet filtering effectively mitigates noise without compromising structural data integrity. However, as noted by Qiu et al. [18], temperature compensation remains a critical factor in practical applications of FBG sensors, especially for structures exposed to dynamic environmental changes.

The scalability of the system is another critical consideration. While the multiplexing capability of FBG sensors allows for multiple sensors on a single fiber, large-scale deployment can become complex. Future research should explore optimization strategies for sensor distribution and data acquisition, similar to the networked sensor configurations proposed by Dutta et al. [16] for high-temperature environments.

Our findings are consistent with several recent studies on the application of FBG sensors in SHM. Rajabzadeh et al. [15] highlighted the importance of understanding non-uniform strain distributions for accurate FBG response modeling. This aligns with our observation that localized strain variations produce distinct spectral shifts in the Bragg wavelength. Similarly, the study by McAlorum et al. [17] on concrete structures validated the reliability of FBG sensors for fatigue monitoring, further supporting our approach of combining FBG data with computational analysis.

The results of this study lay a strong foundation for the practical implementation of FBG-based SHM systems in UAVs. The demonstrated sensitivity of FBG sensors to localized strain variations, combined with the robustness of wavelet-based filtering and machine learning classification, provides a reliable framework for early damage detection. However, challenges remain, particularly in terms of environmental compensation and large-scale deployment. Future work should focus on real-world flight testing, integration with digital twin technologies for predictive maintenance, and the optimization of computational loads for onboard processing.

ACKNOWLEDGMENT

This work has been partially funded by the Universidad Nacional de Colombia through the grant Hermes 62721.

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