Chapter 15
Effective Structural Health Monitoring of Rotating Propellers using Asynchronous Neuromorphic Tracking

Guillermo Toledo, Wyatt Saeger, Fernando Moreu, David Mascarenas, Christian Torres, and Jahsyel Rojas

Abstract Structural Health Monitoring (SHM) of rotating propellers has been proved crucial by preventing catastrophic failure, detecting defects early, reducing costs through predictive maintenance and prolonging the lifespan of components. Current techniques for SHM of rotating propellers generally imply high cost, complex installation and configuration or limited effectiveness across different frequency ranges. This study aims to develop and evaluate an effective and efficient Structural Health Monitoring system for rotating propellers using asynchronous neuromorphic tracking. By leveraging advanced neuromorphic cameras and real-time data processing algorithms, the proposed system offers a novel approach to measure the vibrations of the propeller. Elements involved in the displacement data acquisition include Laser Doppler Vibrometer (LDV), scanning galvanometer and Dynamic Vision Sensor (DVS). Out of plane displacement is collected using LDV, which operates through a galvanometer that ensures the laser remains fixed on a specific point on the propeller. Real-time positional data of the propeller is acquired using a neuromorphic camera, which dynamically controls the galvanometer to maintain precision. This research provides a practical and efficient solution for real-time structural health monitoring, offering valuable insights for future engineering applications.

Keywords Neuromorphic camera · Propeller SHM · Tachometer · DVS · Galvanometer · LDV

Introduction

Structural Health Monitoring (SHM) of rotating propellers is a critical component across various industries, including wind energy [1], aerospace [2], and marine [3] applications. Effective SHM plays an important role in preventing failures, detecting defects at early stages, and reducing maintenance costs through predictive strategies. The need for continuous monitoring is fundamental, particularly for high-speed rotating elements, where structural integrity is key to ensure operational safety and efficiency.

Current SHM techniques, such as accelerometers [4], optical methods [5], and motor current analysis [6], present limitations. Accelerometers, while useful for dynamic behavior analysis, have a limited scope for complex or high-frequency vibrations, and their invasive installment can disrupt the dynamics they intent to measure [4]. Optical techniques, including

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laser interferometry and holography, are susceptible to environmental factors such as dust and humidity [7], and they require precise calibration, making them costly and complicated to maintain. Additionally, motor current analysis provides indirect fault detection, usually leading to imprecise diagnostics and limited sensitivity to minor defects.

The development of a novel SHM system utilizing asynchronous neuromorphic cameras aims to address these challenges. Unlike traditional systems that depend on external propeller information for laser positioning [8], the proposed approach leverages the high-frequency tracking capabilities of neuromorphic cameras. This innovation enables instantaneous calculation of the propeller's position, allowing for precise laser orientation that minimizes interference and coordination issues. The ability to measure vibrations remotely without halting machinery represents a significant advancement in SHM technology.

This study aims to develop and evaluate an efficient and effective SHM system for rotating propellers, focusing on the application of neuromorphic tracking for real-time data acquisition. By integrating these advanced technologies, the mentioned system not only enhances measurement precision but also significantly lowers maintenance costs and downtime, thereby extending the lifespan of critical components.

Methodology

This section outlines the methodology developed to create a system capable of monitoring the vibrations of rotating propellers. The scope of this study is ment to track the real-time position of a propeller blade while simultaneously controlling a laser Doppler vibrometer (LDV) for precision measurements. The system combines multiple components including a neuromorphic camera, galvanometer, and data acquisition hardware, all orchestrated to work in sync. The ultimate goal is to demonstrate that the system effectively tracks and measures the dynamic behavior of the propeller in motion, providing accuracy and operational synchronization.

The methodology was built upon the premise of mixing real-time event-based vision with precision laser tracking for vibration analysis. As can be seen in Figure 1, the propeller system was modeled using a small precision lathe, equipped with a plastic propeller approximately 8 inches in diameter. The speed of the propeller was controlled via a mechanism built into the motor, allowing for speeds in between 0 to approximately 2700 RPM. To ensure accurate monitoring of the propeller speed, a tachometer was attached to the lathe with an accuracy of ±5 RPM.

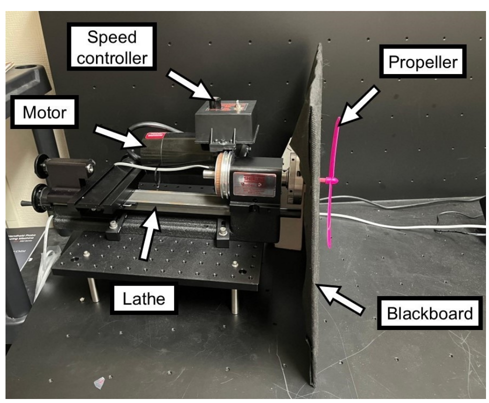


Fig. 1 Propeller set-up

The primary sensing framework incorporated an event-based neuromorphic camera [9], capable of acquiring high-speed changes in the propeller's position. An event-based camera operates by detecting changes in brightness (log intensity) asynchronously at each pixel, unlike traditional cameras that capture full frames at fixed intervals. Each individual pixel in the sensor monitors variation in light intensity and generates an "event" whenever there is a change in brightness that exceeds a previously set threshold detected. Each event contains the pixel's location (x, y), the time (t) of the change, and the polarity, showing whether brightness increased (1) or decreased (0). Events are generated independently, being each one timestamped with microsecond accuracy, allowing event-based cameras to respond rapidly to visual stimuli. Since the output rate depends on the amount of motion or brightness change in the scene, faster movements generate more events per second, making these cameras particularly effective at tracking fast movements without motion blur.

In order to optimize performance, the system was configured to work in a noise-reduced environment. A blackboard was placed behind the propeller to eliminate background noise and ensure that the camera focused exclusively on the movement of the propeller. The camera's output was synchronized with a two-axis galvanometer, that controlled two mirrors responsible for reorienting the laser beam towards the rotating propeller. The galvanometer's movements were driven by analog signals that responded to variations in the propeller's position as detected by the camera. The LDV, a highly sensitive instrument capable of detecting tiny positional variations, was employed to measure the displacement of the propeller on real time. The system was controlled by a Python script executed on a PC, that coordinated the camera, processed the positional data, and converted it into information for the galvanometer.

The tracking system required several key components to function in unison, beginning with the careful integration of the camera, galvanometer, and laser system. The event-based camera constantly provided positional data of the propeller. This data was processed using Principal Component Analysis (PCA) [10] to obtain the angle of the propeller relative to the horizontal plane. Principal component analysis is a linear dimensionality reduction method used to simplify a large data set into a smaller set, while still maintaining significant patterns and trends. Works by finding new axes, or principal components, along which the data shows the most variation. Eigenvalue decomposition is used to find the principal components, which correspond to the axes with the greatest variance.

In event-based applications, Principal Component Analysis (PCA) is an important tool for both reducing noise and obtaining meaningful patterns from large sets of data. In this specific case, PCA plays a vital role in calculating the propeller's angle by analyzing the events generated by the neuromorphic camera. As previously described, the camera creates a cloud of asynchronous events, which, at first glance, appear to have no obvious connection. However, the temporal sequence of these events forms the underlying structure that relates them. By grouping events within small time intervals, it is possible to capture the shape of the propeller. During these intervals, most of the events will cluster along the edge of the rotating propeller, as shown in Figure 2. PCA is applied to these clusters to identify the main direction along which the majority of events align, corresponding to the principal axis of variance. This principal axis represents the dominant direction of the event distribution, which allows the calculation of the angle of the propeller at a given moment.

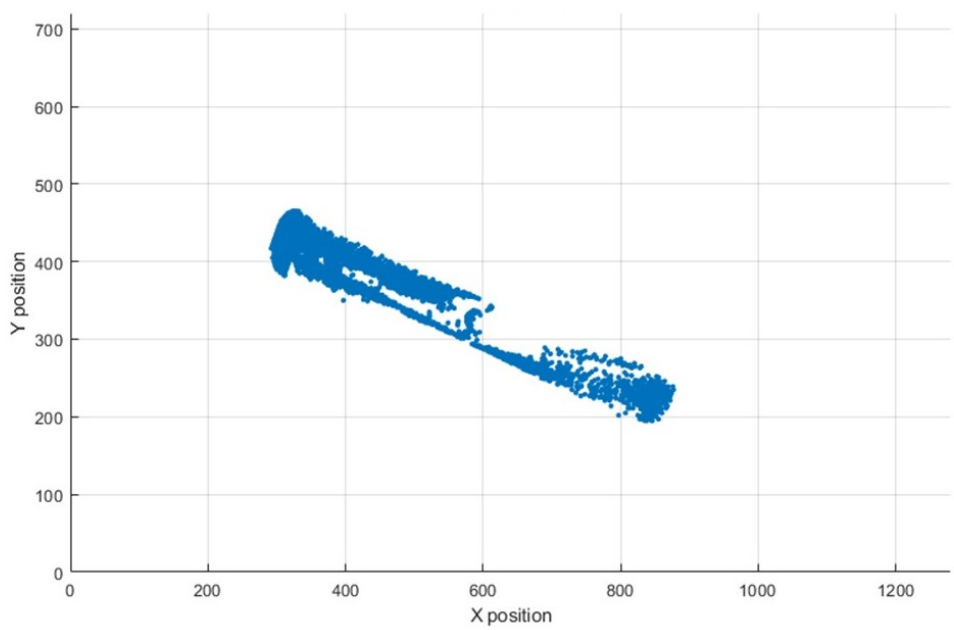
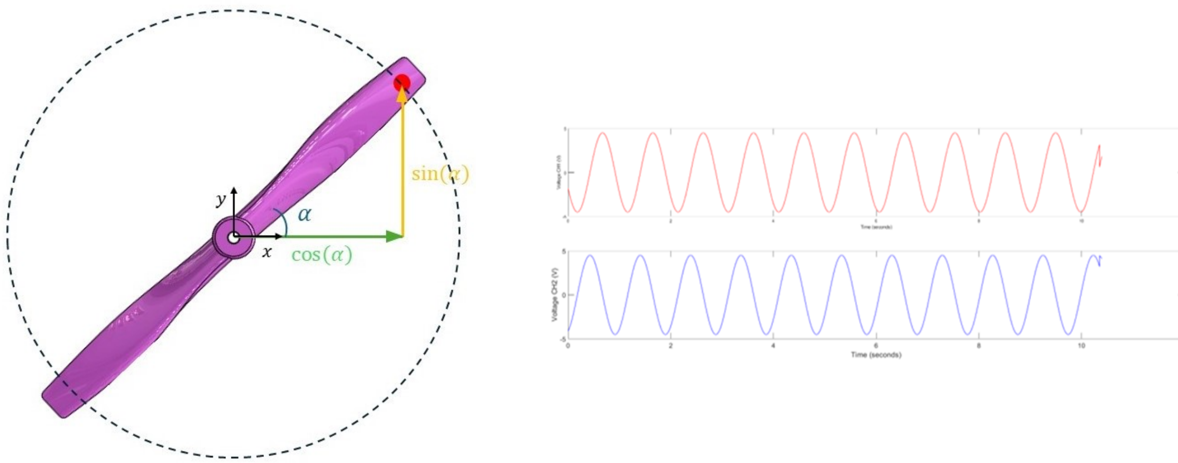


Fig. 2 Events captured during propeller's rotation

The duration of the time intervals chosen for event grouping directly influences the accuracy of the angle estimation. Short intervals result in less events, which leads to higher variability and imprecision in the calculated angle. On the other hand, if the time interval is too long, the propeller will have rotated significantly during the interval, introducing inaccuracy in the angle estimation. Therefore, finding a perfect balance in the interval duration is essential for accurate measurements. Additionally, too short or too large time intervals affect directly the computational load and can reduce significantly the efficiency of the algorithm.

It is also important to note that the effectiveness of PCA in this context is heavily determined by a robust pre-filtering process for the events. Noise captured by the neuromorphic camera can distort the event data and reduce the precision of the PCA-based angle calculation. Hence, adequate filtering to get rid of redundant or noisy events is a crucial step to ensure the accuracy and reliability of this technique.

As the Figure 3a shows, once the angle of the propeller was obtained, it was then used to calculate the sine and cosine of the angle for both the vertical and horizontal axes, providing the necessary input for controlling the galvanometer's mirrors. The galvanometer, which operated through analog signal input, shown in Figure 3b received these values and modified the position of its mirrors to ensure that the laser beam remained fixed on a specific point on the propeller blade. The LDV, reflected by the mirrors, measured the blade's displacement, capturing the small variations that occur during the propeller's rotation.



(a) (b)

Fig. 3 Propellers angle transformation into different independent analog signals. (a) Sine and cosine decomposition; (b) Galvanometer 2 axis input

The entire process was iterated at high frequency to ensure smooth tracking of the propeller's motion and to minimize delay between the camera's input and the galvanometer's response. While the system is designed to operate at high speeds, the current experiment was conducted at lower RPMs to mitigate the effects of processing delay, which has not yet been fully optimized.

This initial iteration of the methodology laid the groundwork for integrating the various components, ensuring that data from the camera could be processed in real time, transformed into control signals for the galvanometer, and used to direct the laser towards the moving propeller. Although the system is still in development, these initial results confirm the viability of the approach and demonstrate that the core components function in synchrony to track the propeller's motion accurately.

Analysis

To confirm the functionality of the camera and the program's capability to detect the propeller and obtain its angle, multiple tests were conducted. The results were positive, demonstrating that when using a blackboard as a backdrop, the program reliably detects the propeller consistently, as illustrated in Figure 4. The angle calculations for each time interval were also successfully achieved, as shown in Figure 5.

In order to assess the laser's operation through the galvanometer's small mirrors, a controlled test was conducted. A 'ground truth' test involved pointing the laser directly at the tip of the propeller. Motion was induced and captured by the laser on the opposite side of the propeller, as shown in Figure 6a. This test was then replicated with the propeller, galvanometer, and laser mounted in the setup, directing the laser through the galvanometer's mirrors, as shown in Figure 6b. The results confirmed that while the laser could measure through the galvanometer, tasks such as calibration proved challenging. When using the mirrors, the system lost a significant portion of its reliability, detecting only a small fraction of what would normally be captured under direct conditions, and became sensitive to substantial movements, risking going out of range. So far, the only tests conducted with the laser have been static, collecting data without rotating the propeller; dynamic testing is planned for future iterations. The graph shown in Figure 6b exhibits some variation in between different induced movements due to the low intensity of the return signal captured by the laser, which at times caused a shift in the graph's baseline. This issue is expected to be addressed in future work.

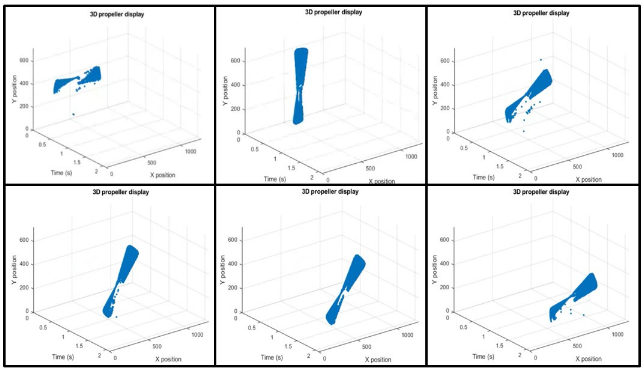


Fig. 4 Detected propeller at different timestamps

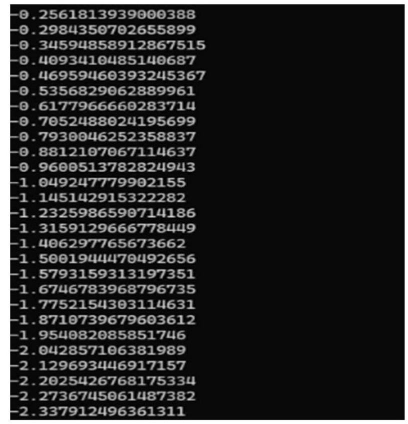
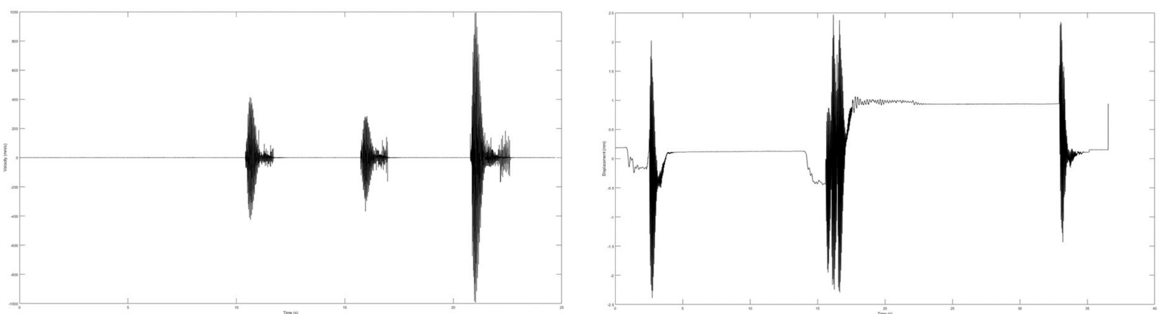


Fig. 5 Angles in radians calculated by the code



(a) (b)

Fig. 6 Displacement tests conducted. (a) Laser directly pointing at propeller; (b) Laser reflected through galvanometer

Regarding the integrated operation of all system components—namely, the detection of the propeller, angle calculation, information transmission, and mirror position updating—tests were performed where the propeller was spun at varying speeds to observe the mirror movements. The results, shown in Figure 7, indicate that the system can accurately detect the propeller, process information, calculate the angle, and adjust the mirrors accordingly. However, it is important to note that the Python code is not yet optimized, and current hardware limitations create processing delays, causing the laser to move at the same speed as the propeller with a slight lag.

Data acquisition and processing

Initially, the code utilized time intervals to group data, process it, and iterate through the cycle. This approach led to varying data group sizes based on rotational speed, causing slow responses at high speeds and significant delays. To address this issue, the decision was made to implement event-based grouping, maintaining a quasi-constant iteration time regardless of rotational speed.

Furthermore, the original approach involved using two separate Python scripts: one optimized for controlling the camera and processing all data, and the other for operating the data acquisition system (DAQ) and generating the analog signal. It became apparent that communication issues between the scripts increased delays significantly, prompting the integration of both functionalities into a single multifunctional script.

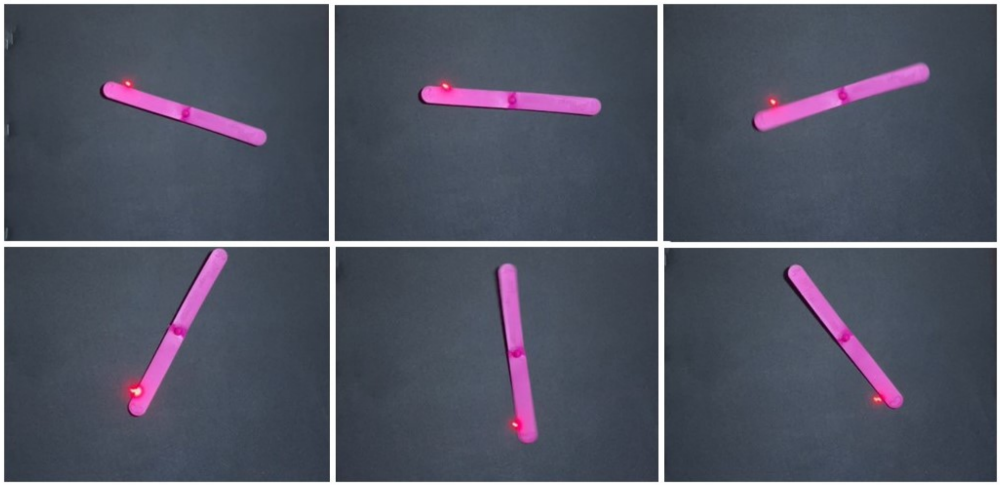


Fig. 7 Laser autonomously following the propeller

Analysis of results

This study establishes a comprehensive framework for monitoring the health of rotating propellers, providing a reliable basis for further research and application. The iterative testing process has validated the core functionality of the system components, ensuring that the camera, laser, and galvanometer can work together effectively. Future refinements, including optimizing code and addressing hardware limitations, will enhance the system's performance and reliability in dynamic conditions. This work not only advances the monitoring capabilities of rotating propellers but also lays the groundwork for implementing predictive maintenance strategies in various engineering applications.

Conclusion

This study has demonstrated the viability of using asynchronous neuromorphic tracking for real-time structural health monitoring (SHM) of rotating propellers. The system proposed offers a positive enhancement over traditional techniques by offering a non-invasive and efficient technique for tracking the position of the propeller and monitoring its structural integrity. The integration of a galvanometer-reflected laser system and a neuromorphic camera allowed to measure propeller displacement in real time, although some challenges stand, particularly in reducing the delay observed in the galvanometer response.

The tests conducted validate the system's capability to detect and track the propeller's movement consistently and accurately. Real-time tracking has been successfully demonstrated, though with a slight processing delay due to hardware limitations and non-optimized code. Further improvements, especially in software optimization and hardware performance, are expected to address this problem, enhancing the system's real-time responsiveness.

Laser measurements through the galvanometer's mirrors have been proven feasible in static conditions, marking an important milestone in the system's development. Although signal loss and sensitivity to substantial movements were observed, these challenges are anticipated to be mitigated in future dynamic tests, which will provide a more comprehensive understanding of the system's robustness under operational conditions.

Ultimately, this study presents a promising alternative to existing SHM techniques. The ability to track propeller motion with high precision and to maintain continuous monitoring without requiring machine stoppages offers clear advantages in terms of maintenance cost reduction and system reliability. Future work will focus on refining the system for dynamic testing and further improving the integration of the neuromorphic camera with the galvanometer, paving the way for even more effective real-time monitoring solutions.

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