DOI: 10.3217/978-3-99161-057-1-061

LiDAR for vibration monitoring of infrastructure: stretching limits by spatio-temporal time domain frequency analysis

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ABSTRACT: Structural health monitoring (SHM) is crucial for ensuring the integrity and safety of infrastructure. Traditional vibration analysis techniques rely on sensors such as Inertial Measurement Units (IMU) and Global Navigation Satellite Systems (GNSS), total stations (TS) and fibre-optics (FO), which require a physical attachment to structures in the observation process. However, Light Detection and Ranging (LiDAR) offers a contactless alternative, enabling high-resolution, time-synchronized observations that capture spatially continuous deformation information. This paper presents an innovative framework for SHM that leverages LiDAR-based time-domain frequency analysis to monitor dynamic structural behavior effectively. By integrating spatio-temporal modeling techniques, we establish a robust methodology for detecting oscillations and deformations in infrastructure. Our approach enhances current SHM practices by providing a scalable solution that does not require physical sensor deployment. Thus, this methodology provides information in much higher spatial resolution compared to the aforementioned approaches. The proposed methodology is evaluated by controlled experiments, demonstrating its applicability to real-world SHM scenarios and its potential for continuous, non-invasive structural assessment.

KEY WORDS: Structural Health Monitoring; Laser Scanning; B-Splines; Harmonic Oscillation; Pont Cloud.

1 INTRODUCTION

Structural integrity is a fundamental concern in civil engineering, necessitating continuous monitoring of deformations and vibrations in infrastructure. Bridges, buildings, and other structures are subject to environmental and mechanical forces, including wind, traffic loads, temperature variations, and seismic activity. These forces induce static and dynamic deformations, which must be accurately tracked to prevent structural failures.

Traditionally, SHM relies on point-based sensors such as Global Navigation Satellite System (GNSS) [1, 2], Inertial Measurement Unit (IMU) [3, 4], total stations [5], and fiber-optic (FO) [6, 7] sensors, which provide precise motion data but require physical attachment to structures (Fig. 1). Optical sensors, including cameras [8, 9, 10], Vibrometers [11, 12, 13, 14], and Light Detection and Ranging (LiDAR) [15, 16], offer contactless observations, reducing maintenance effort and enabling long-term deployment. Among these, LiDAR has gained prominence due to its ability to capture high-resolution, time-synchronized spatial data, making it well-suited for SHM applications.

While prior research has explored LiDAR-based monitoring, empirical validation and integration into SHM workflows remain limited. This study addresses these gaps by presenting a comprehensive framework for contactless structural vibration monitoring using LiDAR. Our research focuses on leveraging time-domain frequency analysis to capture oscillatory behavior and quantify structural deformations more effectively.

This paper addresses the following research questions:

- Can LiDAR-based time-domain frequency analysis provide reliable results for SHM applications?
- How does point-wise processing compare to area-wise processing in structural vibration analysis?
- Do observation residuals exhibit systematic patterns that can inform SHM decision-making?

We answer those questions applied to SHM methodologies by integrating 3D point clouds of LiDAR, that improve vibration analysis, uncertainty quantification, and structural condition assessment.

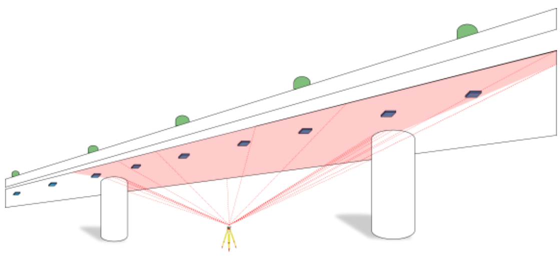

Figure 1. Potential 4D bridge monitoring with GNSS (green), IMU (blue) or LiDAR (red)

2 SPATIO-TEMPORAL PROCESSING

LiDAR sensors naturally observe their surroundings with a high point sampling rate of several MHz and a spatial resolution in the mm-level. This observation principle enables to record high frequent 4D (3D + time) deformation signals of structures, as displayed in Figure 1 in comparison to using IMU and GNSS sensors. To use LiDAR point clouds for vibration monitoring, we present within this work an implementation of spatio-temporal connections, which we evaluate experimentally. Therefore, we first introduce into our experimental setup within section *2.1* to show a coarse

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overview of the object and used sensor. In section *2.2*, we briefly describe our developed methodology to tackle 4D LiDAR data processing. Lastly, we discuss results regarding the outcome and limitations in section *2.3*.

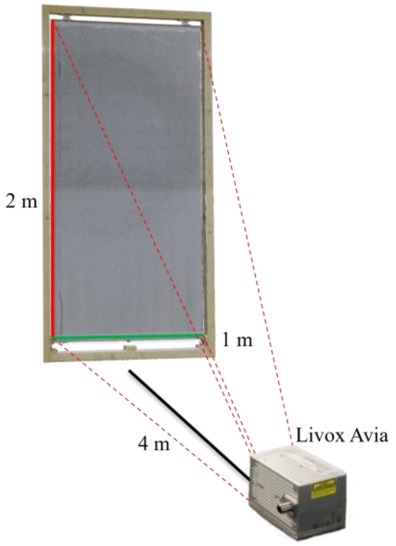

Figure 2. Experimental measurement setup

2.1 Experimental Setup

We evaluate our methodology using continuous observations of micro-electro-mechanical system (MEMS) LiDAR sensors to capture the periodic motion of a forced-excited acrylic glass sheet in Figure 2. This sheet is two by one meter and clamped on the upper and lower sides. Since it is also erected vertically, gravity acts asymmetrically on the test construction.

Our experimental setup simulates real-world conditions by introducing controlled periodic excitation forces induced by a linear actuator with a frequency of about 0.3 Hz. Furthermore, we test the adaptability of our approach across different configurations and object geometries to assess its scalability.

The selected process enables a continuous frequency mode description of a dynamically oscillating object, which ensures accurate spatial approximation and robust frequency estimation, enabling a fully automated analysis using low-cost sensors.

2.2 Methodology

Our approach harnesses LiDAR data to exploit its contactless observations and high sampling rate for time domain frequency estimation [17]. However, dimensions are limited to the LiDAR sensors used in respective monitoring settings [16]. To further enhance processing efficiency, we integrate point cloud observations within a time-domain framework directly. This reduces computational complexity by minimizing intermediate processing steps while maintaining spatial and temporal coherence.

In our workflow, we first implement an initial frequency estimation process based on spectral analysis techniques in the time domain, ensuring that dominant oscillation modes are accurately captured. Furthermore, consecutive points and their spatial neighborhoods facilitate establishing temporal and spatio-temporal connections, allowing direct oscillation modeling simultaneously in time and the metric space. By introducing spatial B-spline modeling, we establish smooth spatial transitions between neighboring observations [16]. Additionally, we connect observations in time by their underlying periodic signal. With both spatial and temporal connections, we formulate spatio-temporal connections

$$w(u,v) = \mu(u,v) + \\ + \sum_{i=0}^{N} a(u,v) \cdot \cos(2\pi f_i t) + b(u,v) \cdot \sin(2\pi f_i t)$$

as a combination of the Fourier Series [18] and functions used in geometric modeling [19]. By employing a sophisticated mathematical model in time t, we approximate components like an immovable mean surface $\mu(u,v)$, amplitude variations, and phase shifts corresponding to frequencies f_i by Fourier parameters $a(u,v)$ and $b(u,v)$ [20]. Except frequencies, all components are described as geometric functions expressed with their first and second principal component u, v in Figure 3 and the movement in time along the third principal component w. Figure 4 displays the signal w along the time axis t (not sorted for u, v) for experimental data of 100 sec: Clearly, the oscillations are visible.

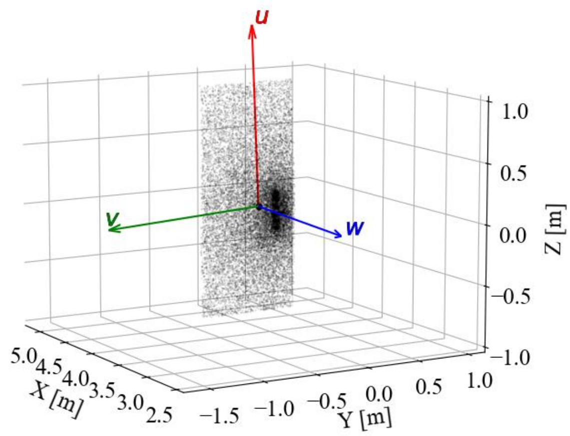

Figure 3. Observation point cloud with its principal components u, v, w.

We further quantify parameter uncertainty to evaluate the reliability of estimated variables, thereby enabling robust movement and vibration analysis of spatially connected surfaces. Generally, our method simplifies the representation of periodic signals while preserving essential spatial characteristics for interpretation.

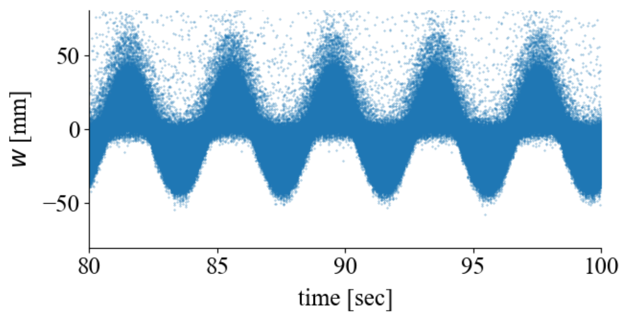

Figure 4. Part of the noisy time series observed along principal component w

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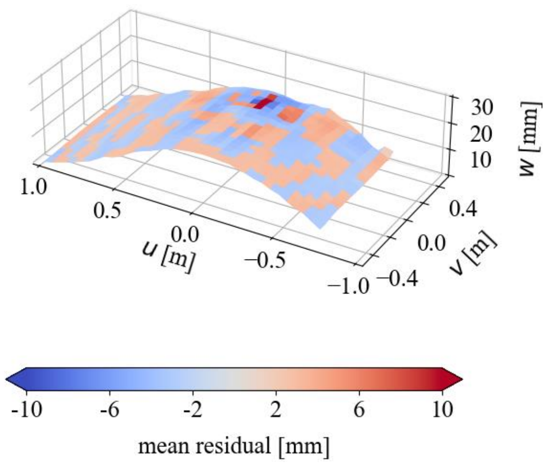

Figure 5. mode shape of the dominant amplitude with overall mean residuals as colors

2.3 *Results and discussion*

Our developed methodology effectively captures and describes enforced motion in both space and time. The integration of LiDAR-based time-domain frequency analysis offers a significant advancement in dynamic object monitoring, reducing reliance on traditional sensor frameworks. Moreover, it automatically combines observations compared to the individual processing of individual sensors e.g. IMU and GNSS.

Thus, we can explore interdependencies between parameters and their impact on results, highlighting the adaptability of our approach across different LiDAR systems. Besides the continuous amplitude shape shown in Figure. 5, we further analyze residuals from estimated parameters to identify systematic patterns that may indicate underlying structural characteristics in Figure 5. Therefore, our results show that continuous processing in the time domain produces higher fidelity reconstructions compared to point-wise approaches like mode description using IMU and GNSS sensors. Additionally, uncertainty propagation studies reveal the high sensitivity of estimated frequencies concerning sensor noise as well as environmental factors at the observation sight [16].

We further investigate the influence of different geometric modeling methods for establishing spatio-temporal relationships. The results indicate that B-spline modeling outperforms polynomial approximations in capturing smooth transitions while maintaining high-frequency response accuracy [16]. This highlights advantages of flexible basis functions in vibration analysis applications.

3 CONCLUSION

Our study demonstrates that LiDAR-based time-domain processing enables high-resolution monitoring of dynamic objects, offering advantages over traditional sensor-based methods as contactless observations and processing of the full object. The developed methodology ensures robust frequency estimation, efficient uncertainty quantification, and improved adaptability across different application domains.

Future research will extend our methodology to real-world scenarios such as bridge vibration analysis, integrating additional sensor modalities for enhanced robustness. Herein, we will also evaluate the limits of our approach in more detail. Further improvements will focus on refining uncertainty quantification and optimizing computational efficiency to facilitate large-scale implementations. Additionally, we aim to investigate the potential for hybrid sensor fusion, combining LiDAR data with conventional methods to enhance the accuracy and robustness of vibration analysis in complex monitoring environments.

ACKNOWLEDGMENTS

This research was funded by German Research Foundation (DFG) under grant number 536704264, project "Processing models for analyzing the 3D vibration response of structures using terrestrial laser scanners (PROVILAS)"

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