Application of LiDAR technology for identifying surface anomalies in concrete structures through Reflective Intensity analysis

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Keywords: LiDAR, Infrastructure analysis, Structural Health Monitoring (SHM), Reflective Intensity

Abstract

Structural inspection is crucial for comprehensive risk management, especially given the accelerated deterioration caused by factors such as climate change and obsolescence. The accurate determination of the percentage of surface damage is fundamental for optimizing maintenance decision-making and the administration of resources for infrastructure preservation. This work presents a methodological exploration to assess the superficial condition of a concrete pedestrian bridge located over an urban river. The study focuses on determining the structural conditions by calculating the percentage of surface damage to evaluate maintenance needs. For data acquisition, Light Detection and Ranging (LiDAR) technology is employed using a Terrestrial Laser Scanner (TLS) Trimble X7 laser scanner, generating a 3D point cloud that models the bridge surface with precise spatial coordinates. The methodology utilizes the reflective intensity of the laser pulses to obtain quantitative information about the surface. This approach allows for the precise identification, demarcation, and quantification of deteriorated areas. The application of this methodology facilitates a non-invasive and detailed diagnosis of the surface condition, providing quantitative and visual information that can enhance the maintenance planning of critical infrastructure such as pedestrian bridges.

1. Introduction

Regular and technical inspection of civil infrastructure is essential to ensure the functioning and safety of cities and populations. The monitoring of these elements is not an isolated process, it serves as a forecasting tool that allows vulnerabilities to be identified before they escalate to systemic failures (International Organization for Standardization, 2025)

Different international organizations have emphasized the importance of infrastructure management, in changing the perspective and from seeing it as a reactive model in the face of disasters, to seeing it as a culture of proactive prevention. Through global regulations and frameworks, these bodies tell us that constant inspection and strategic planning are the most effective tools to anticipate risks and ensure that infrastructure not only withstands impact, but becomes the central axis of collective security.

An example of this is the recently created ISO 22372:2025 standard, which offers a series of recommendations for planning, maintaining, and strengthening infrastructure resilience, regardless of sector or geographic location. This standard integrates the United Nations Principles for Resilient Infrastructure, and states that an inspection should go beyond simple physical maintenance, and focus on the ability of assets to resist, absorb and recover quickly from disasters. Infrastructures that are not inspected under resilience criteria turn out to be fragile, putting social well-being and economic stability at risk in the face of the effects of climate change, which are increasingly severe and frequent, and other anthropogenic threats (United Nations Office for Disaster Risk Reduction, 2023).

In terms of international management, infrastructure resilience is a priority reflected in Goal 9 of the Sustainable Development Goals (SDGs), which seeks to develop safe, sustainable and high-quality infrastructure to enhance human development (UN, n.d.) This goal is directly related to Goal D of the Sendai Framework, which sets the goal of significantly reducing disaster damage to critical infrastructure and disruption of basic services (United Nations Office for Disaster Risk Reduction, 2019). Therefore, carrying out systematic inspections should not only be complying with technical standards; it also represents an act of ethical and political responsibility. It is necessary to ensure that bridges, electricity grids and water systems are able to sustain the population even in the most adverse conditions, preventing crises from becoming permanent catastrophes.

Traditionally, infrastructure inspections are performed using visual methods. However, the main limitation of traditional visual inspection is the accessibility to all deteriorated areas of the structures. Currently, to overcome these deficiencies, new technologies offer more effective and non-invasive methods for the detection and quantification of anomalies, providing a superior alternative to traditional visual inspection (Salamanca Céspedes & Pérez Castillo, 2008), allowing for the generation of 3D geometries known as point clouds. To achieve this, LiDAR uses an emitter that measures the time and calculates the distance traveled by laser pulses until they impact the surface of an object and return to the sensor, thereby generating a point with three-dimensional coordinates (Gisasola, 2018). One of the advantages of using LiDAR technology lies in its capacity to model the surface in three dimensions with centimeter-level detail (El-Diasty, M., et al., 2025), capturing the geometric complexity of certain structures.

Another distinctive advantage of LiDAR over other remote sensors, such as RGB imaging systems, is the acquisition of reflection intensity values. This magnitude is intrinsic to the physicochemical properties of the material and its color, the nature of the surface (transparent or matte), and, fundamentally, the incidence angle of the light beam on the studied surface (Otgonbayar, et al., 2025, Słomiany, et al., 2026). While RGB sensors can misinterpret dark shadows or dirt as structural anomalies like oxidation, reflective intensity measures a physical property of the material, providing a more reliable diagnostic tool (Pereira, A., et al., 2021).

The collection of quantitative information can be used as a non-invasive and detailed diagnosis of the surface condition, which benefits the maintenance planning of infrastructure with the goal of extending its service life. By carrying out constant monitoring to identify vulnerabilities that compromise the structural condition, early action can be taken, thereby preventing incidents, especially given the progressive increase in the magnitude and constancy of natural phenomena due to climate change.

Previous research, such as that by Ono et al. (2020), has developed methodologies for the automatic detection of surface anomalies (primarily corrosion) using point clouds. In this context, the use of reflective intensity stands out; a key advantage over RGB images is its applicability in nighttime capture.

This paper contributes to:

1. Demonstrating the effectiveness of LiDAR as a non-invasive tool for structural inspection, overcoming the accessibility limitations of traditional visual methods.

2. Generating and analyzing point clouds to obtain detailed quantitative information on surface conditions for improved diagnostic accuracy.

3. Advancing methods for detecting structural vulnerabilities using LiDAR-derived features, including reflective intensity, to support early maintenance and extend infrastructure service life.

4. Highlighting the advantages of LiDAR-based anomaly detection over visual and RGB-based approaches, particularly under low-visibility conditions such as nighttime inspection.

2. Methodology

2.1 Field survey and Pre-processing

A high-precision field survey was conducted to obtain information on a concrete pedestrian bridge crossing an urban river, located in Monterrey, Nuevo León, Mexico. The instrument used was a Trimble X7 laser scanner (Fig. 1). This scanner is characterized by its wide scanning range, with a full horizontal field of view of 360° and a vertical field of 282°, with the only operational blind spot being the area located just below the base of the instrument. For scanning measurements, it employs a Class 1 laser with a wavelength of 1530–1570 nm, which operates within the near-infrared (NIR) spectrum, ensuring safety and accuracy.

To ensure data quality, the scanner stations were strategically positioned along the structure. This planning ensures full visibility of the bridge's structural components and to reduce angular deformations, due to the angle of the laser, or "shadow" effects, achieving high-resolution data capture with a minimum number of stations.

To transition the source data to a refined 3D model, two essential steps were followed:

Registration and alignment: Initial processing was performed using Trimble Perspective software. In this stage, the different individual scans are precisely stitched together into a single coordinate system. The process produced a high-resolution point cloud with an average registration error of 2.5 mm.

Data refinement and cleansing: The unified point cloud was then imported into CloudCompare software for noise extraction. This phase focused on refining the dataset by removing points that did not correspond to the bridge structure, such as local vegetation, passing vehicles, and pedestrians, which for the next steps would make it difficult to visualize and analyze the main structural geometry.

Figure 1. Location of the analyzed bridge and example of scanner setup.

2.2 Identification of non-homogeneous study zones

To precisely locate the surface areas that present the most significant levels of anomalies, the "reflective intensity" analysis tool was used. The fundamental principle of this tool is in its ability to interpret the color scale based on the backscattered energy of the laser pulses; that is, the specific amount of energy that returns to the sensor after impacting the bridge surface.

The use of this tool aided in the diagnosis of the structure and was instrumental in identifying specific sections whose intensity signatures differed significantly from the characteristics of the sound concrete. These differences often indicate inhomogeneous surfaces caused by various physical and chemical factors, including increased surface roughness, localized moisture retention, or the presence of corrosion.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLIX-B2-2026-1297-2026

Through this diagnostic evaluation, sections with anomalies were highlighted and segmented for further analysis. For the specific purposes of this research, a representative segment of approximately 8.3 meters in length was selected. This study area is located in one of the clearings of the bridge structure, on its lower face (see Fig. 2), being a critical point of view to evaluate the integrity of the materials in a high exposure area.

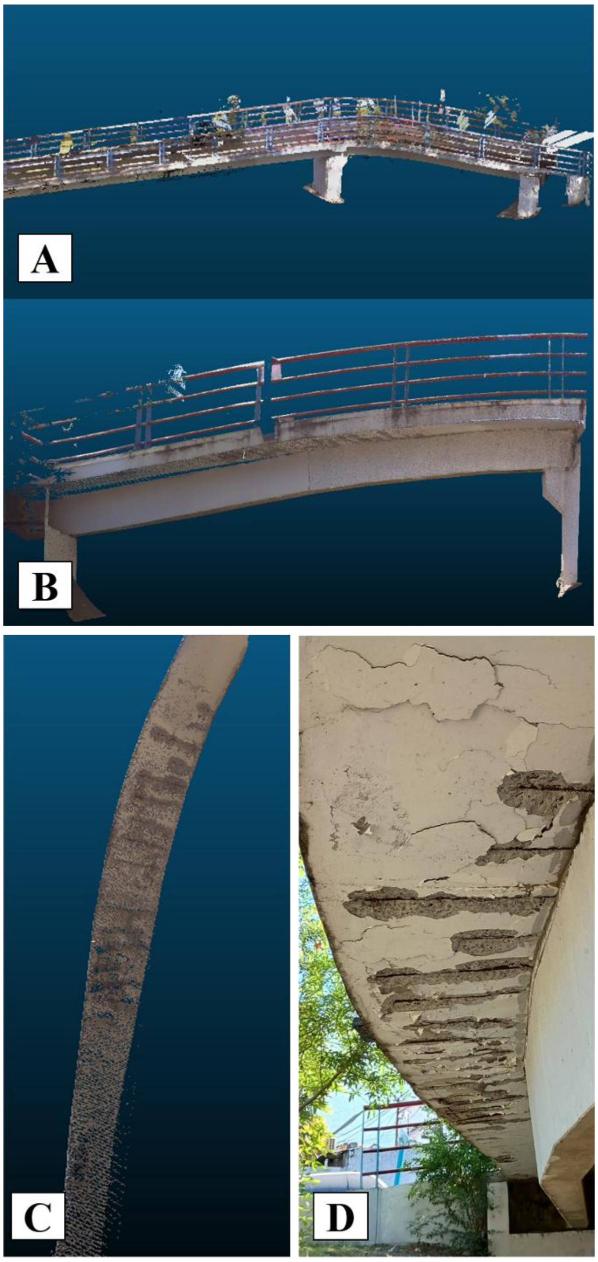

Figure 2. Analyzed point cloud, A) Complete bridge, B) Section used for analysis and C) Photograph of the anomalies found on-site.

2.3 Segmentation, logging and quantitative anomaly extraction

Starting with the dense point cloud coming from noise cleanup, it is segmented to isolate the main area of interest. To ensure the highest level of accuracy, the structural element was further subdivided into individual faces to precisely calibrate and adjust the reflective intensity according to the specific orientation and surface characteristics of each plane. Once the surfaces were isolated, the anomalies detected were recorded and visually accentuated using color saturation techniques, making it easier to distinguish between the different types of surface degradation.

As can be seen in Figure 3, a clear contrast is established between a homogeneous surface (representing solid concrete) and a non-homogeneous surface that exhibits significant anomalies, such as structural cracks and exposed reinforcing steel. To objectively differentiate these areas, the statistical distribution of data within the software intensity histogram was analyzed. This analysis was instrumental in establishing definitive limits of the structure's reflectivity intensity that accurately represent the physical anomalies.

After establishing these thresholds, the "Filter by Value" tool based on reflective intensity signatures was used to perform a specific extraction of the data points. This operation resulted in the generation of two distinct point clouds (Fig. 4):

Homogeneous zone: A set of control data with similar geometric characteristics, without the presence of surface anomalies.

Non-Homogeneous Zone: A dataset containing only quantifiable anomalies that were previously bounded.

The generation of these two data sets provides the necessary information to perform a quantitative assessment of the structural integrity of the bridge.

2.4 Quantification of the Percentage of Damage

The quantitative evaluation of structural anomalies is determined by a density analysis of previously generated point clouds. Using the precise point count of each dataset, the percentage of damage can be accurately calculated as a proportion of the anomalous points to the total surface area, as well as to the area studied. This analytical approach offers the flexibility to be applied at multiple scales: it can be employed to assess the condition of a specific section of the bridge, or it can be extended to provide a comprehensive assessment of the entire structure. This method ensures that both minor local defects and broader structural patterns can be effectively identified and quantified.

The percentage of damage is determined using the point count from generated point clouds, which can be calculated for a specific section or for the total structure.

The percentage of anomalies within a specific study section (P_{AS} P_{AS}) is calculated as the ratio of the number of points corresponding to the anomalies ($n_A n_A$) to the total number of points in that section ($n_S n_S$), as shown in Equation 1:

$$P_{AS} = \left(\frac{n_A}{n_S}\right) * 100 \quad (1)$$

The percentage of anomalies for the total structure ($P_{AT} P_{AT}$) is also calculated, using the total number of points in the anomalies ($n_A n_A$) and the number of points in the entire structure ($n_T n_T$), as shown in Equation 2:

$$P_{AT} = \left(\frac{n_A}{n_T}\right) * 100 \quad (2)$$

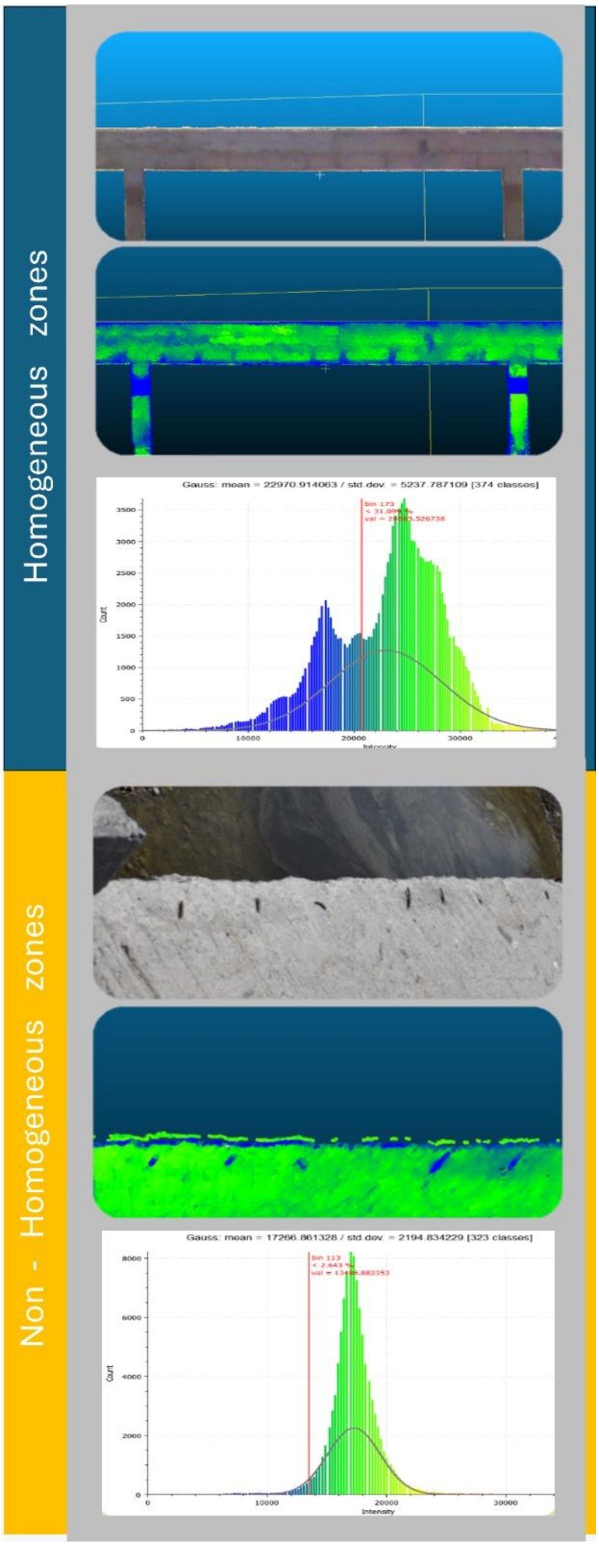

Figure 3. Differences in histograms obtained for homogeneous and non-homogeneous zones.

3. Results

Following the systematic calculation of the percentage of detected anomalies at both the localized and global scales, the following results were obtained:

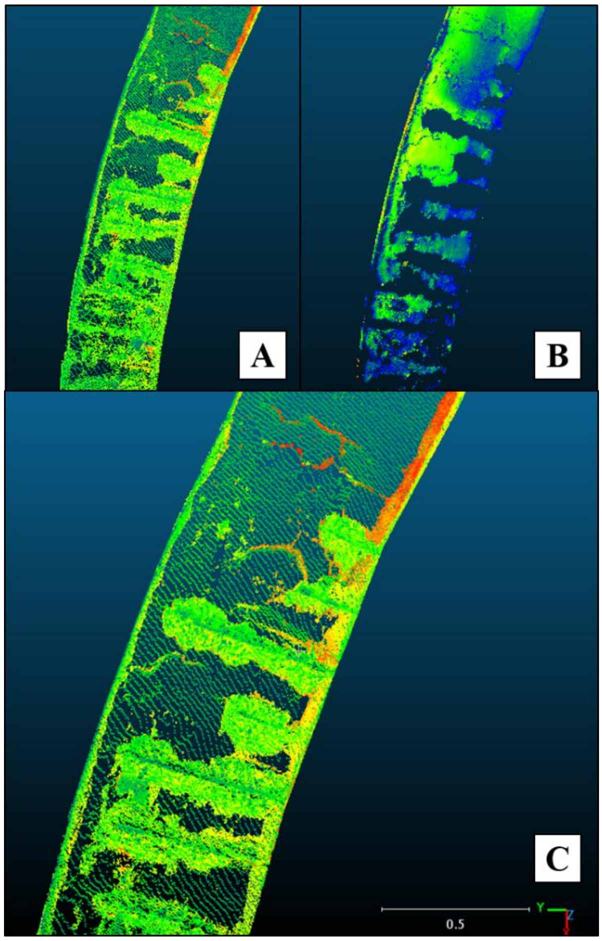

Figure 4. Segmentation of anomalies zones, A) non-homogeneous, B) homogeneous, and C) close-up of the point cloud for visualization of anomalies such as exposed steel reinforcement bars, cracking, and concrete detachment.

When focusing the analysis strictly on the individual section previously isolated, it was determined that the anomalies occupy 13.24% of that specific area's total point cloud. This indicates a significant concentration of surface degradation within that particular structural face.

In contrast, when the scope of the evaluation is expanded to encompass the entirety of the bridge structure, the data reveals that the specific zone under study accounts for 1.59% of the total damage identified across the complete structural model (Table 1). This dual-perspective analysis provides a clearer understanding of how localized defects contribute to the overall deterioration of the asset, allowing for a more prioritized approach to maintenance and structural repair.

	Number of points	Number of points in the anomalies	Percentage of anomalies
PAS	5,152,766	682,569	13.24%
PAT	42,934,355		1.59%

Table 1. Percentage of anomalies.

https://doi.org/10.5194/isprs-archives-XLIX-B2-2026-1297-2026

4. Discussion

This study implemented a non-invasive methodology based on LiDAR technology for the surface evaluation of concrete structures, highlighting the potential of Reflective Intensity. The results demonstrate the method’s capability for the identification, logging, delimitation, and quantification of the percentage of anomalies by means of point counting in the non-homogeneous zones detected.

The resulting values of reflective intensity were conditioned by the in intrinsic properties of the material (i.e. the colour or the opacity) also, the captured geometry, and specifically the incidence angle. The degradation of the materials was different among the surfaces, and the sensor response tended to make them uniform. On the contrary, when the presence of pathologies was observed, such as moisture, exposed rebar, or corrosion, the reflective intensity presented differences for both the roughness and composition of the target. Observing these irregularities can be determined that the local incidence angle as well as the reflectivity, may cause significant variations among the recorded intensity values.

The reflective intensity heterogeneity demonstrates that the LiDAR based method has the capability to assess anomality’s for the bridge’s concrete structures. Somehow, this information can quantify the logging, delimitate, or quantify the percentages of deterioration, by recognizing the non-homogeneous zones of the structure.

It should be noted that the identified reflective intensity values are specific to the structure under analysis; other assets will exhibit different values depending on their construction materials, environmental exposure, and the specific types of deterioration present.

The integration of LiDAR technology and the possibility of a highly accurate and non-invasive data move beyond traditional method limitations and supports the principles and purposes of the International Standard ISO 22372, the UNDRR Principles for Resilient Infrastructure, the SDG 9, and the Sendai Framework, all of them guaranteeing that critical infrastructure for the countries or cities could remain through a resilient lifespan, and be able of protecting socio-economic stability against the ever-increasing pressures of a changing global climate.

5. Conclusions

A non-invasive methodology based on LiDAR technology through the Trimble X7 sensor was used for the assessment of concrete bridge structures, resulting in the highlighting of the potential of reflective intensity for this type of evaluations.

The advantage of the proposed method is the possibility of a permanent monitoring; the assessment of how the deterioration evolves. This understanding is critical for the inspection and preventive maintenance management of structures. Also, it could give the possibility of accurately identify the real affected zones. And be precise in the planning as well as optimizing resources.

The main limitations for this method, however, is that it can only be useful for surface inspection. Hence, in some cases where the deterioration is severe or when the risk of internal integrity it must be accompanied with non-destructive testing or specific internal examinations.

6. Acknowledgements

The authors thank the Secretariat of Science, Humanities, Technology, and Innovation (Secihti) for awarding scholarships to our bachelor students of the Faculty of Civil Engineering, and students of the Master of Science in Environmental Engineering at the Autonomous University of Nuevo León. We also acknowledge the Department of Geomatics at the Institute of Civil Engineering for providing the tools and resources necessary to carry out this research.

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