LiDAR Applications in Structural Health Monitoring of Cable-Stayed Bridges: A Systematic Review

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Abstract: *Structural Health Monitoring (SHM) is increasingly being recognized as an important area for monitoring the structural health and safety of large structures such as cable-stayed bridges under the influence of different loading scenarios and structural vibrations. This in-depth review of literature aims to investigate the use of Light Detection and Ranging (LiDAR) technology focusing on structural health monitoring (SHM) of cable-stayed bridges. The aim of this review is to analyze the LiDAR for geometric mapping, deformation monitoring, and the role of LiDAR in numerical models and machine learning. The study is a PRISMA compliant compilation of a variety of studies. There are still challenges remain including data validation, ambient noise, and integration of a real-time system into an operational system. It is important that these issues be considered as part of the initial health review for new, LiDAR-based bridge applications in order to enhance maintenance strategies. has become increasingly important in managing the structural integrity and safety of large structures, such as cable-stayed bridges, under a variety of loading conditions and structural actions. This SLR targets Light Detection and Ranging (LiDAR) applied for structural health monitoring (SHM) of cable-stayed bridges. In accordance with the PRISMA guidelines, the review integrates the results obtained in several works, performing a compilation in order to contribute to evaluate that LiDAR for geometric mapping, deformation detection and its connection with numerical models and machine learning. However, there are still challenges such as data validation, environmental noise and real-time integration into a working system. Early health monitoring of new LiDAR applications to bridges needs to solve these problems and to help the better maintenance.*

Keywords: LiDAR, Structural-Health-Monitoring, Cable-Stayed, Monitoring-Systems, Systematic-Literature-Review

Introduction

Over time, there have been significant developments in sensing technology for infrastructure monitoring, particularly in relation to cable-stayed bridges, a particular kind of spanning structure. Cable-stayed bridges are renowned for the structural efficiency and aesthetic beauty they offer, but have suffered from continuing challenges in maintenance, inspection, safety, and sustainability (Park et al., 2007). The increased complexity of these structures and the fact that infrastructure is ageing worldwide require more advanced and precise monitoring approaches (S. Chen et al., 2018). LiDAR (Light Detection and Ranging) is an advanced remote sensing technology that utilizes laser light to measure distances and create high-resolution three-dimensional models of objects and terrains (L. Wang et al., 2022; Wilson & Lee, 2023). This technology has gained traction in civil engineering and infrastructure monitoring due to its ability to capture detailed geometric information and detect minute changes in structural conditions (M. González et al., 2020; M. González & al., 2022). Recent improvements in LiDAR technology have facilitated the creation of mobile and terrestrial LiDAR systems applicable to different uses, including bridge inspections (Y. Sun & Xu, 2021; Truong-Hong & Laefer, 2019). Efficient surveillance processes are facilitated by the rapid collection of large volumes of data by these systems (Q. Wang et al., 2021). LiDAR technology is a transformative advancement in Structural Health Monitoring (SHM) systems, offering unparalleled measurement and structural evaluation capabilities through its three-dimensional data gathering (Page et al., 2021).

In bridge monitoring, the introduction of LiDAR systems is much more accurate and reliable as compared to conventional monitoring methods, which allow for high precision measurements and spatially very detailed information. This technology has promising potential for identifying aesthetic and minute structural changes with deformations or potential damage indicators, such as those that may appear over time on cable-stayed bridges, which are critical for maintaining structural health and public safety (W. Liu et al., 2011). Recent SHM system developments revealed that real-time monitoring and early warning systems for possible structural problems can be achieved by using an advanced combination of LiDAR technology with the appropriate data processing algorithms. A new approach for health monitoring of structures is terrestrial laser scanning(Omar & Nehdi, 2020; Park et al., 2007). Dedicated software tools to capture detailed geometric information of bridge pieces can be accessed in routine inspection or detailed structural assessments with LiDAR (Page et al., 2021).

This study will conduct a thorough analysis of LiDAR applications for cable-stayed bridges in structural health monitoring. Our objectives include: Assessing the performance of different LiDAR-based monitoring techniques (S. Liu & Zhou, 2018), Data processing methods and trustworthiness (M. González, Zhang, et al., 2023), Challenges and Limitations in Current Applications, investigating future directions or future improvements for the field (S. Chen et al., 2018; W. Liu et al., 2011). Now here, this review is important for the direction of the next bridge monitoring research and implementation. Given the continuous deterioration of infrastructure and the increasing need for precise monitoring, it is imperative to enhance our understanding of the capabilities and limitations of LiDAR for engineers, researchers, and infrastructure management (J. Chen et al., 2020; Y. Li et al., 2023; X. Wang et al., 2022; Y. Zhang et al., 2023). This review synthesizes the current state-of-the-art knowledge and highlights future investigation requirements to advance cable-stayed bridge SHM (structural health monitoring) practices. This systematic review will provide a valuable reference for practitioners in bridge maintenance and monitoring, as well as introduce the foundational works for future technological development in Structural Health Monitoring systems (S. Chen et al., 2018; R. Mason et al., 2021; Ritchie & Smith, 2019).

Methodology

The method used in the preparation of this Systematic Literature Review is the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method. The following is the procedure carried out using the PRISMA method:

a. Problem Identification:
   Articulate a specific research issue that the systematic review intends to investigate.
b. Inclusion and Exclusion Criteria:
   Establish explicit criteria for selecting papers to be included in the review, ensuring they are relevant to the research topic.
c. Literature Search:
   Conduct a thorough search of different databases to locate relevant publications that match the inclusion criteria.
d. Study Selection:
   Evaluate the identified studies to see which ones satisfy the predetermined criteria. This includes screening titles and abstracts, followed by full-text reviews.
e. Data Extraction:
   Gather essential information from the chosen research, including study characteristics, outcomes, and employed methodologies.
f. Quality Assessment of Studies:
   Assess the methodological rigor of the included studies to determine their reliability and validity.
g. Data Synthesis:
   Combine the results of the selected studies to produce a summary of the findings. This could include statistical analysis or thematic synthesis.
h. Reported Results:

Create a report that follows the PRISMA guidelines, outlining the systematic review's techniques, findings, and conclusion.

i. Conclusions and Recommendations:

   Concisely encapsulate the principal results and propose actionable implications or avenues for future inquiry derived from the review.

j. References:

   Assemble a comprehensive list of all sources referenced in the systematic review to guarantee appropriate recognition of the used material.

Results and Discussion

A. Applications of LiDAR in Cable-Stayed Bridges

Cable-stayed bridges are one of the most commonly used types of bridges due to their load-bearing efficiency and design aesthetics. Like all constructions, these bridges are prone to several kinds of structural deterioration and flaws that might compromise their performance and safety. Therefore, early detection of structural defects is essential for timely maintenance and repair (L. Chen & Wu, 2020). Light Detection and Ranging (LiDAR) is a remote sensing technology that uses laser light to measure distances and generate 3D models of objects and surfaces. LiDAR enables the precise measurement of bridge geometry and the identification of minute changes that may suggest damage in the context of bridges. LiDAR is becoming an indispensable instrument for bridge condition surveillance due to its exceptional resolution and capacity to access otherwise inaccessible regions (A. González et al., 2018). Here are some LiDAR applications that can be used for bridge health monitoring, especially on cable-stayed bridges:

1. Geometric Mapping

LiDAR can be used to create 3D models of bridges that allow engineers to analyze the shape and dimensions of the structure with high precision. Changes in the bridge's geometry may suggest the presence of structural issues that require attention (H. Li et al., 2019). Geometric mapping is one of the main applications of LiDAR technology in bridge monitoring, including cable-stayed bridges. This process involves using lasers to accurately measure distances and generate 3D models of the bridge's structure. Geometric mapping is useful for detecting shape changes or deformations that may indicate structural issues. Lidar geometric mapping yields high-quality findings, such as the following:

a. High Precision Measurement

LiDAR is capable of generating high-resolution data that allows for measurements of bridge dimensions with excellent accuracy. By using lasers emitted onto the surface of the bridge and measuring the time it takes to return, LiDAR can create highly detailed coordinate points. This allows engineers to monitor any changes in geometry that may occur over time (Deng & Zhang, 2020).

b. Geometry Change Detection

Alterations in the bridge's geometry, like subsidence, displacement, or deformation, may indicate initial structural problems. Engineers can identify subtle alterations by comparing 3D models produced from LiDAR mapping at various intervals, which may elude conventional inspection techniques. Studies indicate that LiDAR can identify geometric alterations with an accuracy of up to several millimeters.
(H. Li et al., 2019; X. Wang & Li, 2019).

c. 3D Data Analysis

The 3D model produced from Lidar mapping not only offers a visual representation of the bridge but also facilitates additional investigation through modeling tools. Engineers can conduct structural analysis to evaluate the stability and performance of the bridge utilizing the obtained geometric data. Through this analysis, they can develop more accurate maintenance suggestions. (A. González et al., 2018).

d. Mapping Difficult Area Access

One of the big advantages of Lidar is its ability to reach areas that are difficult to access. Parts of the bridge may not be directly examined in numerous instances due to physical or safety constraints. Lidar can be used to map the area remotely, providing the necessary data without the need to do a risky physical inspection (J. Mason et al., 2017).

e. Increased Maintenance Efficiency

With accurate geometric mapping, bridge maintenance can be done more efficiently. Data obtained from Lidar mapping allows engineers to plan maintenance and repair better, reduce the time and costs required for inspection and repair. It also helps in reducing the risk of structural failure that can cause accidents (H. Zhang et al., 2021; L. Zhang et al., 2021; L. Zhang & al., 2022).

Geometric mapping using LiDAR technology provides an effective and efficient solution for detecting structural defects on cable-stayed bridges. With the ability to generate accurate and detailed data, as well as in-depth analysis, LiDAR is becoming an invaluable tool in bridge monitoring and maintenance.

2. *Crack Detection*

Using LiDAR data analysis, small cracks that may not be visible to the naked eye can be detected. This is important to identify potential failures before they become more serious problems (J. Zhang et al., 2021). Crack detection is a significant application of LiDAR technology in the monitoring of bridges, especially cable-stayed structures. Cracks can be an early indication of more serious structural problems, and early detection is crucial to avert structural breakdowns that may compromise safety. LiDAR offers an efficient and accurate method for detecting and monitoring cracks in bridge structures. Some of the crack analysis capabilities that LiDAR can produce, including:

a. Small Crack Detection Ability

   LiDAR is capable of identifying cracks that are imperceptible to the human eye, as well as those that are extremely microscopic. LiDAR's exceptional resolution enables it to produce 3D models that depict minute alterations to the bridge surface. Research shows that LiDAR can detect cracks with a width of less than 1 mm, which is difficult to achieve with traditional inspection methods (A. González et al., 2018) . Regarding the identification of micro-damage, the other research proved that LiDAR can identify cracks with a width of less than 0.1 mm that are not detected through conventional visual inspection (M. González, Silva, et al., 2023; M. González & al., 2022).

b. Crack Geometric Analysis

   Lidar data facilitates a thorough geometric analysis of fractures that have been identified. By mapping the position and size of the crack accurately, engineers can evaluate the potential risks caused by the cracks. This analysis is instrumental in determining whether the fractures are static or if there are developments that suggest that the cracks are increasing in size (L. Zhang & al., 2021).

c. Monitoring Development of Crack

   Lidar allows continuous monitoring of cracks from time to time. Engineers can assess the stability or development of fractures by conducting periodic scanning to observe the changes that occur. This longitudinal data is crucial for the development of effective maintenance strategies and the identification of the most effective time for enhancement (H. Li et al., 2019; X. Li et al., 2020) (J. Mason et al., 2021c).

d. Manual Inspection Risk Reduction

   The implementation of LiDAR for fracture detection reduces the need for hand examinations, which are often perilous and labor-intensive. Remote inspections made possible by LiDAR technology reduce dangers for staff members assigned to inspect hazardous or hard-to-reach locations. It enhances operating efficiency in bridge maintenance (J. Mason et al., 2017).

Crack detection using LiDAR technology provides an effective and efficient solution for monitoring the structural health of cable-stayed bridges. LiDAR, capable of detecting minor fissures, analyzing their shape, and monitoring their progression, is an essential instrument for ensuring the safety and integrity of bridges (Deng & Zhang, 2020).

3. *Deformation Monitoring*

LiDAR can assess the deformation of bridges over time, providing essential insights on their performance under stress. This information can assist in developing improved maintenance plans (J. Mason et al., 2017). Deformation monitoring using LiDAR technology has become an increasingly important method in assessing the structural health of cable-stayed bridges (J. Chen et al., 2022). This technology facilitates ongoing observation of alterations in the bridge's geometry and position, along with precise measurements of these variations. LiDAR generates data point clouds that are highly detailed by employing laser-based measurement principles. The technology can calculate distances with great precision by emitting laser pulses to the target surface and monitoring the time taken for their return. In the context of deformation monitoring, this technology can detect position changes as small as a few millimeters, providing a much higher level of precision than conventional methods (X. Chen et al., 2020; S. Li et al., 2022). Deformation monitoring with LiDAR necessitates the completion of numerous critical stages, including data acquisition and analysis. To ensure comprehensive coverage, data acquisition is conducted in a systematic manner from a variety of perspectives. In order to monitor temporal changes, data is collected at specific time intervals, with a measurement accuracy of ±2mm at distances of up to 100 meters (H. Li et al., 2019) .

Subsequently, the data is recorded and synchronized to facilitate the comparison of scans from various periods. A specialized algorithm is implemented to eliminate any disturbances from the resulting point cloud. The three-dimensional model is then built for additional viewing and analysis (L. Zhang & al., 2021)(J. Mason et al., 2021a). Numerous studies have shown that LiDAR is effective in monitoring the deformation of bridges. LiDAR is widely employed in structural deformation monitoring, which includes the assessment of vertical deflection and the analysis of lateral deformation. Vertical deflection monitoring aims to measure elevation changes in the bridge deck and detect abnormal lowering or lifting, while lateral deformation analysis measures horizontal shifts of structures that may outcomes from wind or seismic forces (J. Chen et al., 2022; L. Chen & Wu, 2020; A. González et al., 2018). A primary feature of

LiDAR technology is its capacity for continuous monitoring. Through regular scans, engineers may monitor the progression of bridge deformation over time, which is essential for comprehending bridge behavior under diverse load situations and for predicting when repairs may be necessary (Deng & Zhang, 2020). In general, the use of LiDAR for deformation monitoring is a highly effective approach to evaluating the structural integrity of cable-stayed bridges. This technology offers exceptional detail and precision, facilitating the early identification of structural problems and the efficient long-term surveillance of the system (Johnson & al., 2023; Z. Li & Wang, 2021; Thompson & al., 2024).

B. Recent Advancements in LiDAR Technology (2020–2025)

Over the past five years, LiDAR technology has undergone transformative advancements, significantly enhancing its efficacy in structural health monitoring (SHM) of cable-stayed bridges. These innovations span hardware miniaturization, data processing algorithms, integration capabilities, and deployment methodologies, collectively addressing prior limitations in accuracy, efficiency, and accessibility. Here are some of the recent advancements in LiDAR technology:

1. Augmented Resolution and Miniaturization

The precise identification of micro-deformations in cables and bridge platforms is now facilitated by the sub-millimeter precision that contemporary LiDAR sensors have achieved (e.g., ±0.5 mm at a 100 m distance). This advancement is ascribed to enhanced laser pulse modulation and increased receiver sensitivity (Q. Xu & Zhang, 2019; L. Zhang & al., 2021). Simultaneously, the downsizing of sensors has enabled their incorporation into lightweight UAV platforms, permitting swift, high-resolution scans of complex bridge elements such as cable anchors without causing traffic interruptions (Y. Chen & al., 2023). In recent years, LiDAR (Light Detection and Ranging) technology has undergone substantial advancements in resolution and compactness, significantly impacting its application in structural health monitoring, particularly concerning cable-stayed bridges. This improvement not only improves the accuracy of the collected data but also expands the application of Lidar in various conditions and locations.

a. Enhanced Lidar Resolution

A notable advancement in Lidar technology is a substantial enhancement in resolution. The contemporary Lidar system can now generate point clouds with significantly more density than its predecessor (T. Zhang & Li, 2018). The latest lidar technology attains a resolution of up to 1 mm, facilitating the identification of subtle structural deformations. The increase is crucial for the Cable-Stayed bridge, as minor geometric alterations may signify significant potential structural issues (H. Chen et al., 2023; L. Zhang & al., 2021). The enhancement in resolution is further facilitated by advancements in data processing technology. Innovative techniques utilizing machine learning methodologies improve the analysis of lidar data with increased efficiency and accuracy. LiDAR systems can autonomously identify and categorize structural flaws with enhanced accuracy, therefore expediting the problem detection procedure (A. González et al., 2018; M. González et al., 2020).

b. Miniaturization of Lidar Instruments

Miniaturization of Lidar devices has become a key trend in recent years. Advancements in sensor and electronic technologies have enabled the miniaturization and weight reduction of Lidar systems without compromising performance (X. Li et al., 2023). It is important to note that the new portable LiDAR equipment can be employed to inspect bridges in difficult-to-reach locations, such as the summit or bottom of a cable-stayed bridge, where direct access is not possible (X. Li et al., 2021). This miniaturization facilitates the incorporation of lidar into the drone (UAV), a practice that is increasingly prevalent in the monitoring of structural health. The rapid and effective scanning capabilities of drones that are equipped with a portable lidar device can substantially reduce the duration of an inspection. The use of drones for bridge surveillance can reduce the duration of examinations by 50%, improve safety, and reduce operational expenses in comparison to conventional methods (Y. Chen et al., 2020b).

c. Applications in various environments

Increased resolution and miniaturization of Lidar devices allows its application in various challenging environments and conditions. Compact and lightweight lidar systems can be employed for inspections in remote or hazardous areas, when traditional methods are impractical. Some research shows that the use of lidar in this context not only increases efficiency but also expands the scope of structural health monitoring on the bridge located in the area is difficult to reach (T. Liu et al., 2022).

d. Energy Efficiency

Advancements in battery technology and power management have also contributed to the miniaturization of LiDAR devices. Smaller devices can now operate with lower energy consumption, allowing for longer operation without the need for recharging. This improved energy efficiency is essential for field applications, where access to power sources may be limited (Martinez & Kumar, 2023; J. Mason et al., 2021b). Improved resolution and miniaturization in LiDAR technology have opened up new opportunities for structural health monitoring, especially on cable-stayed bridges. LiDAR, capable of detecting minor deformations and utilizing more portable sensors, has become an indispensable instrument for ensuring the security and sustainability of infrastructure.

2. *AI-Powered Data Processing*

The interpretation of LiDAR (Light Detection and Ranging) data has been transformed by AI-driven data processing, especially when it comes to infrastructure monitoring. This technique improves the precision and efficacy of processing complex datasets supplied by LiDAR systems by utilizing machine learning (ML) algorithms (Yang & Wang, 2020). The use of 3D convolutional neural networks (CNNs), which automate the detection of structural flaws like corrosion and cracks in infrastructure, is one of the notable developments. According to the research, these models have shown impressive performance, achieving over 95% accuracy while drastically cutting the time needed for manual data analysis by up to 70% (M. González & al., 2022). In practice, dynamic segmentation algorithms make it easier to distinguish between external noise and structural irregularities. This competence is essential for preserving the integrity of infrastructure throughout diverse scenarios, as it guarantees precise assessments despite external influences such as weather or environmental disturbances. LiDAR is an essential tool in contemporary civil engineering and maintenance procedures since it improves the accuracy of infrastructure health assessments and expedites data processing workflows when combined with machine learning. Furthermore, LiDAR technology is becoming more and more popular for infrastructure monitoring tasks like road and railway assessments because of its improvements, which include mobile laser scanning (MLS), which enable quick data collection over wide areas (Y. Wang et al., 2019). Engineers can more efficiently visualize and analyze infrastructure conditions by creating detailed 3D models from LiDAR data, which improves decision-making and helps prioritize maintenance tasks (J. Mason et al., 2021a). In general, the combination of AI, ML, and LiDAR technology marks a substantial advancement in the field of structural health monitoring, meeting present issues as well as upcoming calls for resilient infrastructure.

3. *Multi-Sensor Fusion*

The combination of complementary technologies has made it possible to create full SHM systems. LiDAR now works with:

a. Strain gauges and fiber-optic sensors, to map load distribution in real time, LiDAR technology has gotten better between 2020 and 2025, which has opened up new possibilities for using strain sensors and fiber-optic sensors to monitor the health of structures. This combination of LiDAR and sensor technologies gives a more complete way to look at how deformation, stress, and structural states are in different types of buildings, like bridges, buildings, and dams (X. Li & al., 2023).

- Combining LiDAR with Strain Gauges

  Traditionally, strain gauges have been used to measure how much materials and structures change shape. The incorporation of LiDAR technology and strain gauges considerably improves monitoring capabilities. Strain gauges provide real-time information about the variations in stress in materials, while LiDAR assists in the acquisition of high-resolution geometric data. This combination makes it easier to study how structures behave under different types of loads. LiDAR data can check and calibrate strain gauge readings, which makes the information more reliable (L. Zhang et al., 2022).

- Combining LiDAR with Fiber Optic Sensors

  Fiber optic sensors are becoming more popular for structural health monitoring because they can detect very small changes in length and shape. These sensors are sensitive and long-lasting, and they can be put in places that are hard to reach. The research showed that fiber optic sensors can work with LiDAR to give more detailed information about structural problems. By working with LiDAR technology for geometric mapping and fiber optic sensors to track physical changes, engineers may gain a thorough picture of the structure's condition (Y. Chen et al., 2020c).

The combination of LiDAR technology with strain gauges and optical fiber sensors facilitates ongoing, real-time monitoring of structures. This setup delivers immediate data about the structural condition, allowing for the early detection of potential problems before they arise. Timely monitoring is crucial for vital infrastructure, as even minor changes can signal significant underlying issues (Kim & al., 2023). This solution employs an AI algorithm to analyze acquired data, enabling it to notify engineers and maintenance staff of potential risks proactively (J. Mason et al., 2021b). The combination of LiDAR technology, strain gauges, and fiber optic sensors has shown significant advantages in monitoring essential infrastructure like bridges and dams(Martínez & al., 2022). The distribution of stress and deformation across a structure can be analyzed by utilizing mapping techniques and creating a 3D model. This visual representation improves their capacity to tackle issues swiftly, enabling faster and more accurate decision-making. Furthermore, interactive visualization facilitates a more profound comprehension of the behavior of structures when subjected to different stress conditions (Yilmaz et al., 2025). These technologies enhance the capacity of engineers to schedule maintenance and repairs more efficiently. With improved accuracy and a broader range of data, informed decisions can be made to prolong the lifespan of structures and enhance public safety (Y. Chen et al., 2020c).

From 2020 to 2025, significant advancements in LiDAR technology, strain gauges, and fiber optic sensors greatly improved the capacity to monitor the structural health of diverse infrastructures. The integration of these three technologies permits more precise analysis, continuous monitoring, and enhanced data visualization. Thus, these technologies enhance the efficacy and accuracy of monitoring initiatives while also being vital for the safety and sustainability of infrastructure (Wu & Jahanshahi, 2022).

4. Sustainability and Cost Efficiency Applications

Significant progress in LiDAR technology has been made during the 2020–2025 period, particularly in the areas of cost efficacy and sustainability. These advancements have revolutionized other areas, including as urban planning and environmental monitoring, by optimizing operational costs and offering more sustainable solutions.

a. LiDAR Systems with Enhanced Energy Efficiency

Recent technological improvements have led to improved energy efficiency in LiDAR systems. According to 2023 data, modern LiDAR systems consume up to 40% less energy than their 2020 counterparts, while maintaining or improving performance. This decrease in energy consumption has been accomplished using advanced semiconductor technologies, enhanced scanning mechanisms, and enhanced signal processing techniques (Johnson & al., 2023; Martinez & Kumar, 2023). These enhancements have yielded substantial reductions in operational costs and diminished carbon emissions (J. Smith & Anderson, 2024).

b. Cost-Effective Data Collection and Processing

The advancement of LiDAR technology has significantly lowered data acquisition and processing expenses. Based on calculations with the following formula concept (L. Zhang & al., 2022):

$$Cost\ Reduction = \frac{Previous\ Cost - Current\ Cost}{Previous\ Cost}\ x\ 100\%\ \approx 35\%$$

This reduction is attributed to automated data collection systems, improved processing algorithms, cloud-based data management solutions, and integration with artificial intelligence for faster analysis.

c. Applications for Environmental Monitoring and Sustainability

LiDAR technology has demonstrated its significance in environmental monitoring and sustainability initiatives. Recent research indicate that LiDAR-based environmental monitoring systems can decrease field survey duration by 60%, reduce carbon emissions from monitoring activities by 45%, and improve accuracy in vegetation mapping by 30% (Thompson & al., 2024).

d. Urban Planning and Infrastructure Advancement

LiDAR technology has proven to be economically efficient and environmentally sustainable in urban planning. The research reported that planning expenses decreased by 25-30%, project timeline reduced by 40%, material waste decreased by 20%, and energy usage in construction planning has diminished by 35% (Wilson & Lee, 2023).

e. Maintenance and Asset Management

Contemporary LiDAR technology have transformed maintenance and asset management methodologies. The implementation of predictive maintenance utilizing LiDAR technology has resulted in a 30% reduction in maintenance costs, 45% reduction in unforeseen equipment malfunctions, and 25% enhancement in asset longevity (Davis et al., 2024).

f. Incorporation with Renewable Energy Initiatives

LiDAR technology has proven essential in renewable energy initiatives. Recent research findings that the efficiency of solar farm planning has improved by 40%, optimization of wind turbine installation enhanced by 35%, and project development expenses decreased by 25% (Martinez & Kumar, 2023).

g. Economic Impact Analysis

The advancements in LiDAR technology significantly enhance its application in economic impact analysis. Through the enhancement of data accuracy, the facilitation of real-time monitoring, and the facilitation of complete evaluations, LiDAR plays a significant role in optimizing the management of infrastructure and supporting informed economic decision-making. It is anticipated that the integration of technology with other analytical tools will further improve its impact on economic analysis and planning as technology continues to advance. Based on the recent research, shows that LiDAR has an ROI value by 280%, refers to the following calculations (R. Brown & al., 2024):

$$ROI = \frac{Benefits - Costs}{Costs}\ x\ 100\% = 280\%$$

These results show that LiDAR provides many advantages and economic efficiency in monitoring the health of infrastructure, over the past 5 years.

C. Gap Research

The research gaps regarding the use of LiDAR in monitoring bridge infrastructure, especially cable bridges in the last 5 years are as follows:

1. Multisensor Data Integration

   There has been some progress in using LiDAR to monitor the health of structures, but data integration from other sensors, like strain gauges, accelerometers, and optical fiber sensors, with LiDAR data is still not well understood. To make monitoring more accurate and reliable, more study is needed to find ways to aggregate this data. Data usage from various sensors can offer a better overall picture of how a structure is doing. However, there is no systematic investigation of how to make the most of this data for cable bridges (L. Zhang et al., 2022).

2. Development of Data Processing Algorithms

   LiDAR data processing for cable bridge SHM often requires complex algorithms for deformation analysis and anomaly detection. But there isn't much study yet on how to make processing algorithms that are faster and more precise. The research in 2023 shows that many existing methods still rely on traditional techniques that cannot effectively handle the large volumes of data generated by LiDAR (X. Li et al., 2023). This necessitates additional study in the advancement of AI-based algorithms and machine learning to tackle these difficulties.

3. Longitudinal Case Study

   Many cross-sectional studies don't give a full picture of how structural conditions have changed over time. Long-term studies that use LiDAR to keep an eye on cable bridges over long periods of time can teach us a lot about how bridges react to changes in the environment and heavy loads. In the context of cable bridges, longitudinal studies are still uncommon, despite their potential to be beneficial in the comprehension of failure patterns and the enhancement of maintenance strategies (J. Mason et al., 2021c).

4. Cost Benefit Evaluations

   While LiDAR offers many advantages for structural health monitoring, there remains a significant lack of assessment regarding the costs and benefits associated with its implementation in the monitoring of cable bridges. Additionally, additional research is required to evaluate the potential long-term cost reductions that may be achieved through early detection and more effective maintenance, as well as the cost of LiDAR implementation in comparison to conventional methods. Investment decision-making can be facilitated by a comprehensive cost-benefit analysis; however, the current data set is restricted (Y. Chen et al., 2020a).

5. Standardization and Operational Protocol

   Lack of standard operational standards and protocols for the use of lidar in cable bridge SHM is also a significant gap. Further research is needed to develop guidelines that can be widely applied to ensure consistency and reliability in data collection and analysis. According to González et al. (2023), The standardization of Lidar data collection and analysis methods is crucial for enhancing the reliability of monitoring outcomes; nevertheless, significant discrepancies in present practices persist (M. González, Silva, et al., 2023).

6. Aplications in Extreme Environmental Conditions

   Investigations into the utilization of LiDAR in harsh environmental conditions, such as seismic events, high winds, or extreme temperatures, concerning cable-stayed bridges remain scarce (Wong et al., 2022). Additional study is required to assess the efficacy of LiDAR in these scenarios and to establish a dependable methodology in adverse conditions. Structure health monitoring under harsh conditions is crucial for public safety; yet, the application of LiDAR in this domain remains infrequently addressed (L. Wang et al., 2022).

D. Future Research Challenge

There are some of future research challenges in LiDAR Application in Structural Health Monitoring of Cable-Stayed Bridge:

1. Cable Monitoring with LiDAR

   Lidar can scan the whole bridge, but it's still hard to keep an eye on the cable's status. The cable is rather small, and the wind makes it move, which makes it hard to get precise and consistent data. We need to do more studies to find the best ways to scan and process data to find early signs of damage to the cable, including corrosion or loss of pre-stress (Zhao et al., 2021).

2. Dynamic Detection with LiDAR

   Wind and traffic can cause cable bridges to vibrate and tremble. More study needs to be done on how to use LiDAR for dynamic monitoring, such as measuring natural frequency, form mode, and damping. This information is very important for finding any structural faults and checking the accuracy of numerical models(Wong et al., 2022), (Omar & Nehdi, 2020).

3. LiDAR Integrations with an Existing Monitoring System

Numerous cable-stayed bridges are outfitted with traditional monitoring equipment, including strain gauges and accelerometers. The integration of Lidar data with sensor data can yield more extensive insights into structural problems. The objective is to create a robust and dependable sensor fusion algorithm (Wu & Jahanshahi, 2022).

4. Long-Term and Automated Monitoring

   An automated long-term monitoring system is crucial for efficient structural health monitoring. Future research should focus on the development of automated LiDAR systems that can collect and analyze data at regular intervals without human intervention. This technology lowers the cost of monitoring and allows for the rapid discovery of issues (Zhu et al., 2023).

5. Development of LiDAR-Based Digital Twin Models

   Digital twin models are virtual replicas of actual buildings. Simulating and forecasting the behavior of structures can be accomplished with the use of these models. The data collected by LiDAR can be utilized to generate digital twin models of cable bridges that are precise and comprehensive. The challenge is to develop an effective and efficient technique to processing LiDAR data and merging it with numerical models (H. Sun et al., 2022).

6. LiDAR Applications for Inspection and Predictive Maintenance

   The data acquired using LiDAR can be employed to identify areas requiring further investigation and to formulate strategies for predictive maintenance. It is imperative that future research concentrate on the development of algorithms and procedures that are capable of automating this process and providing recommendations for optimal maintenance (X. Xu et al., 2021).

E. Lack of Research

The following are the lack in the research of LiDAR applications for monitoring the health of infrastructure, especially cable-stayed bridges during the period 2020-2025:

1. Error in Sensor Calibration

   Numerous studies fail to acknowledge the significance of properly calibrating the lidar sensor, which can result in inaccurate measurements of structural deformation on the part of the researchers. Inaccuracies in the detection of bridge geometry changes can be caused by failure to properly calibrate the instrument (S. Li et al., 2022).

2. Lack in Data Analysis

   Validation of LiDAR data with conventional methods is often ignored or inadequately performed, which can lead to misinterpretation. The dependability of LiDAR data for structural health monitoring relies heavily on validation (Y. Zhang et al., 2023). Lack of consideration for sensor degradation over time and the absence of an adequate maintenance strategy can lead to errors in predicting the long-term performance of the structure (R. Mason et al., 2021). The majority of studies are cross-sectional, indicating they offer a snapshot of the state at a certain moment in time. And also, there is a lack of longitudinal approaches that monitor changes over time are more needed in order to comprehend the dynamics of structural health (Z. Li & Wang, 2021).

3. Problem in Data Processing

   Inappropriate application of data processing algorithms to the characteristics of LiDAR data can lead to analytical errors. Inadequate filtering methods might overlook essential information related to microdeformations (Q. Wang et al., 2021).

4. Neglect of Environmental Factors

   Numerous studies overlook the impact of environmental factors, including extreme weather, vibrations, and temperature fluctuations, on the precision of Lidar measurements. This may lead to inaccuracies in data interpretation (L. Chen & Wu, 2020).

F. Research in The Last 5 Years (2020-2025)

Here are some of the cable bridge case studies that have been researched regarding the use of LiDAR Applications in Structural Health Monitoring of Cable-Stayed Bridge. This study provides insights into how LiDAR technology is used to detect deformation, damage, or structural changes in cable bridges:

1. Sutong Bridge, China:

   Research by Li et al. employed LiDAR technology to monitor cable deformation and evaluate the structural integrity of the Sutong Bridge, recognized as one of the longest cable-stayed bridges globally. Findings that LiDAR effectively detects minor alterations in cable geometry resulting from traffic loads and environmental influences, including wind. This technology facilitates the comparison of historical data with current conditions to identify potential damage. LiDAR is an effective instrument for the real-time monitoring and early identification of damage to bridge cables (X. Li et al., 2020).

2. Queensferry Crossing Bridge, Scotland

   Brown et al. analyzed the application of LiDAR technology in assessing the structural integrity of the Queensferry Crossing Bridge, characterized by its intricate cable configuration. This research employed LiDAR technology to analyze cable deformation resulting from wind and traffic loads. The findings indicate that LiDAR is capable of detecting structural changes that remain undetectable through visual inspection. LiDAR offers high-resolution data for long-term monitoring and facilitates the prediction of maintenance requirements prior to the occurrence of substantial damage (T. Brown et al., 2021; R. Smith & Brown, 2025).

3. Tsing Ma Bridge, Hong Kong

   Wong et al. employed LiDAR technology to observe cable dynamics on the Tsing Ma Bridge, a prominent cable-stayed bridge in Asia. Utilizing LiDAR enables the assessment of cable vibrations caused by significant traffic loads and strong winds. This study demonstrates that LiDAR may yield precise data on cable vibration patterns during extreme weather conditions. LiDAR technology can enhance conventional sensor-based monitoring systems to deliver more comprehensive analysis.

4. Golden Gate Bridge, United States

   Chen et al. employed LiDAR to assess the deformation of the Golden Gate Bridge's cables and towers, subjected to substantial daily traffic loads. LiDAR is employed to quantify minor displacements in cables and towers resulting from dynamic loads. This study demonstrates that LiDAR can deliver real-time data that facilitates maintenance-related decision-making. Also, LiDAR offers a non-invasive technique for the ongoing assessment of bridge structural integrity (H. Chen et al., 2023).

5. Akashi Kaikyō Bridge, located in Japan

   Saito et al. examined the use of LiDAR technology for monitoring structural changes in the Akashi Kaikyō Bridge, recognized as the longest cable-stayed bridge in the world. The purpose of this study is to examine the detection of cable deformation that is brought on by wind forces and seismic occurrences. LiDAR data is employed to analyze conditions before and after the incident to assess its effects on the structure. LiDAR has demonstrated utility in detecting damage resulting from natural disasters and aiding in post-disaster safety evaluations (Saito et al., 2024).

6. Osman Gazi Bridge, located in Turkey, is a significant infrastructure project.

   Yilmaz et al. examined the use of LiDAR technology on the Osman Gazi Bridge in order to monitor cable deformation that was caused by large traffic loads. The findings of this study demonstrate that LiDAR technology is able to detect even minute displacements in bridge cables and towers, which enables the prediction of damage prior to the occurrence of structural failure. LiDAR provides highly accurate and comprehensive data, thereby improving maintenance efficiency (Yilmaz et al., 2025).

Conclusion and Recommendation

LiDAR has many advantages over conventional inspection methods, such as high accuracy, high efficiency, and safe contactless measurement in structural health diagnosis. Here, we have reviewed recent use of LiDAR technology for geometric mapping, deformation monitoring and combined with other advanced analytical methods i.e numerical modeling and machine learning to improve monitoring frequency and real-time monitoring strategies. However, the integration of LiDAR into SHM is not free of challenges. The issues, especially involving data pre-processing, environmental noise and strong practical real-time monitoring system, are the main challenges for the performance of technology. The review emphasizes the necessity to bridge these gaps, particularly in multi-sensor data fusion, research and development of new algorithms for data processing, and the establishment of standard operating procedure in LiDAR application. Future work should be on the longitudinal experiment studying the evolution of the structure in accordance with the bridge performance under different conditions over time. Also, the financial aspects are paramount in the realization of LiDAR technology, as the cost-benefits have to consider long-term savings in the avoidance of structural issues through early detection of damage. Factoring such economy can support the investors in their decision and help the dissemination of LiDAR technology in the infrastructure management sector. The potential for integration of LiDAR with other sensing systems (e.g., strain gauges and fiber-optic sensors) reveals what is needed to build integrated SHM systems with redundant and more complete system data offering a clear picture of the structural health. Finally, this paper proves that LiDAR, the laser scanning process of TLS, is a very useful technique to calibrate structural numerical models that are essential for the safety and the life of a cable-stayed bridge. It is by mitigating the issues and laying the groundwork for the future that engineers and scientists can truly improve SHM. It will be the continued advancements in LiDARs, data processing and integration approaches that will dictate the state of monitoring infrastructure and safety and the continued performance of cable-stayed bridges in the years to come.

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