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Low-Cost Efficient Wireless Intelligent Sensors for Railroad Bridge Displacement Monitoring

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Abstract

Railroad bridge owners need practical methods to measure bridge behavior under train operation. However, accurate displacement monitoring of railroad bridges remains challenging because field responses are often small, and access is limited. Conventional displacement sensors may require fixed references, line-of-sight setup, wired power, or local communication infrastructure. This study develops and validates a portable, low-cost, efficient wireless intelligent sensor (LEWIS 7) for railroad bridge displacement monitoring. The system integrates acceleration-based displacement estimation, event-triggered recording, energy harvesting, and Long-Term Evolution for Machines (LTE-M) cellular data transmission into a self-powered sensing node that does not require wired power or fixed internet at the bridge site. The developed system has a total hardware cost of less than \$170 and integrates a tri-axial Micro-Electro-Mechanical Systems (MEMS) accelerometer, rechargeable battery power, solar charging, and cloud-based data transmission. An event-triggered algorithm records short data windows only during train-induced vibration, reducing unnecessary data storage and power consumption. Laboratory validation was performed using a shaker and Laser Doppler Vibrometer (LDV) under sine sweep and random excitation. The sensor was then deployed on a timber railroad bridge in Albuquerque, New Mexico, from January to May 2026. Quantitative validation was performed during three live Rail Runner train crossings using an LDV reference measurement. The measured bridge response was approximately 1 mm, and LEWIS 7 estimated the transverse displacement with an average RMSE of 0.17 mm and an average peak-to-peak displacement error of 0.08 mm.

Keywords: Railroad Bridge Displacements, Structural Health Monitoring, Wireless Sensor, Internet of Things, LTE-M.

1 Introduction

Railroad bridges operate under repeated train loading, changing environmental conditions, aging materials, and maintenance constraints. These factors can influence vibration characteristics, displacement response, stiffness, and serviceability over time [1–5]. Recent field studies have demonstrated the value of measuring train-induced dynamic response in railway bridges and transition zones using different sensing technologies [6,7]. Structural health monitoring can therefore provide measured information to support the assessment and management of bridges under operating conditions [8–10]. This capability is particularly important for railway infrastructure because field access is restricted, measurement windows are short, and instrumentation must not interfere with normal train operation [11,12].

Displacements of railroad bridges under trains can provide additional information to infrastructure owners if they are easy and simple to collect. Railroad bridge displacement is commonly investigated as indicator of bridge behavior and global structural health [13,14]. Displacement response is directly related to structural flexibility [15], load-carrying behavior [16], serviceability [17], and possible changes in structural condition. Researchers in the past have measured railroad bridge displacements during train passages, demonstrating the value of displacements to quantify bridge condition changes under real operating conditions [18, 19]. However, direct displacement measurement in the field is often difficult, especially for bridges located in active rail corridors where access is limited and installation time must be reduced.

Bridge displacement measurement techniques provide owners with access to displacement in the field. The contact-based sensors such as accelerometers [20], strain gauges [21–23], and global navigation satellite systems (GNSS) [24,25] have been widely used in structural testing

and monitoring. These techniques can be useful in some testing conditions but are not always practical for railroad bridge monitoring. LVDTs, for instance, require a fixed point of reference for measuring displacement [26] and establishing that reference point near an active railroad bridge can be challenging. It is easier to install accelerometers on the bridge but the estimation of displacement from acceleration requires a careful signal processing because integration can result in drift [27]. Strain gauges give local response measurements, but their readings depend on the place of installation and can be influenced by temperature as well as quality of bond [28]. GNSS can be used without a nearby fixed reference point, but it may not be suitable when the bridge displacement is very small [29]. There is an interest in exploring simple, portable and practical bridge displacement solutions, including non-contact methods.

Noncontact methods have also been used to measure bridge displacement. Different systems include laser systems [30], radar [31,32], and camera-based approaches [33,34]. These methods are useful because they can measure the bridge response without installing a sensor directly on the structure. In field applications, however, they are not always easy to use. They can be expensive, usually need a clear line of sight to the measurement point, and often require careful alignment before testing can begin. For this reason, they are commonly more suitable for controlled tests or short-term validation than for continuous monitoring of many railroad bridges. These limitations make them useful for validation and short-term testing, but less practical for scalable, long-term monitoring across a large railroad bridge network, motivating the low-cost wireless approach.

The main contributions of this study are as follows: (1) a low-cost wireless sensing system, with a total hardware cost of less than \$170, is developed for railroad bridge monitoring, making it affordable for practical railroad applications, (2) an event-triggered sensing algorithm is proposed to automatically detect train passages and initiate data recording only during periods of meaningful vibration, thereby reducing energy consumption, preserving battery life, and keeping the sensor in sleep mode for most of the monitoring period, which is beneficial for long-term deployment while minimizing the need for frequent access to the infrastructure, (3) a wireless transmission framework based on cellular communication is implemented, eliminating the need for fixed internet infrastructure at the monitoring site, and (4) the proposed system is successfully applied on a railroad bridge under real operating conditions. The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 presents the design requirements for railroad bridge monitoring. Section 4 describes the developed sensor system and methodology. Laboratory-scale and field deployment validations are presented in Sections 5 and 6, respectively. Finally, the discussion, railroad owner evaluation and concluding remarks are provided in Sections 7, 8, and 9.

2 Literature Review

Wireless sensing has become a practical way to monitor civil infrastructure in the field rather than only in the laboratory. Such monitoring is especially valuable where installation access, cabling cost, and maintenance effort determine whether a system can be used outside a research setting. Early work by Lynch and Loh [35] and Spencer et al. [36] established the central motivation for wireless smart sensors: reducing the cost and logistical burden of instrumentation while moving data processing from a central computer to the sensing node itself. This shift was important for bridges because the number of potential measurement locations is large, the available power and communication bandwidth are limited, and the cost of installing and protecting cables can exceed the cost of the sensors. Subsequent smart-sensor frameworks, including the work of Abdulkarem et al. [37], Nagayama and Spencer [38], and Jo et al. [39], showed that synchronized sensing, reliable communication, and autonomous operation could be integrated into deployable wireless networks rather than treated as separate

laboratory functions. These early efforts established wireless sensing as a viable field tool, which motivated the larger full-scale bridge deployments.

Full-scale bridge applications are helpful to demonstrate both the potential and the practical limitations of wireless structural health monitoring systems. Dense wireless deployments on highway and cable-supported bridges, including the work of Cho et al. [40] and Jang et al. [41], showed that wireless smart sensors can support modal identification, response monitoring, and distributed data management in the field; the Jindo Bridge deployment involved 70 sensor nodes measuring 661 channels of data and remains one of the largest wireless SHM networks for a cable-stayed bridge. Research led by Ni et al. on long-term monitoring systems, including the Guangzhou New TV Tower [42] and Hong Kong bridge network [43], emphasized that SHM must address system reliability and data interpretation under changing operational conditions, not only measurement accuracy. Li et al. reinforced this perspective through integrated sensing and decision support for bridge management [44], and Siringoringo and Fujino [45] confirmed that wireless networks can stand 45 month continuous operation on a highway bridge in Japan. These studies helped move SHM toward practical implementation, but many systems still relied on gateway computers, specialized sensor boards, or permanent installations that are difficult to justify for short-span, rural, or railroad bridges requiring rapid deployment and low maintenance.

Railroad bridges introduce additional constraints because measurements must be obtained during train passages, access windows are short, and instrumentation must not interfere with operations. Previous research demonstrated the use of wireless smart sensors for railroad bridge monitoring under revenue-service traffic, and related campaign-style work by Spencer et al. [46] emphasized portability and periodic deployment rather than permanent installation. These studies are directly relevant to railroad owners because they show how wireless sensing can be used under live train loading; however, they also point to a continuing need for simpler systems that can be installed, removed, and redeployed by field personnel with minimal external infrastructure. For timber railroad bridges, Moreu et al. [3], Ozdagli et al. [18,47], and Liu et al. [26] showed that displacement response is a useful indicator for condition assessment, but that practical displacement measurement remains challenging when fixed reference points, extensive cabling, or line-of-sight instruments are required. Therefore, industry needs a simplified method and tool to enable the displacement measurement during train operations.

Displacement estimation has therefore become an important part of practical bridge SHM. Acceleration-based estimation offers a more portable alternative because accelerometers can be attached directly to bridge components and incorporated into low-cost wireless nodes. Lee et al. [48] proposed a regularized finite impulse response (FIR) approach for displacement reconstruction from acceleration, and Park et al. [49] developed a wireless displacement measurement system on the Imote2 platform enabling reference-free monitoring. Smyth and Wu [50] introduced a multi-rate Kalman filter that fuses acceleration and displacement data at different sampling rates, and Junhee Kim, Kiyoun Kim and Hoon Sohn advanced data-fusion methods combining acceleration with intermittent displacement information [27]. Gomez, Park, and Spencer [20] formalized a reference-free displacement estimation method for railroad bridge applications. Together, these studies show that accelerometer-based displacement estimation can reduce dependence on fixed reference instrumentation, but they also indicate that robust processing and validation remain essential when displacements are small, and that in the field such processing must run on a sensor able to power itself.

Energy supply is another limiting factor in wireless SHM. Battery-powered nodes reduce installation effort, but frequent replacement is not practical for bridges with restricted access or for networks distributed over multiple assets. Farrar et al. framed energy harvesting as a key requirement for embedded SHM systems [51], and Mascarenas et al. [52] explored wireless power transfer for impedance-based sensor nodes. Davidson and Mo [53] and Bonessio et al.

[54] reviewed solar, vibration, wind, and hybrid harvesting strategies for civil infrastructure, while Sonbul et al. [55] observed in a recent systematic review that the energy budget must be designed around the full sensing cycle, including sleep current, event detection, data acquisition, processing, and communication. This observation is especially important for railroad bridges, where useful data occur during discrete train-crossing events rather than continuously. Event-triggered acquisition can therefore reduce power consumption and data volume by keeping the sensor inactive until a meaningful structural response is detected.

Communication architecture also affects whether a monitoring system can be scaled beyond a single demonstration bridge. Many wireless SHM systems use local mesh networks or short-range radio links that require a gateway, base station, or site-specific internet connection [35,41,56]. These architectures are effective for dense deployments, but they are less convenient when the goal is to move a small number of sensors between remote bridge sites [57]. Recent IoT and edge-computing studies have explored long-range communication, cloud storage, and off-the-shelf components as ways to simplify deployment and remote access [37,58–61]. Cellular communication is particularly attractive for railroad corridors because it transmits data through existing public networks without a local base station or wired connection. Di Nuzzo et al. [62] achieved energy-neutral operation by combining low-power MEMS accelerometers with Narrowband IoT cellular connectivity and a small solar panel, while Tronci et al. [63] demonstrated sub-GHz multi-hop communication exceeding one kilometer on the Manhattan Bridge. However, cellular transmission increases power demand relative to short-range radio, which means it must be paired with event-based recording, compact data packets, sleep modes, and an energy-harvesting or rechargeable power strategy. summarizes the literature review in relation to the contributions of LEWIS 7. Prior work has established the value of wireless smart sensors for SHM, the feasibility of railroad bridge monitoring under in-service train loading, the importance of displacement for bridge assessment, and the need for energy-aware autonomous operation. The new contribution of the LEWIS 7 system described in this paper focused on the following: low hardware cost, simple installation, portability, energy harvesting, cellular communication, and acceleration-based displacement estimation suitable for practical railroad bridge deployment [64]. The final section of this paper demonstrates the value of using LEWIS 7 for industry-informed, practical field monitoring. Furthermore, the displacement estimation is validated with ground truth measurements under regular operations. The paper discusses the contributions from previous research regarding displacement measurements and adds the owner perspective on the value of displacements for maintenance and management. The work presented in this paper is an additional step from the existing research community efforts in displacement monitoring towards simplified, owner-focused, portable, very low-cost displacement monitoring.

3 Design Requirements for Railroad Bridge Monitoring

The LEWIS 7 system was developed to address practical requirements for railroad bridge monitoring. Railroad bridges are often located in active corridors where access is limited, installation time must be minimized, and local power or internet infrastructure may not be available. Therefore, a practical monitoring system should be low-cost, simple to install, portable between sites, capable of energy harvesting, able to estimate displacement, remotely accessible, and validated under field conditions.

Table 1: Comparison of selected wireless SHM systems relevant to the present study (N/R = not reported).

Study	Sensor/ Platform	Approximate Cost	Communication	Power Strategy	Displacement Estimation	Deployment Context
Sim and Jang [56]; Nagayama and Spencer [38]	Imote2 + SHM-A board	~\$100/ch.	IEEE 802.15.4 mesh	Battery + power Management	Vibration/modal only	Framework demos; multi-node lab and bridge tests
Jang et al. [41]; Cho et al. [40]	Imote2 + custom boards	~\$100/ch.	IEEE 802.15.4 + gateway	Battery + solar (partial)	Modal Properties	Jindo Bridge, 70 nodes, 661 ch.; long-term cable stayed
Moreu et al [13]; Spencer et al. [46]	Imote2 WSS	Moderate	IEEE 802.15.4	Battery	Bridge response metrics	Railroad bridges; campaign-style under revenue traffic
Park et al. [49]; Gomez et al. [20]	Imote2 + MEMS accelerometer	Low	IEEE 802.15.4	Battery	FIR filter acceleration integration	Lab shear building; railroad bridge field tests
Kim et al. [27]; Kim et al. [65]	Accelerometer + intermittent displacement	N/R	N/R	N/R	Kalman filter data fusion	Lab dynamic experiments
Smyth and Wu [50]	Accelerometer + GPS/displacement	N/R	N/R	N/R	Multi-rate Kalman filter	Numerical + field validation
Siringoringo and Fujino [45]	MEMS accelerometer WSN	Moderate	IEEE 802.15.4	Battery	Seismic response only	Highway bridge, 45-month continuous monitoring
Di Nuzzo et al. [62]	MEMS accelerometer	Low	NB-IoT (cellular)	Battery + solar	Modal analysis only	Building > 10-year project lifetime
Tronci et al. [63]	MEMS accelerometer	Low	Sub-GHz (>1 km)	Battery	Modal analysis only	Manhattan Bridge; long-range multi-hop
Present study (LEWIS 7)	LSM6DSOX MEMS accelerometer	<\$170 total	Cellular (LTE-M)	Battery + solar + sleep	FIR filter accelerometer-to-displacement	Lab + timber railroad bridge; event-triggered, portable

As summarized in Figure 1, these requirements are addressed through three components of the proposed system: the LEWIS 7 hardware, the LEWIS 7 software, and field validation. The hardware supports low-cost deployment, portability, and solar-assisted operation. The software enables event-triggered data collection and displacement estimation from acceleration measurements, and cellular Internet of Things framework allows measured data to be transmitted and accessed remotely without fixed internet infrastructure at the bridge site. Field validation was used to evaluate the performance of the system under live train loading.

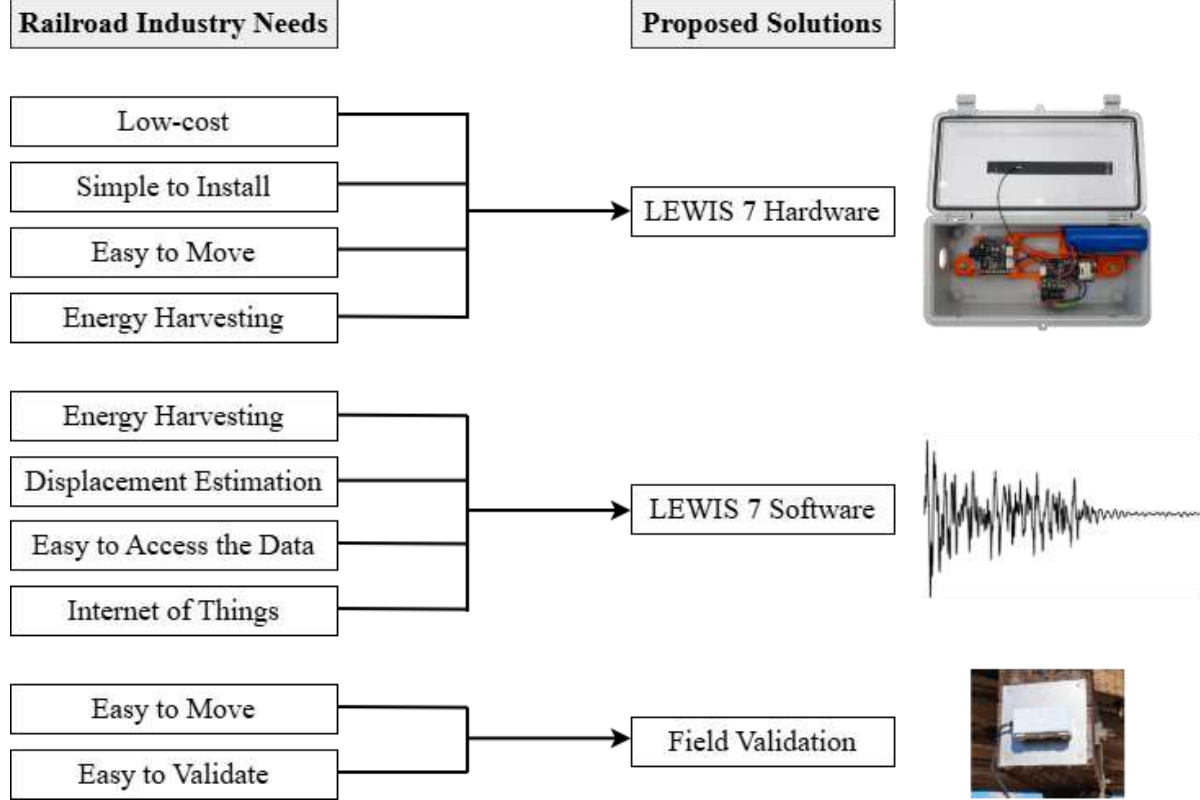


Figure 1: Railroad bridge monitoring requirements and proposed LEWIS 7 bridge monitoring.

Figure 2 shows the conceptual deployment of the LEWIS 7 system on a railroad bridge. In this configuration, the sensor is installed on the bridge to collect train-induced structural response data. The event data are transmitted wirelessly to a remote server for storage, displacement estimation, and visualization.

4 Methodology

The LEWIS 7 methodology is based on an event-driven monitoring approach designed to reduce power consumption and data volume while enabling remote railroad bridge displacement monitoring. The methodology is organized into four main sections: (1) acceleration-to-displacement conversion using a regularized FIR reconstruction method, (2) the LEWIS 7 hardware architecture, including the sensing, power, communication, enclosure, and field-installation components, (3) the software framework, including energy harvesting, event-triggered data collection, and LTE-M cellular transmission, and (4) system integration, which summarizes the complete process from train-induced vibration and data recording to cloud storage, server-side displacement estimation, and remote access.

4.1 Acceleration to Displacement Conversion

The displacement response of the bridge was estimated from the acceleration measured by LEWIS 7 using a regularized finite impulse response (FIR) reconstruction method. This

approach follows the displacement reconstruction framework by Lee et al. [48], in which measured acceleration is related to displacement through a second-order central finite-difference approximation within a finite time window. The method is suitable for field monitoring because it does not require a fixed displacement reference or initial displacement and velocity conditions.

Direct double integration of acceleration is not used in this study because small low-frequency noise components can introduce significant drift in the reconstructed displacement. In addition, the boundary conditions at the beginning and end of each window are generally unknown during field measurements. Therefore, the displacement reconstruction is treated as an inverse problem in which the displacement time history is estimated by minimizing the difference between the measured acceleration and the acceleration approximated from displacement using the finite-difference operator. To stabilize the solution, Tikhonov regularization is applied.

For a measured acceleration vector $\mathbf{a}$, the dynamic displacement vector $\mathbf{u}$ is estimated using Eq. (1):

$$\mathbf{u} = (\mathbf{L}^T \mathbf{L} + \lambda^2 \mathbf{I})^{-1} \mathbf{L}^T \mathbf{L}_a \mathbf{a} (\Delta t)^2 \quad (1)$$

where Δt is the sampling interval, $\mathbf{L}$ is the finite-difference operator matrix, $\mathbf{L}_a$ is the acceleration weighting matrix, $\mathbf{I}$ is the identity matrix, and λ is the regularization factor. The regularization term reduces the effect of unknown boundary conditions and low-frequency noise on the reconstructed displacement. Following Lee et al. [48], the regularization factor was selected as a function of the number of data points in the time window as shown in Eq. (2):

$$\lambda = 46.81 N_d^{-1.95} \quad (2)$$

where N_d is the number of data points in the reconstruction window. In this study, the empirical regularization relationship proposed by Lee et al. [48] was adopted directly. For the present implementation, the sampling frequency was 200 Hz, and the event window was 5 seconds, giving $N_d = 1000$ data points and $\lambda = 6.6 \times 10^{-5}$. The reconstructed displacement obtained from this process represents the acceleration-based dynamic displacement component of the bridge response. In the present study, this processing was implemented on the back-end server after the event data were transmitted from LEWIS 7.

A detailed description of the mathematical formulation, numerical implementation, and experimental validation of this algorithm is provided by Lee et al. [48].

4.2 Hardware

Figure 3 shows the main hardware components used in the LEWIS 7 sensor. The system was designed for field deployment on railroad bridges, where the sensor may need to remain in place for long periods with limited access. For this reason, the hardware selection focused on low cost, low power use, cellular communication, solar charging, and simple installation. The main components include the Particle Boron BRN404X, a cellular antenna, a tri-axial accelerometer, a rechargeable battery, a solar panel, and a charge controller.

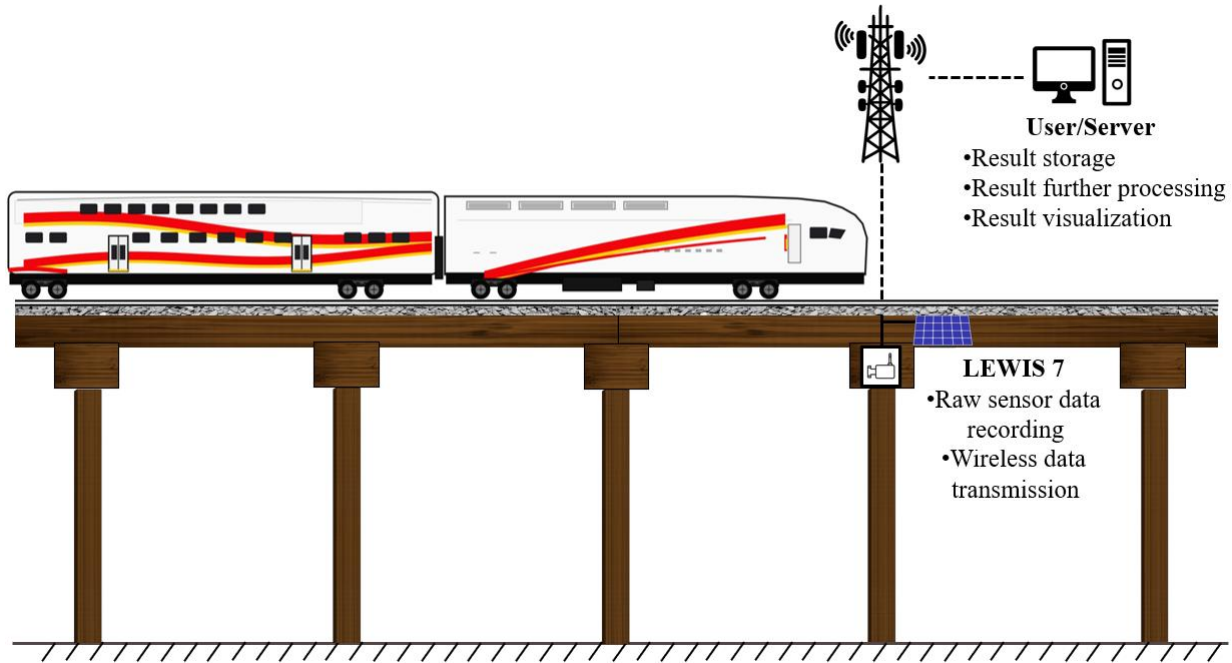


Figure 2: Conceptual deployment of the LEWIS 7 system for railroad bridge monitoring.

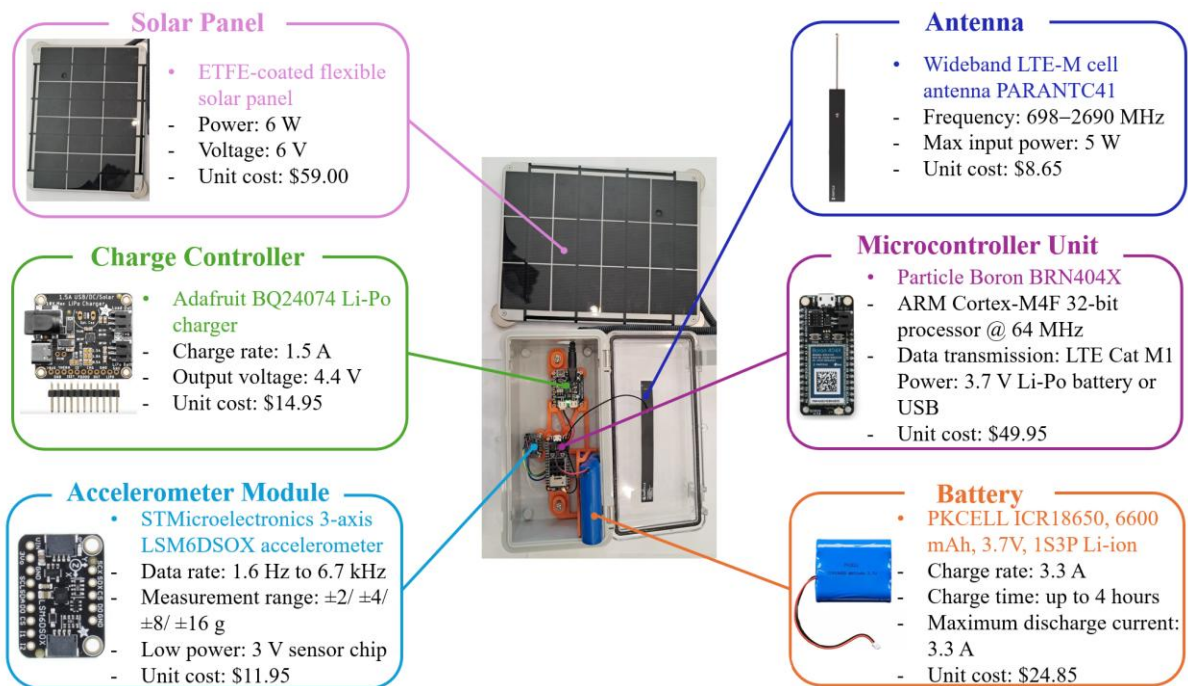


Figure 3: LEWIS 7 components.

4.2.1 Particle Boron and Cellular Antenna

LEWIS 7 uses the Particle Boron BRN404X as the main controller. The board was selected because it combines the microcontroller and cellular modem, reducing the need for an additional communication board or gateway at the bridge site. For field deployment, this is important because fewer components also mean fewer wiring connections and fewer possible failure points.

The cellular signal is supported using the PARANTC41 antenna. With this setup, the sensor can send data directly through the cellular network. This allows LEWIS 7 to be used at railroad bridge locations where Wi-Fi or fixed internet access is not available.

4.2.2 Accelerometer

Bridge response is measured using an LSM6DSOX tri-axial MEMS accelerometer. This accelerometer records acceleration in three directions and is used to detect train-induced vibration. The acceleration signal is also used later for displacement estimation. The accelerometer was selected because it is small, low-cost, and suitable for low-power operation.

4.2.3 Battery and Solar Charging

The sensor is powered by a rechargeable PKCELL ICR18650 battery with a capacity of 6600 mAh and a nominal voltage of 3.7 V. A 6 W, 6 V ETFE-coated flexible solar panel is used to recharge the battery during field operation. The charging process is controlled using an Adafruit BQ24074 LiPo charge controller.

The battery was used as the main power source, while the solar panel was added to recharge it during field deployment. Because train events occur only during limited periods, the sensor does not need to remain fully active all the time. Instead, it stays in a low-power state between events and wakes up only for sensing, recording, or data transmission. This reduces power use and limits the need for frequent battery replacement.

4.2.4 Hardware Connection

Figure 4 shows the wiring layout of the LEWIS 7 system. The battery, solar charger, accelerometer, Particle Boron, and cellular antenna are connected in one compact unit. With this layout, the sensor can measure acceleration, handle the recorded data, and send the results through the cellular network from the bridge site.

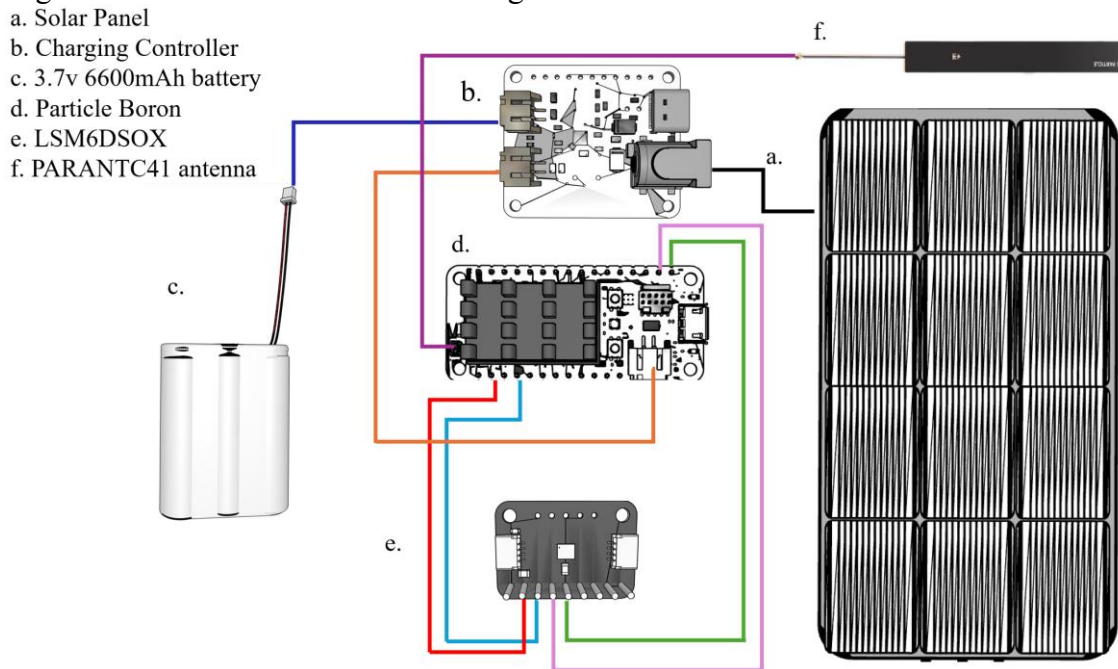


Figure 4: Hardware connection diagram of the LEWIS 7 system.

The internal components were mounted on a custom-designed 3D-printed support to keep them fixed inside the enclosure. The mount was designed to hold the components in fixed positions and reduce movement during vibration. Figure 5 shows the mount geometry used to secure the components and reduce unwanted movement during vibration.

4.2.5 Field Deployment Design

The electronics are placed inside a weather-resistant box for outdoor use. The sensor is fixed inside the enclosure so that its orientation does not change during monitoring. The enclosure and mounting components were kept simple to reduce cost and make the system easier to assemble and install in the field.

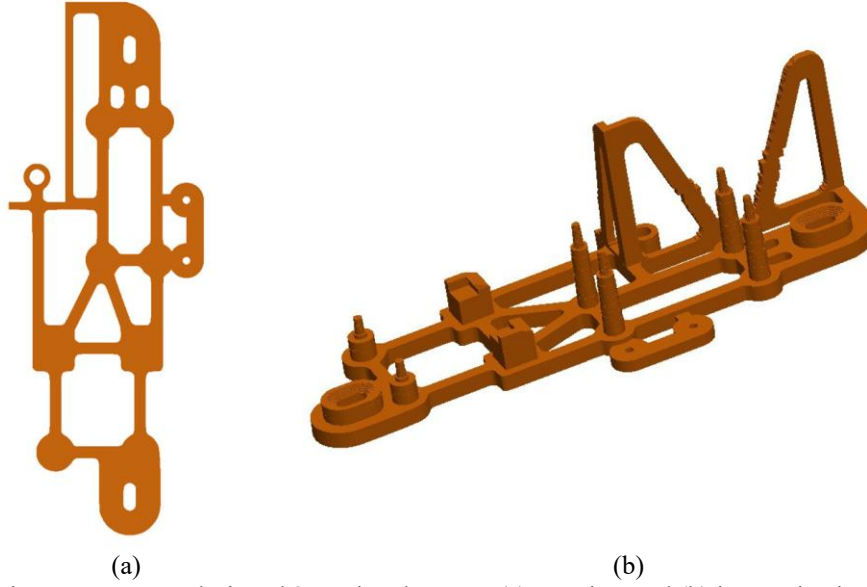


Figure 5: Custom-designed 3D-printed mount; (a) top view and (b) isometric view.

Figure 6 shows the installation design used to attach LEWIS 7 to the timber bridge component. An ABS waterproof electrical junction box was selected as the sensor enclosure because it provides durability, water protection, heat dissipation, low cost, and ease of field installation. The cable entry is protected using an IP67-rated waterproof gland to reduce the risk of water damage during outdoor deployment. To obtain reliable acceleration measurements, the sensor must move together with the bridge component. Therefore, the installation surface was prepared before sensor placement. The timber surface was ground and leveled using a grinder and sanding wheel. A 3.2 mm steel plate was then bonded to the timber surface using wood-to-metal adhesive, and each corner was secured using 50.8 mm deck screws. The LEWIS 7 sensor was attached to the steel plate using a magnetic mount. This installation procedure reduces local mounting vibration and helps ensure that the measured acceleration represents the structural response of the bridge.

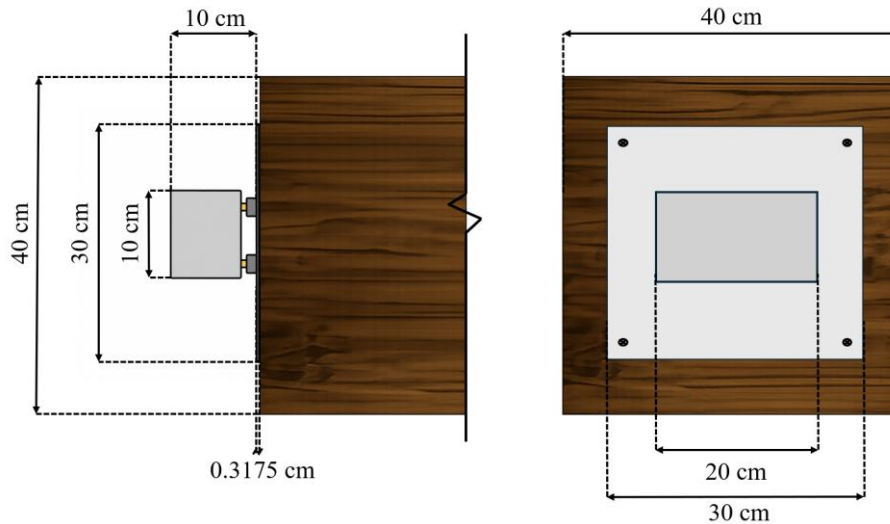


Figure 6: Installation design for LEWIS 7 on a timber bridge component using a bonded and screwed steel plate with a magnetic sensor mount.

Table 2 summarizes the time required for the LEWIS 7 field-installation procedure. The system was installed in approximately 4 minutes and 20 seconds, demonstrating that the proposed mounting method enables rapid field deployment with limited equipment and labor, which is a priority for the railroad management team as well as bridge inspectors interested in using sensors to monitor bridge displacements in their network.

Table 2: Time required for field installation of the LEWIS 7 system.

Installation activity	Description	Approximate time
Surface preparation	Grinding, sanding and leveling the timber surface	120 seconds
Steel-plate installation	Applying the wood-to-metal adhesive for the steel plate	60 seconds
Mechanical fastening	Securing the steel plate using four deck screws	40 seconds
LEWIS 7 attachment	Attaching the enclosure to the plate using the magnets	10 seconds
System check	Confirming cellular connection and data recording	30 seconds
Total installation time	Complete field installation	4 mins 20 seconds

4.3 Software

4.3.1 Energy Harvesting

The LEWIS 7 power system combines a rechargeable 6,600 mAh lithium battery, a solar panel, and event-triggered operation in which the node wakes only to capture and transmit data during a train passing. Node consumption was measured directly in the laboratory with an inline USB power meter. The cellular modem on the Particle Boron is the largest power user, and it draws more current when transmitting often and less when idle. A short measurement would therefore miss this variation, so consumption was logged over a three-hour run with two transmission events per hour. The node drew 108 mAh, an average of about 36 mA at the 5 V bench supply.

Translating this to battery demand requires two corrections: the 3.7 V battery supplies proportionally more current than the 5 V source (a factor of $5/3.7 \approx 1.35$, giving ≈ 49 mA), and the 3.7 V regulator is not perfectly efficient (a 20% allowance is applied). On this basis, the battery alone supports roughly 108 to 136 hours of operation on a full charge, with no solar input. In the field, however, the deployed node has operated continuously for more than six months without recharging or maintenance, each train passing confirmed by live receipt of the transmitted record at the server. Because this far exceeds the battery-only estimate, the solar panel sustains day-to-day operation while the battery buffers at nighttime and low-light periods. This solar-assisted strategy is consistent with earlier results in the LEWIS program. Solar-charged low-cost nodes have remained operational across a multi-month remote deployment [66]. The objective is to sustain low-maintenance operation on hard-to-reach railroad bridges.

4.3.2 Data Collection from the Field

The accelerometer was selected based on three main considerations: its ability to capture the vibration levels expected during train passages on railroad bridges, its suitability for low-power operation, and its low cost. To reduce unnecessary energy consumption and data storage, the sensor remains in sleep mode when no significant vibration is detected and activates only when the measured acceleration exceeds a predefined trigger threshold.

The threshold-based event detection concept is illustrated in Figure 7. The system continuously monitors the measured acceleration and compares it with a threshold value of 25 mg (0.245 m/s^2). When the acceleration remains below this threshold, no event is recorded. Once the measured response exceeds the threshold, the system records acceleration data for a 5 s window. This threshold was selected based on laboratory testing so that recording begins once the bridge response exceeds the minimum vibration level of interest. The 5 s recording duration was selected based on the train speed and train configuration considered in this study, for which the train passage at the sensor location was typically shorter than this interval.

The operational sequence of the sensing and triggering process is shown in Figure 8. After startup, the firmware initializes the cellular modem and enters a connection check routine. Connection attempts are issued repeatedly over a limited interval, with short low-power pauses between attempts to limit current draw. Once a cellular connection is established, the system checks the sensor status and begins monitoring bridge vibration. If the measured acceleration exceeds the trigger threshold, the sensor records the event, compresses the collected data, and then returns to a low-power state after data handling is completed.

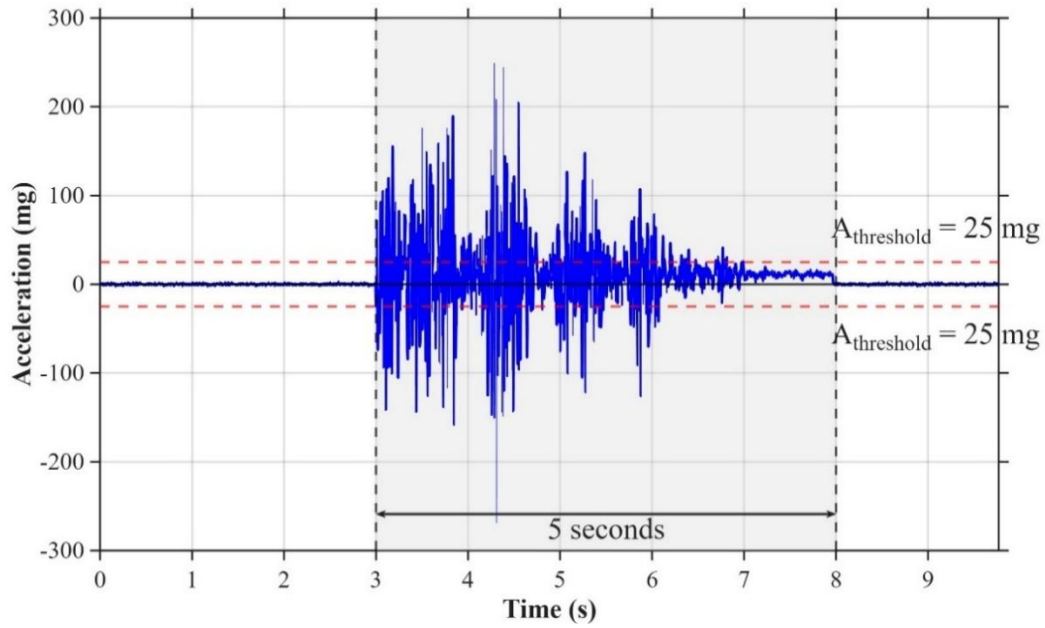


Figure 7: Threshold-based trigger used by the LEWIS 7 sensor.

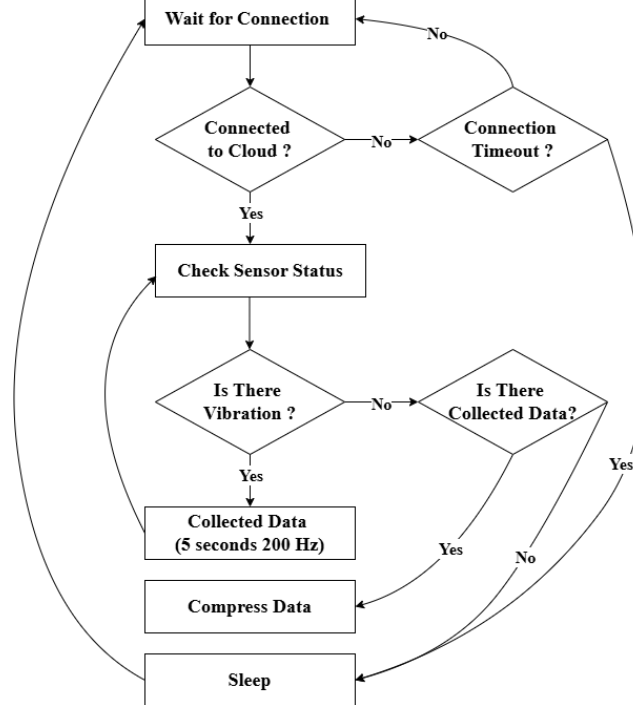


Figure 8: Flowchart of the LEWIS 7 sensing and event-triggered data collection process.

The data publishing and transmission sequence is shown separately in Figure 9. Once compressed data are available, the system prepares the data for upload and transmits the recorded event to the remote server in chunks through the cellular network. After each chunk is sent, the firmware waits for a published response and checks whether additional data remains in the queue. If more data is available, the system continues transmitting until the full event has been delivered. After successful transmission, the device returns to sleep mode and remains ready for the next train event.

4.3.3 Wireless Transmission

The proposed monitoring system uses a cellular-based data transmission architecture to enable remote access to structural response data without reliance on site-specific internet infrastructure. This design allows deployment at railroad bridge sites where wired internet or local wireless gateways are not available, which is typical for many rural corridors.

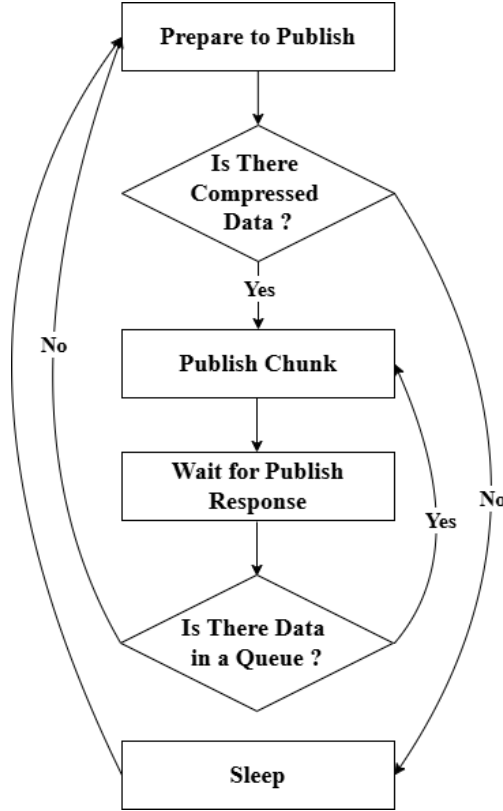


Figure 9: Flowchart of the LEWIS 7 data publishing and transmission process.

Following transmission from the sensor, data is routed through the cellular network to a Particle Cloud that manages message delivery between the sensor node and the back-end server. In the present implementation, this intermediate layer is used to forward event-based data packets rather than continuous data streams, which limits communication overhead and cellular usage. This approach eliminates the need for on-site data loggers and reduces field maintenance requirements associated with wired or gateway-based systems.

When a cellular connection is available, the sensor transitions from idle monitoring to event-based data handling. During train passages, acceleration response data associated with each event is recorded and subsequently transmitted through the cellular network for remote access. Based on field testing, the cellular transmission rate is approximately 1 kB/s, while the recorded event files in this study were typically between 4 and 6 kB. As a result, the end-to-end data transmission process, from event completion to data availability on the server, generally requires about 5 s, with observed variations of ± 1 s depending on cellular network conditions. The transmitted data is received and stored at the back-end server, where it is made available for visualization and review through a web-based interface. After data transfer is completed, the sensor returns to a low-power monitoring state and remains ready for subsequent train events.

4.4 System Integration Summary

The proposed end-to-end system is summarized in Figure 10. The train induced vibration record is selected for energy efficient monitoring of the rail runner train crossing event and the sequence evolves from recording, transmission, storage, server analysis, and user sharing. The implementation needs to be validated first in the laboratory (section 5) and later in the field for cost-effective railroad owner use and comparison (section 6).

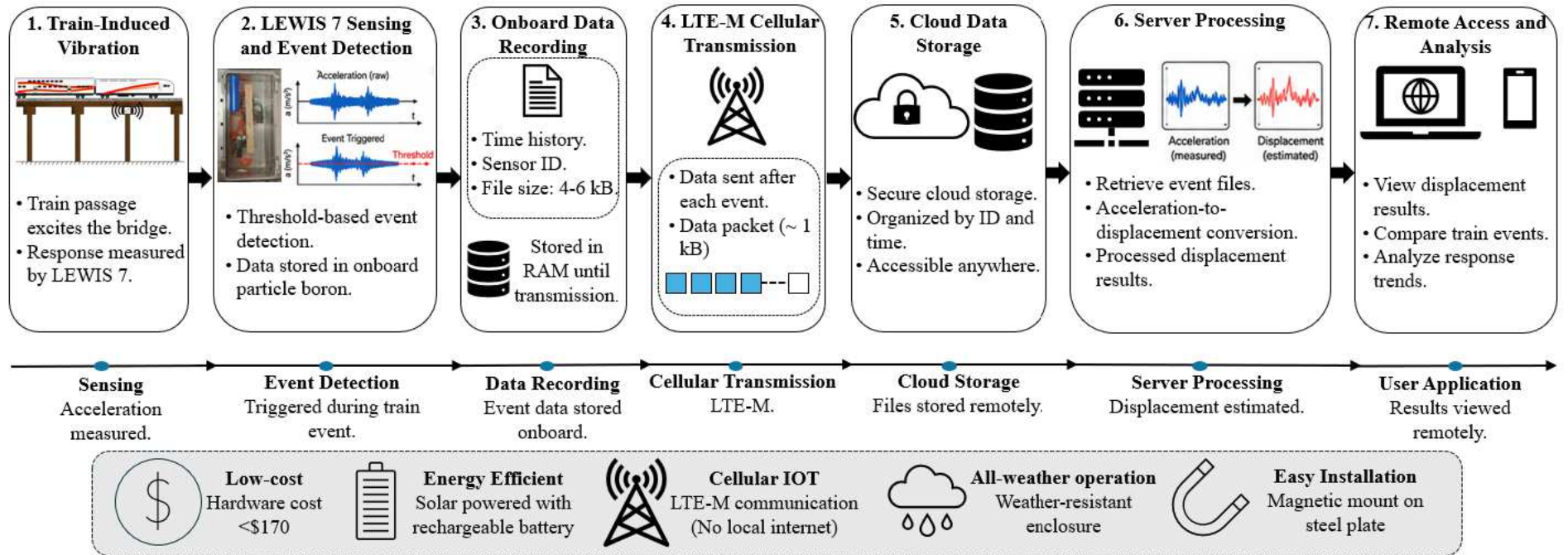


Figure 10: End-to-end data acquisition, cloud storage, server-side acceleration-to-displacement conversion, and remote analysis architecture of the LEWIS 7 monitoring system.

5 Lab Validation

LEWIS 7 was validated against Laser Doppler Vibrometer (LDV) by comparing displacement response under controlled excitation conditions. Figure 11a shows an overview of the laboratory setup. Figure 11b shows the main components used in the test, including the LEWIS 7 sensor, shaker, LDV, data acquisition system, and supporting equipment. LEWIS 7 was rigidly installed on an ELECTRO-SEIS APS-400 shaker [67] using a magnet. The sampling rate of the developed sensor was set to 200 Hz. The sensor was placed on the shaker, and the recorded acceleration data were transmitted wirelessly through the cellular network for displacement estimation.

An RSV-150 LDV from Polytec Inc. [68] was installed approximately 5 m away from the shaker to provide reference displacement measurements. The LDV output was digitized using a Dewesoft data acquisition system [69] at a sampling rate of 500 Hz. The input excitation signal used to drive the shaker and generate horizontal motion was controlled using a Vib-Pilot data acquisition system [70].

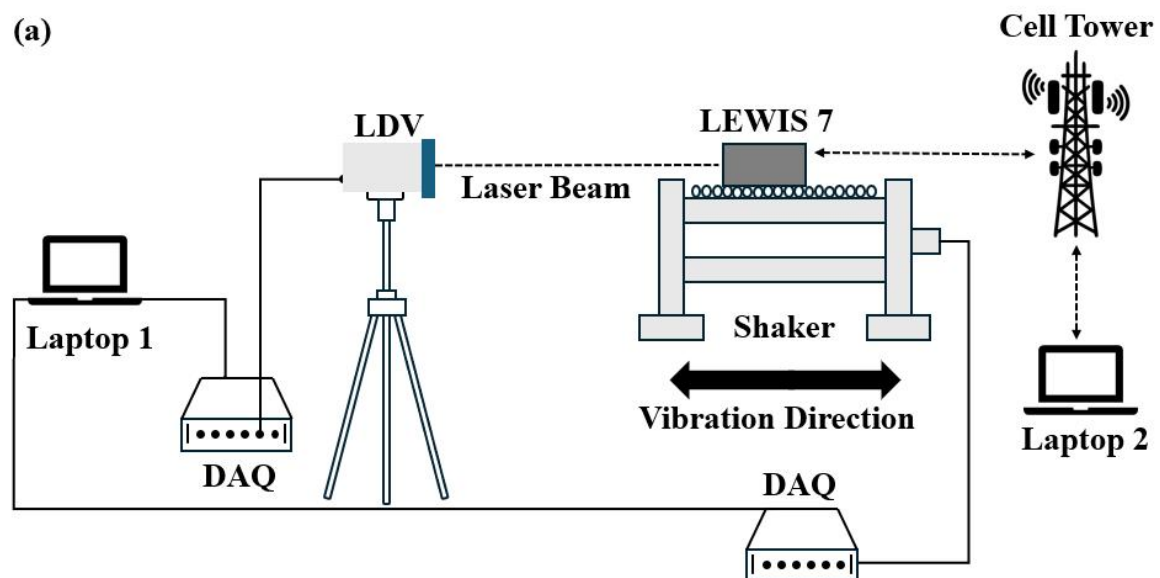


Figure 11: Experiment setup on shaker: (a) overview of sensor setup and (b) the LEWIS 7 sensor, data acquisition device, LDV used in this test, APS-400 Electro Seis shaker, and supporting equipment.

Two laboratory tests were conducted to evaluate the displacement estimation performance of LEWIS 7. In the first test, a 40 s sine sweep excitation ranging from 3 to 10 Hz was applied to the shaker. In the second test, a 40 s random excitation within the same frequency range of 3 to 10 Hz was used. The displacement responses estimated by LEWIS 7 and measured by LDV are compared in Figure 12 and Figure 13.

The results show that the displacement response estimated by LEWIS 7 was in good agreement with the reference displacement measured by the LDV. The comparison was evaluated using the root mean square error (RMSE) and the absolute maximum displacement difference. For the sine sweep excitation, the RMSE and absolute maximum displacement difference were 0.05 mm and 0.04 mm, respectively. For the random excitation, the RMSE and absolute maximum displacement difference were 0.05 mm and 0.14 mm, respectively, as summarized in Table 3.

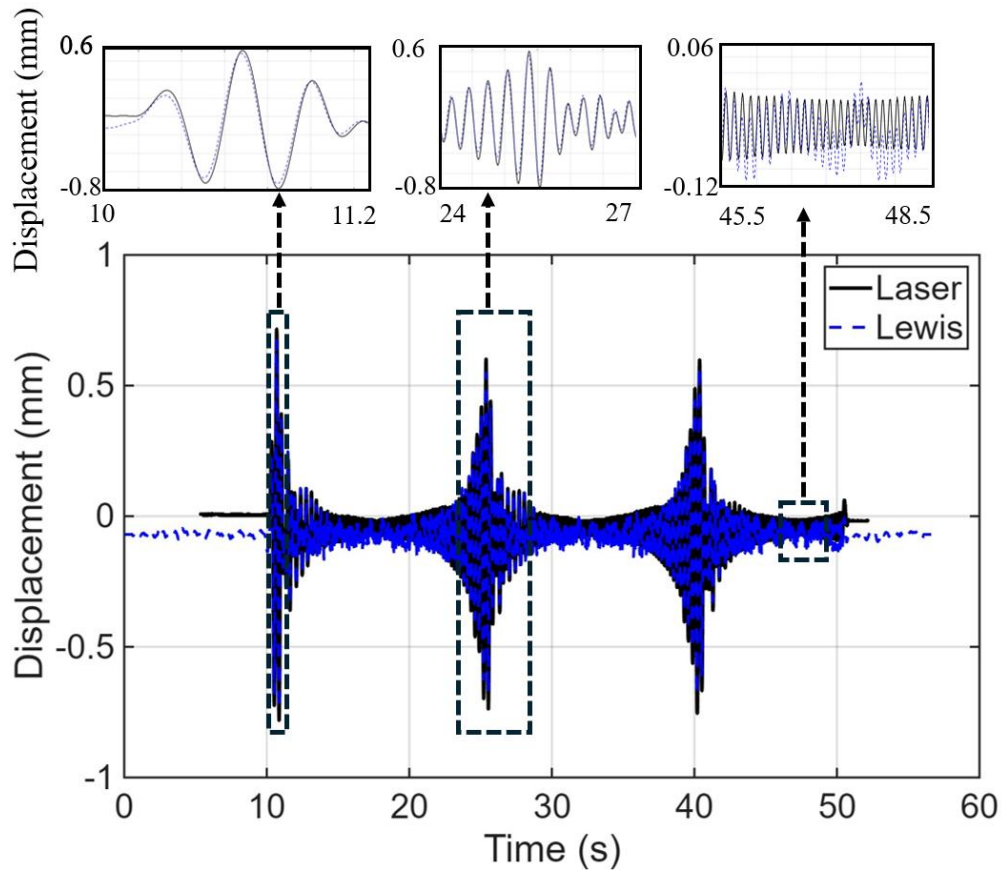


Figure 12: Displacement comparison between LEWIS 7 and LDV under sine sweep excitation.

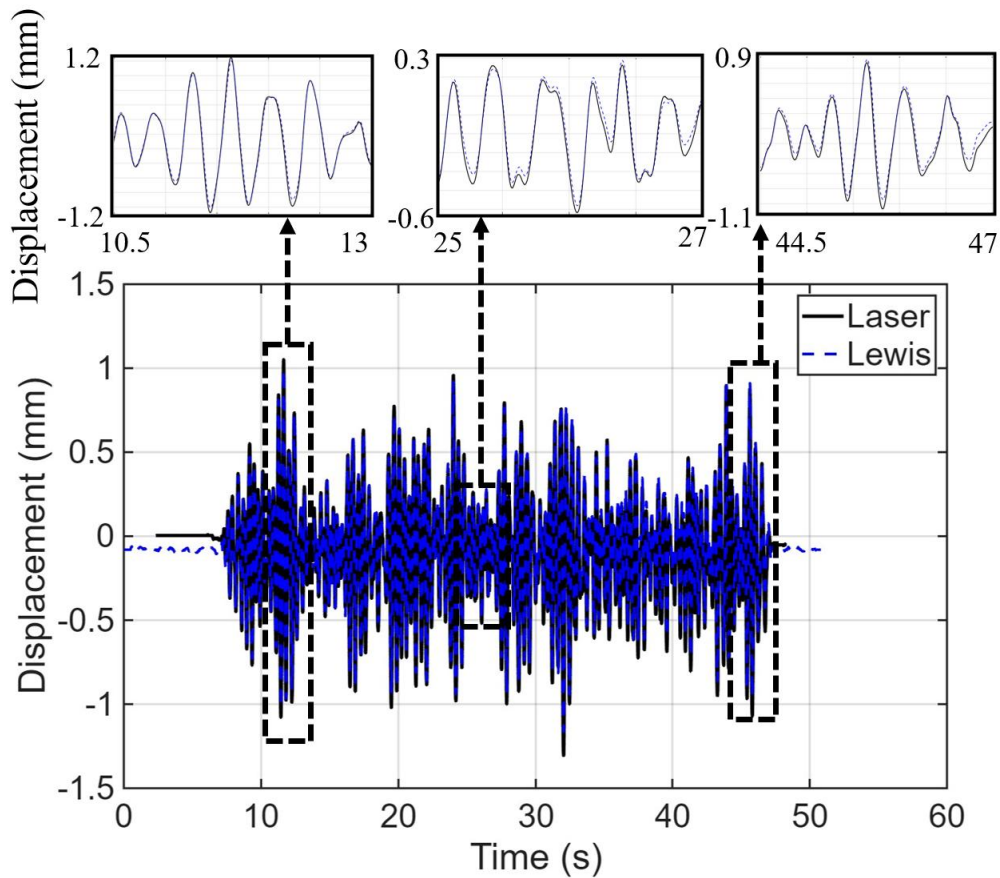


Figure 13: Displacement comparison between LEWIS 7 and LDV under random excitation.

Table 3: Comparison of maximum absolute displacement and RMSE between LEWIS 7 and the LDV reference measurement under sine sweep and random excitation.

Type of excitation	Absolute Maximum Displacement			RMSE (mm)
	LEWIS 7 (mm)	LDV (mm)	Error (mm)	
Sine Sweep	0.73	0.78	0.05	0.05
Random	1.16	1.30	0.14	0.05

The laboratory tests established that LEWIS 7 reconstructs displacement to within sub-0.06 mm RMSE under known excitation and a fixed, ideal mounting condition. Similarly, the data acquisition and transmission were successfully tested in the server and user end. However, laboratory validation cannot reproduce the field variables that most affect estimation accuracy, communication reliability, and energy consumption under multiple train crossing events, making field evaluation a priority for the practical implementation of this SHM system in industry. The field deployment was therefore designed to demonstrate operation and to also test whether the accuracy established in the laboratory persists when these uncontrolled variables are introduced.

6 Field Deployment Validation

6.1 Field setup

To evaluate the field performance of LEWIS 7 under real operating conditions, the sensor was deployed on a timber railroad bridge in Albuquerque, New Mexico. The field setup is shown in Figure 14.



Figure 14: Field validation setup on a timber railroad bridge; (a) laser and sensor relative view from the upstream; (b) railroad crossing event validation monitoring.

Figure 15 shows the bridge consisting of 12 spans supported by 11 piers. LEWIS 7 was installed on pier cap number 7, approximately 2.4 m above ground, to measure the transverse response of the bridge during train crossings.

A Polytec RSV-150 LDV was positioned on the ground approximately 5 m from the sensor and used as the reference displacement measurement system. The LDV beam and the LEWIS 7 sensor were aligned at the same measurement level, so no inclination correction or geometric projection was required. The train consisted of four cars with total length approximately 104 m and travelled at approximately 33.5 m/s (121 km/h).

This study investigates the performance of the railroad timber bridge selecting different traffic directions and weather conditions. In particular, we collected three different train-crossing events that enable the comparison of railroad bridge performance: one southbound crossing (Test 1) and two northbound crossings (Test 2 and 3). Tests 1 and 2 were conducted

on May 20, 2026, while Test 3 was conducted on January 30, 2026. This design enables a controlled, repeatable comparison in which each LDV-referenced event serves as an independent replication of the displacement-estimation method under a distinct operating condition. It also establishes a replicable field validation methodology by demonstrating the system's performance and providing a framework that can be consistently applied for future, more extensive monitoring campaigns across different bridge types and operating conditions.

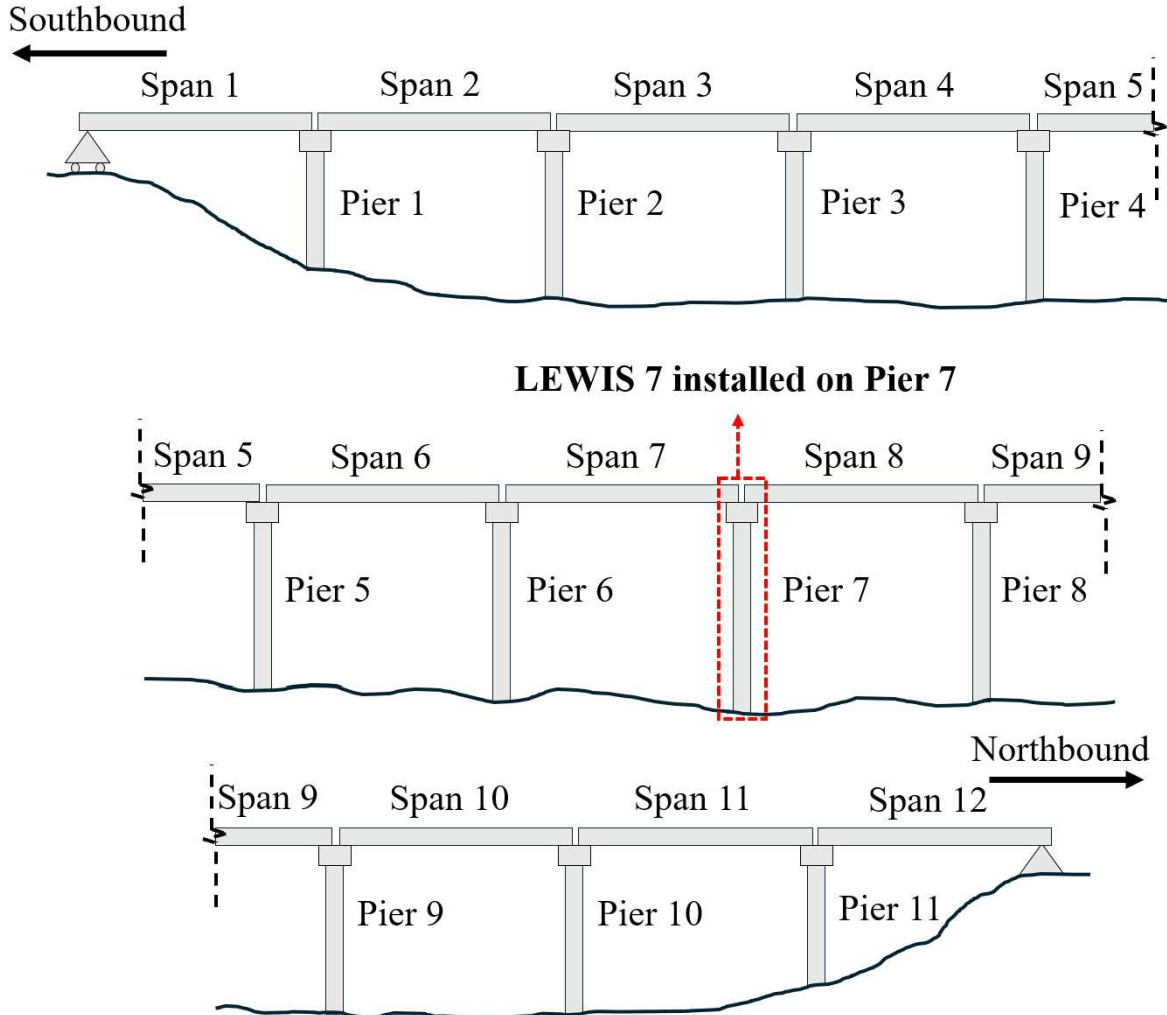


Figure 15: Layout of the timber railroad bridge showing the span configuration and LEWIS 7 installation location.

6.2 Test 1

Figure 16 shows the time-domain displacement response estimated by the LEWIS 7 compared with the LDV reference measurement for Test 1. This test was conducted during a southbound Rail Runner train passage on May 20, 2026. The bridge response was small, with a peak-to-peak displacement on the order of approximately 1 mm. Even at this small displacement level, LEWIS 7 followed the general response trend measured by the LDV and captured the primary transverse bridge response during the train crossing.

Figure 17 shows the corresponding frequency-domain comparison. Both LEWIS 7 and the LDV captured the dominant low-frequency bridge response. Small differences were observed between the two measurements, but LEWIS 7 identified the primary frequency content of the bridge response during the train passage.

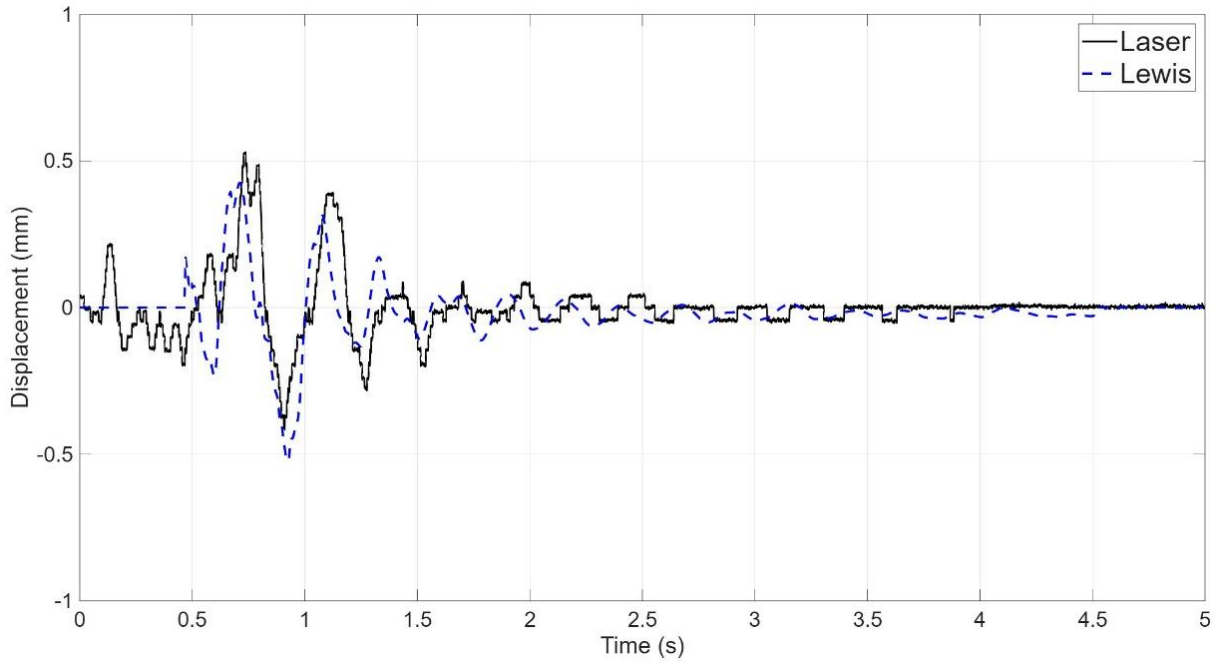


Figure 16: Test 1 time-domain comparison between LEWIS 7 and LDV reference measurement.

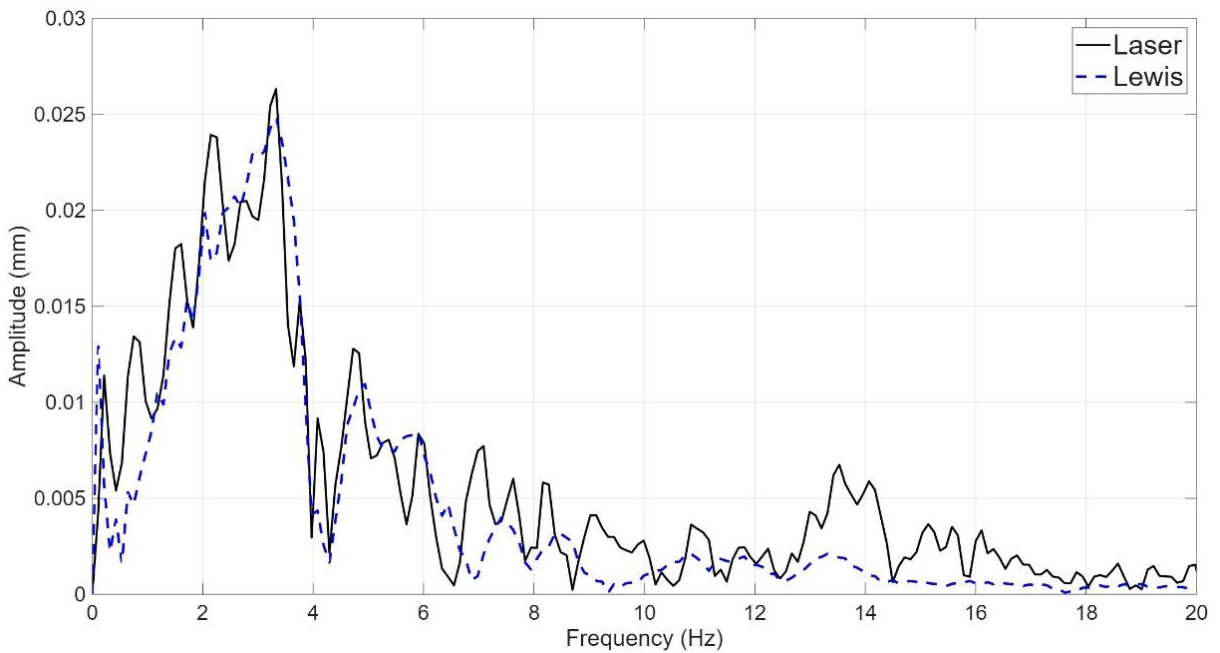


Figure 17: Test 1 frequency-domain comparison between LEWIS 7 and LDV reference measurement.

6.3 Test 2

Figure 18 shows the time-domain displacement comparison between LEWIS 7 and the LDV reference measurement for Test 2. This test was conducted during a northbound Rail Runner train passage on May 20, 2026. Similar to Test 1, the measured bridge displacement was small, and LEWIS 7 captured the main displacement trend observed by the LDV measurement.

The agreement between the two responses indicates that LEWIS 7 can provide repeatable displacement estimation under a different train direction on the same day. This result is important because the bridge response may vary depending on train direction, loading condition, speed, and operational variability.

Figure 19 shows the corresponding frequency-domain comparison for Test 2. Both LEWIS 7 and the LDV reference measurement identified the same dominant frequency peak, showing strong agreement in the frequency-domain response.

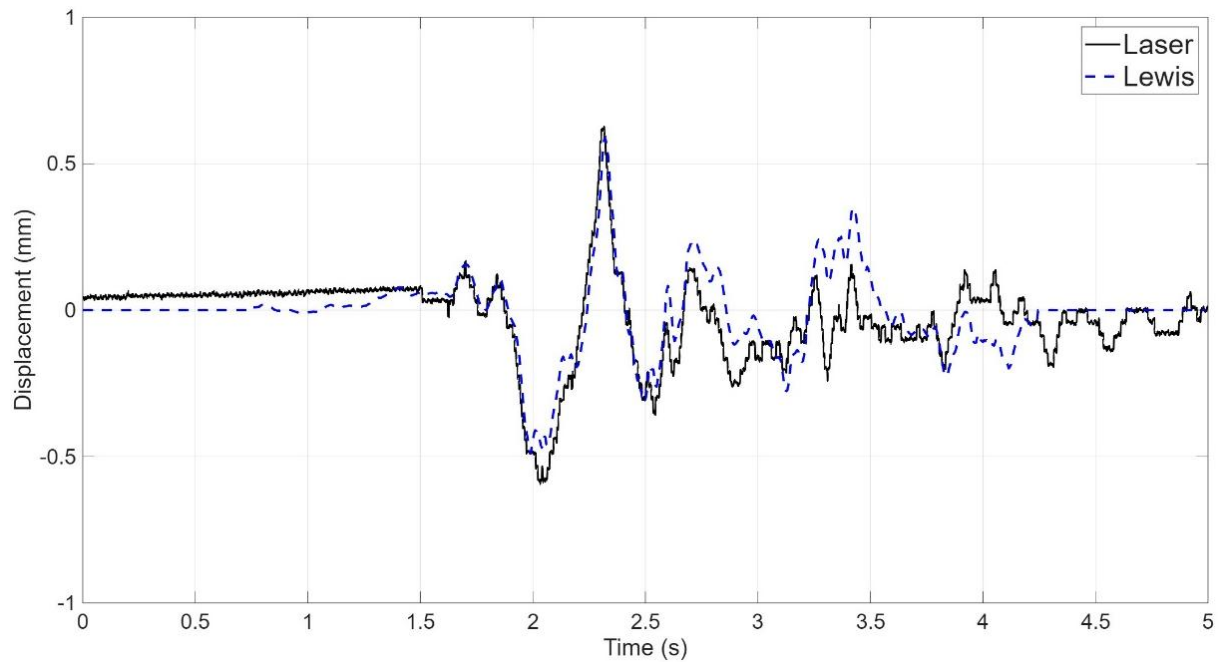


Figure 18: Test 2 time-domain comparison between LEWIS 7 and the LDV reference measurement.

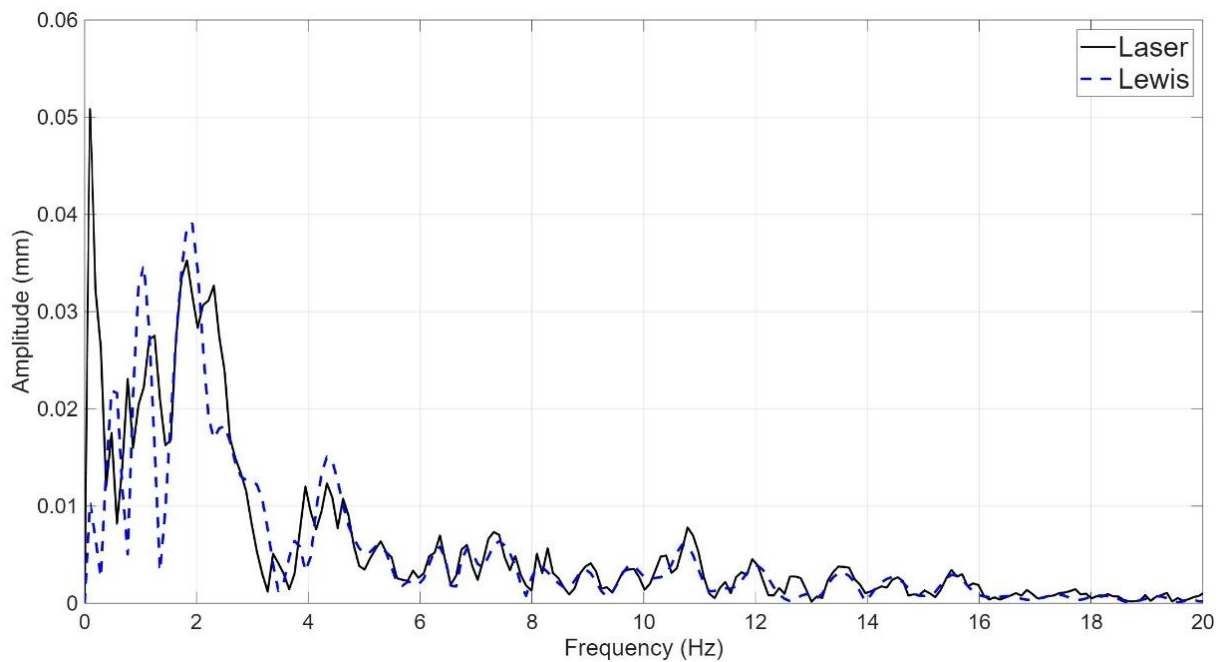


Figure 19: Test 2 frequency-domain comparison between LEWIS 7 and LDV measurement.

6.4 Test 3

Figure 20 shows the time-domain displacement comparison between LEWIS 7 and the LDV reference measurement for test 3. This test was conducted during a northbound Rail Runner train passage on January 30, 2026. LEWIS 7 captured the main displacement trend measured by the LDV, with small differences in local amplitude.

This test is important because it was conducted several months before the May 2026 tests. The agreement observed in the January and May tests indicates that LEWIS 7 can provide repeatable displacement estimates across independent field events collected during separate field campaigns.

Figure 21 shows the corresponding frequency-domain comparison for Test 3. Both LEWIS 7 and the LDV measurement identified the same dominant peak frequency.

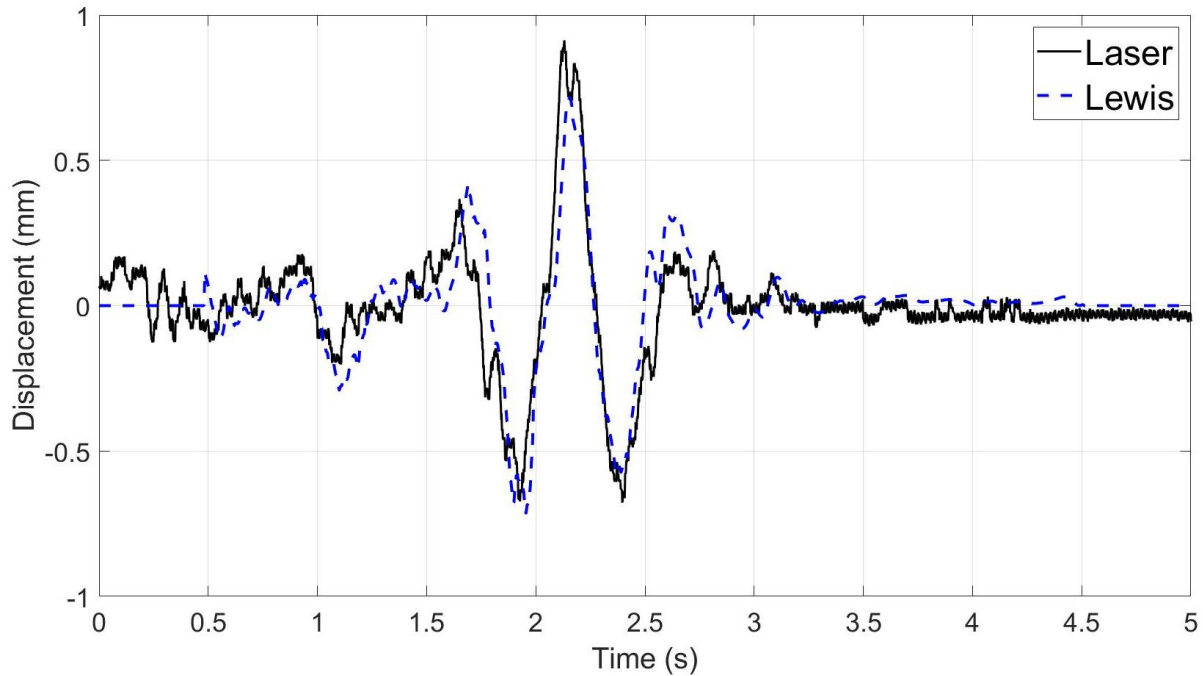


Figure 20: Test 3 time-domain comparison between LEWIS 7 and LDV reference measurement.

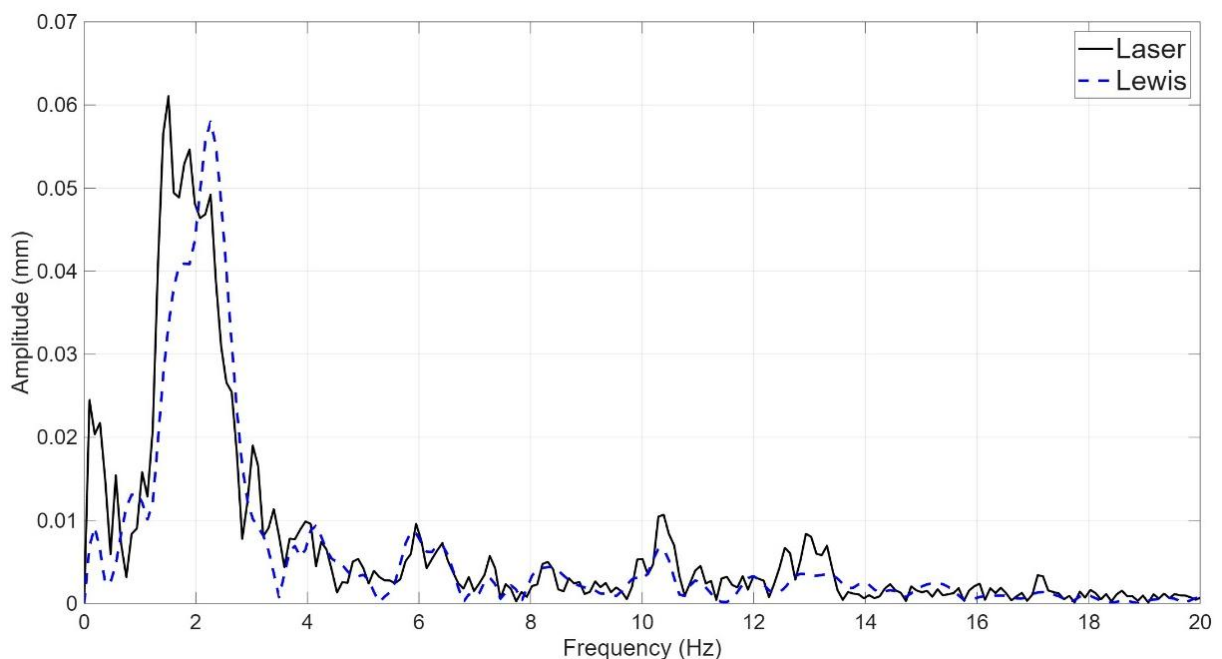


Figure 21: Test 3 frequency- domain comparison.

6.5 Summary of Field Validation

The three field validation tests demonstrate the ability of LEWIS 7 to estimate railroad bridge displacement under live train loading. Test 1 was conducted during a southbound train crossing

on May 20, 2026. Test 2 was conducted during a northbound train crossing on May 20, 2026. Test 3 was conducted during a northbound train crossing on January 30, 2026. Therefore, the validation includes different train directions, independent train events, and measurements collected across multiple months.

Across the three tests, LEWIS 7 showed good agreement with the LDV reference measurement in both the time and frequency domains. Table 4 shows the peak-to-peak displacement error ranged from 0.00 mm to 0.13 mm, while the RMSE ranged from 0.07 mm to 0.25 mm. The lowest errors occurred for the northbound May crossing, and the highest for the northbound January crossing, indicating that estimation error scaled with response amplitude and could be potentially affected by temperature rather than with train direction: the January event produced the largest peak-to-peak displacement (1.57 mm) and correspondingly the largest absolute error. All three errors remained under approximately 10% when normalized by the measured peak-to-peak displacement, indicating that relative accuracy was maintained even as the response magnitude varied. The acceleration-to-displacement estimation method introduces uncertainty because displacement is reconstructed from acceleration rather than measured directly. In this study, the field comparison with the LDV reference measurement showed displacement-estimation errors on the order of approximately 20% for small-amplitude (~ 1 mm) bridge responses. These differences may be attributed to signal processing, low-frequency drift, field noise, time synchronization, event-window assumptions, and sensor installation conditions. Even at this level, the estimates captured the peak-to-peak magnitude, dominant frequency, and overall response trend that owners rely on for tracking bridge behavior, quantities for which a 20% tolerance on a sub-millimeter response is sufficient to distinguish normal from anomalous crossings.

Table 4: Time-domain comparison of peak-to-peak displacement and RMSE between LEWIS 7 and LDV reference measurements during live train loading.

Train Direction	Time	Peak-to-Peak Displacement (mm)			RMSE (mm)
		LEWIS 7	Laser	Error	
Southbound	May 20, 2026	1.19	1.09	0.10	0.18
Northbound	May 20, 2026	0.91	0.92	0.00	0.07
Northbound	January 30, 2026	1.57	1.43	0.13	0.25

Table 5 shows the frequency-domain comparison, where the dominant-frequency error ranged from 0.00% to 11.10%, and the displacement-amplitude error ranged from 1.14% to 16.04%. The two northbound events reproduced the dominant frequency exactly (0% error), while the southbound event showed an 11.10% deviation, suggesting that directional differences influenced frequency identification more than amplitude estimation. Amplitude errors were larger than frequency errors across all tests, consistent with the acceleration-to-displacement reconstruction being more sensitive to low-frequency energy content than to the location of the dominant spectral peak. The exact frequency agreement in two of three events indicates that LEWIS 7 reliably captured the primary dynamic characteristic of the bridge, which is the quantity of greatest interest for condition tracking.

Table 5: Frequency-domain comparison of dominant frequency and displacement amplitude between LEWIS 7 and LDV reference measurements during live train loading.

Train Direction	Time	Frequency (Hz)			Amplitude (mm)		
		LEWIS 7	Laser	Error (%)	LEWIS 7	Laser	Error (%)
Southbound	May 20, 2026	1.93	1.73	11.10	0.03	0.03	13.15
Northbound	May 20, 2026	3.33	3.33	0.00	0.02	0.02	1.14
Northbound	January 30, 2026	2.27	2.27	0.00	0.05	0.04	16.04

In each of the three validation events, LEWIS 7 reproduced the displacement response measured by the LDV with similar accuracy, regardless of train direction or deployment date. This event-to-event consistency, while based on a small sample, is a positive indicator of the reliability of the approach in field conditions. The agreement observed for northbound and southbound train crossings indicates that LEWIS 7 can provide stable displacement estimates

under realistic railroad bridge operating conditions. Although the present quantitative validation is limited to three LDV-referenced train crossings, the results demonstrate the feasibility of LEWIS 7 for multi-month field deployment and support its potential for long-term railroad bridge monitoring.

7 Discussion

Several limitations should be considered. First, the recording capacity is limited by the available RAM on the Particle Boron because an external SD card was not included in the current design. In the current implementation, this limits each recorded event to approximately 10 s. This recording duration was sufficient for the passenger train events considered in this study; however, it may not be long enough to capture longer freight train crossings. The decision not to include an external memory card was made to reduce system cost, simplify the hardware, and avoid adding another component that could increase the possibility of hardware failure during field deployment.

Second, the current battery configuration may not be suitable for very busy rail corridors or long freight trains, where frequent or extended recording events would increase power demand.

Third, the LEWIS 7 system was designed to capture bridge response only during train-passing events, rather than continuously monitoring the complete structural behavior of the bridge. Therefore, each event is processed as an individual dynamic response window, and the displacement estimation assumes that the bridge starts from its equilibrium position before the train passage and returns to its equilibrium position after the event. This assumption is reasonable for isolated train events but may not fully represent bridge behavior under continuous traffic, overlapping events, long-duration loading, or residual displacement effects.

8 Railroad Owner Evaluation

The New Mexico Rail Runner Express evaluated the practical value of the LEWIS 7 system from the perspective of the owner's interest. From the railroad owner's perspective, the following practical considerations were listed:

- Rapid installation and limited access time: the installation approach consisted of four steps, approximately taking 1 minute each: (1) pile cap external surface grinded prior to plate installation; (2) plate glued; (3) four screws installation; (4) sensor attached to the plate with magnets. LEWIS 7 can be installed quickly during short field access windows.
- Portability between pile caps and different bridge locations: This approach also allows the sensor to be removed and relocated easily between bridge piers and moved to other bridge sites if needed. According to the railroad, the plate can be left in the pile cap without any concern. The magnetic attachment allows the sensor to be moved from one bridge to another by removing the sensor and leaving the steel plate in place. This is useful for railroad owners because it reduces repeated installation effort and supports monitoring across multiple bridge sites.
- Low visibility and field protection against vandalism: The sensor and mounting plate were painted with a colour like the timber bridge components, making the system less noticeable during field deployment. The cables were tied and hidden behind the solar panels. This reduces the likelihood of public interference, theft, or damage while keeping the installation practical for railroad environments. The railroad is aware of the importance of preventing vandalism.
- Cellular communication without fixed internet: The LTE-M cellular communication capability eliminates the need for fixed internet infrastructure at the bridge site. This is important for New Mexico Rail Runner Express because installing fixed internet would be expensive and not scalable, as every new bridge sensing would require a dedicated router.

- Solar-assisted, optimized low-cost operation: The railroad wanted a system able to measure high volume of train crossings (as much as 30/day) without external energy. The LEWIS 7 low-cost, solar-assisted, power optimized sensing design proved energy efficiency both in winter and summer seasons. The energy-efficiency of the system is important for railroad owners because bridge access is limited and repeated maintenance visits can be costly and difficult to schedule around train operations.
- Displacement-based information: Railroad owners were interested in displacement response as a measure of train crossing behavior and serviceability. The LEWIS 7 system provides acceleration-based displacement estimates, which according to the owners can assist to better understand bridge behaviour over time. The Railrunner is interested in comparing the following: peak-to-peak displacements, differences between Northbound and Southbound, effect of velocity on displacements, effect of seasons on displacement. The collection of bridge displacements is of interest to the Railrunner.
- Validation with reference instrumentation: The comparison with LDV measurements provides an initial level of confidence in the sensor results which increases the trust of the Railrunner engineers in the LEWIS 7 displacement estimations. This validation is important from the owner perspective because it helps demonstrate that the displacement estimates from LEWIS 7 are reasonable and can be used as practical field data. In order to satisfy the Railrunner, we collected displacements at three different times from the same railroad bridge for validation purposes.

Table 6 summarizes the railroad owner evaluation by linking the main owner requirements, the corresponding LEWIS 7 capabilities, and future improvements needed for broader field implementation. Based on the Rail Runner evaluation, LEWIS 7 is a good monitoring tool that can inform subsequent detailed bridge inspection or high-precision reference instrumentation if required from the displacement data. The system can help railroad owners observe bridge global response trends, compare displacement responses across train events, organize bridge response data into meaningful groups, and identify bridges that may require additional evaluation. Future owner-focused improvements include longer recording duration for various freight trains, longer onboard train-crossing recording capabilities for freight trains of 1.6-3.2 km long, additional power capabilities for sites with high traffic demand, additional field validation events in three measurement directions, and deployment across multiple bridge types and operating conditions.

Table 6: Railroad owner evaluation of LEWIS 7.

Owner Requirement	LEWIS 7	Future Improvement
Rapid installation	Four-step installation completed within a short access window (<5min)	Further simplify mounting
Portability	Magnetic attachment allows relocation between bridge locations	Develop mounts for other bridge types
Low visibility	Sensor and cables were concealed to reduce vandalism risk	Add stronger protection where needed
Remote communication	LTE-M removes the need for fixed internet or a local gateway	Evaluate performance in low-signal areas
Low-maintenance power	Solar charging and sleep mode supported multi-month operation	Increasing power capacity for busy corridors
Displacement information	Provides Peak-to-peak displacement and event comparison	Establish normal ranges and alert threshold
Validation	Compared with LDV during three train crossing	Add more tests and bridge locations
Extend event monitoring	Current recording duration captured the evaluated train events	Increase storage and recording duration

9 Conclusion

This study summarizes the development of a LEWIS 7 sensing system to support long-term event-based monitoring of railroad bridges. The main contributions of this study were the development of a low-cost wireless sensing system, the integration of LTE-M cellular communication for remote data transmission, the use of event-triggered recording to reduce power consumption and data storage, and the implementation of an acceleration-based displacement estimation approach to measure bridge displacement. Laboratory and field tests were conducted to evaluate the performance of the LEWIS 7 system. The sensor was first validated in the laboratory using controlled sine sweep and random excitation tests, where the displacement estimated by LEWIS 7 showed good agreement with the LDV reference measurements. The system was then deployed on a timber railroad bridge under live train loading, where it successfully captured small transverse displacement responses on the order of approximately 1 mm.

The field validation tests were conducted during independent train-crossing events in January and May 2026, including both northbound and southbound train passages. The agreement observed between LEWIS 7 and the LDV reference measurements across these separate field tests provides preliminary evidence of consistent sensing performance across separate field deployments. These results support the feasibility of LEWIS 7 as a low-cost, portable, energy harvesting, and easily deployable sensing platform for railroad bridge displacement monitoring under field operating conditions.

Future work will include additional field validation over longer monitoring periods, different bridge types, train directions, train speeds, and environmental conditions to further evaluate the repeatability and robustness of LEWIS 7. Future versions of the system may also include additional sensing capabilities, such as strain measurement, to provide a more complete assessment of railroad bridge behavior.

Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

Acknowledgments

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