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Low-cost, efficient wireless intelligent sensors (LEWIS) measuring real-time reference-free dynamic displacements

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ABSTRACT

According to railroad managers, displacement of railroad bridges under service loads is an important parameter in the condition assessment and performance evaluation. However, measuring bridge responses in the field is often costly and labor-intensive. This paper proposes a low-cost, efficient wireless intelligent sensor (LEWIS) platform that can compute in real-time the dynamic transverse displacements of railroad bridges under service loads. This sensing platform drives on an open-source Arduino ecosystem and combines low-cost microcontrollers with affordable accelerometers and wireless transmission modules. The proposed LEWIS system is designed to reconstruct dynamic displacements from acceleration measurements onboard, eliminating the need for offline post-processing, and to transmit the data in real-time to a base station where the inspector at the bridge can see the displacements while the train is crossing, or to a remote office if so desired by internet. Researchers validated the effectiveness of the new LEWIS by conducting a series of laboratory experiments. A shake table setup simulated transverse bridge displacements measured on the field and excited the proposed platform, a commercially available wired expensive accelerometer, and reference LVDT displacement sensor. The responses obtained from the wireless system were compared to the displacements reconstructed from commercial accelerometer readings and the reference LVDT. The results of the laboratory experiments demonstrate that the proposed system is capable of reconstructing transverse displacements of railroad bridges under revenue service traffic accurately and transmitting the data in real-time wirelessly. In conclusion, the platform presented in this paper can be used in the performance assessment of railroad bridge network cost-effectively and accurately. Future work includes collecting real-time reference-free displacements of one railroad bridge in Colorado under train crossings to further prove LEWIS' suitability for engineering applications.

1. Introduction

Recently, the American Society of Civil Engineers (ASCE) released its 2017 Infrastructure Report Card grading the overall quality of the United States (U.S.) infrastructure as D+ [1]. According to this report, the nation's infrastructure is underinvested, in 'poor and at risk' condition, thus exhibiting significant deterioration. ASCE indicates that the existing infrastructure

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should be expanded by maintaining the current installations and building new ones to serve the increasing population and economic activity [2]. Limited investment funding is prohibitive due to funds not being available. Rehabilitating the infrastructure rapidly and prioritization of rebuilding operations calls for data-driven objective decisions. The Department of Homeland Security (DHS) considers freight rail as one of the critical infrastructures in the country [3]. Freight railroads of U.S. are known as the best in the world, operating on 140,000 miles long complex nationwide rail system [4,5]. The Federal Highway Administration (FHWA) forecasts that the demand for the freight shipment over rail will double over the next 20 years [6]. As a result, railroad experts expect that the existing network will exceed its capacity by 2035 [7]. To meet this level of demand, railroads spend $22 billion annually for maintenance and modernization of their infrastructure [8]. Railroad bridges carry 40 tons of freight per person per year and a significant portion of the investment is dedicated to the rehabilitation of them [9]. There are 100,000 bridges, and more than half are at least 100 years old [10]. The Association of American Railroads (AAR) indicates that U.S. railroads should maintain their aging bridge network continuously, to sustain their major and critical role in freight shipping industry [11]. In the last two decades, Structural Health Monitoring (SHM) of critical infrastructure has become one of the main research domains within the civil engineering community [12]. Collecting objective data from sensors connected to structures can be used towards establishing a baseline for informing data-driven decision-making approaches for the rehabilitation of the existing infrastructure.

Due to limited funding and resources, railroads need to prioritize maintenance, repair, and replacement (MRR) of bridges to assure safe, reliable, and cost-effective railroad network operations. Current prioritization practice imposes bridges to be visually inspected in regular periods and under loads. However, the resulting assessments may underestimate the structural capacity of bridge elements [13], may fail to detect damages [12,14] or may not provide reliable and consistent information about the dynamic performance of the bridge [15]. Furthermore, visual inspections of tall, long, and isolated bridges may be challenging since the structural members of interest are difficult to access and observe during train crossing events [16,17]. ASCE emphasizes that the civil engineers of 2025 will be "relying on and leveraging real-time access to living databases, sensors, diagnostic tools, and other advanced technologies to ensure informed decisions" for the preservation and upgrading of the infrastructural integrity [18]. Thus, railroad managers are interested in instrumenting their bridges with sensors that can provide objective measurements about the bridge performance under trains. Revenue service traffic is referred by railroads as service traffic bringing revenue to the railroad company. The main objective of railroads is to safely operate and increase their revenue service traffic. Accordingly, objective data may aid railroads in prioritizing their MRR decisions and keeping the infrastructure safe and profitable.

In recent years, measuring bridge displacements under train loadings has become a popular research topic in determining the condition of the railroad bridges and improving the safety of infrastructure [19,20]. A recent survey emphasized that railroads are interested in measuring bridge deflection under live load to inform the management of their bridge inventory and MRR prioritization [17,21]. In particular, North American railroads are interested in quantifying displacements of timber railroad bridges, since they comprise 24% of the total inventory length and MRR of timber trestles consumes as much as 40% of the total bridge-maintenance budget for some Class I railroads [22]. Therefore, the authors chose the case of timber railway bridges for this research as a first step for LEWIS validation, prior to further experimentation, including signal processing and field work in different structures in future steps. There are several monitoring approaches focusing on measuring bridge responses under revenue service traffic. For instance, Uppal et al. discussed the relationship between train speeds crossing a timber bridge and the vertical deflection of the span by measuring the responses with linear variable differential transducers (LVDTs) [22]. Likewise, Moreu et al. investigated the service condition of timber bridges by collecting transverse displacements with LVDTs [23]. However, while measuring bridge responses with traditional sensors such as LVDTs provide quantitative data about the condition of the bridges, it is relatively difficult to record such responses because a fixed reference frame to attach the sensor is rarely available [24].

Traditional monitoring approaches often employ wires to reliably collect sensor measurement and store data [25,26]. However, installation of wired sensors can be labor-intensive. For example, Celebi has estimated a cost of about $5000 (USD) per sensing channel [27]. Farrar pointed out that the cost of instrumenting Tsing Ma suspension bridge in Hong Kong with over 350 sensors may have exceeded $8 million [28]. With the rapid advancement in smart sensing and wireless communication technology in the last decade, researchers directed efforts towards the use of wireless smart sensors (WSS) to cost-efficiently monitor critical infrastructure [29–33]. One of the first known WSS for the monitoring of railroad bridges, *BriMon* is formed by Chebrolu et al. [34]. This WSS is based on the TmoteSky sensor board [35,36] and can capture bridge vibrations with a sampling rate of up to 20 Hz. Bischoff et al. developed WSS also based on the TmoteSky sensor board to measure strains of railroad bridges at a sampling rate of 100 Hz [37]. Klis et al. developed energy-efficient algorithms using spectro-temporal compressive sensing approach on WiseNode wireless nodes, a platform similar to the TmoteSky [38,39]. Hay et al. used MicroSABRE WSS for monitoring the crack growth of steel railroad bridges using acoustic emission [40]. Flammini et al. proposed a general WSS architecture called SENSORAIL, integrating multiple sensors for a future implementation of railroad infrastructure monitor [41]. Cho et al. [42] used WSS based on Imote2 [43] to obtain dynamic characteristics of a swing truss bridge. Moreu et al. [44–46] and Kim et al. [47] measured displacements of railroad bridges also with Imote2 based WSS. Wang et al. [48,49] and Hsu et al. [50] developed a wireless sensing unit based on ATmega128 microcontroller for structural health monitoring and validated the performance of the unit in a number of case studies. Many of the WSS applications discussed above are either developed in-house, are not accessible by the public, or are commercially available only at high costs. Moreover, the software support for those sensors are limited and the code is often closed-sourced. From a practical standpoint, railroads are interested in easy-to-manage WSS with small development time that can inform of the