Augmenting an existing railway bridge monitoring system with additional sensors to create a bridge weigh-in-motion system and digital twin

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ABSTRACT: Infrastructure asset managers have limited maintenance budgets and require qualitive data on the performance and utilization of their assets in order to prioritize preventative maintenance. A project investigating the potential for using digital twins for infrastructure asset management provided an opportunity to augment an already extensive fiber-optic strain-based bridge structural health monitoring system with additional sensors measuring both deck rotation and axle positions. Data from the new and existing sensors is fed to a database in near real time. In addition to a simple web-based visualization (dashboard), the data from the system can be utilized by a number of different analytical back-ends which together form a Digital Twin of the bridge. The first of these back-ends provides a bridge weigh-in-motion system, but other back ends are possible including statistical finite element analysis models or Bayesian or computer vision-based train categorization systems. This paper details the design and implementation of the augmented system including the additional hardware and software required. Constrains included the requirement to install the new sensors and cabling quickly during a time-limited overnight possession of the bridge. Challenges included the need to correctly timestamp the incoming data from the various separate sensor systems so that the results obtained could be compared and combined correctly. This paper includes some preliminary data demonstrating that the newly augmented system is capable of providing useful data to the asset owner.

KEY WORDS: Fiber-optic sensors, Railway Bridge Weigh-In-Motion, Digital Twin.

1 INTRODUCTION

In 2015, several new railway bridges, were built in Staffordshire U.K. Two of these bridges, one pre-stressed concrete, one steel – each with insitu poured concrete decks - were instrumented with Fiber-Bragg Grating (FBG) strain and temperature sensors during construction as part of a previous research project [1]. These sensors were installed partly as a sensor deployment study to investigate the feasibility of using FBG sensors in real-world infrastructure and construction, and to investigate the early behavior of these structures during construction and in early service. Later, monthly site visits were undertaken during 2017 to demonstrate the continuing functionality of the FBG sensors, and assess their ongoing potential value to the asset owner.

Later, in 2021, the addition of a permanent power supply at the bridge sites has allowed for 24/7 monitoring of the two bridges, and also made possible the installation of additional instrumentation on the steel bridge (referred to as bridge IB5) to measure tilt and vibration, and the real-time position of the train axles. A camera system was also installed to enable the identification of unusual train types. Together with the previously installed FBG sensors, these new sensors, have permitted the creation of a bridge weigh-in-motion system on bridge IB5 with data being transmitted in near real-time to a back-end database powering a digital twin system.

2 THE EXISITING MONITORING SYSTEM

The original fiber-optic monitoring system was installed during the construction of bridge IB5 in 2015. It consisted of 32 fiber-optic cables. The cables located along the longitudinal elements of the bridge each have 20 FBG sensors, while cables on elements in the transverse direction have 7 FBGs. Vertical stiffeners have between 2 and 6 FBG sensors. Both strain and temperature FBG sensors were installed [1]. In addition to sensors on the structural elements of the bridge, three railway sleepers were also instrumented with FBG sensors [2].

Figure 1. Bridge IB5

Originally, there was no permanent monitoring equipment installed on site as there was no power supply. During site visits, the FBG sensors were read using a Micron Optics sm130 interrogator, connected to a Micron Optics sm041 multiplexer. This configuration allows for 16 cables to be connected and interrogated, each at a data rate of up to 250 Hz [3]. During the monthly site visits in 2017, it was usual to obtain baseline static readings from each of the 32 cables, using a subset of 16 cables at a time. A set of 16 was then chosen for dynamic measurements during train crossings.

It had always been a goal of the original research project to permanently install the monitoring equipment on site if a continuous power supply could be provided. This would allow for continuous monitoring, albeit on a pre-chosen subset of 16 cables. Providing a power supply to the bridges proved to be considerably more difficult and expensive than originally anticipated. Despite the cost, Network Rail installed the permanent supplies in January 2021.

3 ADDITIONAL SENSORS

Recent work by O'brien *et. al* [4,5,6] had shown the potential for using rotation measurements for both influence-line based damage detection, and to implement a bridge weigh-in-motion system. This technique had been demonstrated in laboratory-scale experiments. During the installation of the permanent power supply to bridge IB5, it was necessary to close the line during an overnight possession. This provided an opportunity to add additional sensors to the existing bridge monitoring system, and thus an ideal opportunity to implement and test the bridge weigh-in-motion system on a full-scale bridge. Network Rail were agreeable, and able to accommodate access to the bridge to allow the installation additional sensors.

3.1 Accelerometers

For the rotation measurements, four Epson M-A550 QMEMS accelerometers [7] were installed. These were chosen because of their high resolution (0.002 µrad/LSB) and also because the team already had experience of using these sensors on a previous research study on Baildon Bridge, a road bridge in the U.K., where they were used to for ambient vibration monitoring to attempt to detect scour [8]. The accelerometers communicate via RS-485, and data from the sensors are read using a National Instruments cRIO 9063 with a NI 9871 RS-485 module programed to take readings from all four accelerometers simultaneously at 200 Hz.

Figure 2. Epson M-A550 Accelerometer with magnetic attachments and RS-485 cable

3.2 Laser range finders

One of the requirements of the rotation-based damage detection and weigh-in-motion technique is that the position of the axles is known. Examination of data previously collected from the FBG sensors on the structural elements of the bridge, whilst able to pick up individual train bogeys, was not thought to be of sufficient resolution to be able to detect individual axles. For this reason, laser range finders were installed at each end of the bridge in order to detect the timing of each axle entering or leaving the bridge.

The range finders used were Lightware SF30 laser altimeters [9] as shown in Figure 3, which are marketed as small, lightweight sensors for use on small drones. They provide both RS-232 and serial-over-USB interfaces, and also have an 'alarm' signal that can be activated whenever the range is below a user-set threshold – presumably intended for terrain or obstacle avoidance. The raw data from the range finders is logged using a mini-PC on site.

Four range finders were installed on the bridge, two at each end. Two are positioned to detect axles entering or exiting on the northbound track, and two detect axles on the southbound track. Due to access constraints, all the range finders are on the west side of the bridge, and northbound trains obscure line of sight to the southbound track. This is only a problem if two trains cross the bridge at once.

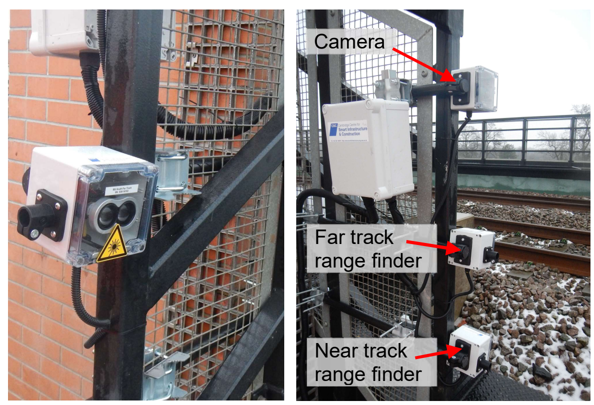

Figure 3. Laser Range Finders installed on southern end of Bridge IB5

3.3 Cameras

Two USB webcams were also installed. These were intended primarily to provide a means of checking the cause of any anomalous data received by the other sensors, for example if two trains crossed the bridge together or if an unusual type of track maintenance vehicle crossed the bridge.

4 DATA ACQUISTION AND SYNCHRONIZATION

The sm130 has 'Sync In' and 'Sync Out' coaxial connectors to allow additional sm130 interrogators to be daisy-chained while still maintaining synchronization by sending a monotonically increasing serial number with each measurement. Installing an additional sm130 would however have increased the cost of the system and required additional space in the cabinet. However, the serial number and timing signal emitted by the Sync Out connector was amenable to being decoded by a program running on a Programmable Real-time Unit (PRU) on a BeagleBone Black [10] single board computer. The LabVIEW program on the accelerometer datalogger was trivially modified to output a similar signal with a serial number for the accelerometer measurements, which is then also decoded by the BeagleBone Black. Finally, the trigger signals from the laser range finders, and a pulse-per second (PPS) signal from a GPS receiver are also fed into spare GPIO lines on the BeagleBone Black via a custom PCB, enabling a common clock to log the timing of measurements from each of the three different sensor systems.

Micron Optics supplies ENLIGHT [3], a Windows-based software package, to control the sm130 and to fetch streaming FBG sensor data. It has a number of useful functions such as being able to convert from raw FBG wavelength values to strains or temperatures, if configured appropriately, and can be configured to record data only when strain thresholds are exceeded. Unfortunately, one function ENLIGHT does not have is the ability to save the serial number of each measurement as part of the output date file. However, Micron Optics does document the API used by ENLIGHT to communicate with the sm130 (Micron Optics Inc., 2013). For this reason, a custom program was written to log data (including the serial number) from the sm130 using the documented API.

5 INSTALLATION

Cable harnesses for the new sensors were prepared prior to the overnight installation. For the north end, these cables need to be long enough to both cross the 26.8 m span of the bridge and reach the equipment cabinet via a circuitous route along the abutment wing wall. The accelerometers were magnetically mounted to the web of the west longitudinal main girder below the top flange at four locations – near the bridge ends and at the quarter and three-quarter-span positions. These sensors used RS-485 signals over Cat5e cabling, while the range finders and cameras required USB connections. As the USB-connected sensors were to be more than 5 m from the mini-PC located in the cabinet, USB-over-Cat5e adapters were used to extend the range. After the cable installation, the original equipment cabinet (which was essentially just a cable reel store) was upgraded with a new, large cabinet complete with a patch panel and 19” racking and shelving, and the fiber-optic cables were cut and re-spliced.

6 DIGITAL TWIN

Data for the accelerometers, and range finders is collected continuously and saved to non-volatile storage on site, whereas data from the FGB strain and temperature is continuously monitored but is only saved when a change in strain is detected. Data from all sensors from the relevant time period is then sent from the bridge location to a database running on an offsite dedicated server.

The database uses the open-source TimescaleDB (based on PostgresSQL) database engine and runs in a Docker container, allowing it, in principle, to be moved to a cloud service in future. The system is designed to allow further Docker containers, each with a different analytical, or modelling functionality or different data visualizations to be added into the system without affecting the others. A simple web-based dashboard allows cursory examination of the data on a per-train basis, for ease of development and debugging. The first analytical back end is the bridge weigh-in-motion system. Another planned back end is one leveraging previous work by Febrianto *et. al* [11] using the statFEM statistical FEA program and making use of both strain data from the FBG sensors and train loading data derived from the B-WIM back end allowing simulations and ‘what-if’ scenario planning based on actual measurements from the real-word structure. In general, the system can be used as a test bed for back ends trialing other analysis techniques such as Bayesian load-estimation and SVM-based train categorization. Together, these different back ends and analytical models form a digital twin of the structure.

7 PRELIMINARY RESULTS

Initial time-synchronized results from the three different sensor systems are shown in Figure 4.

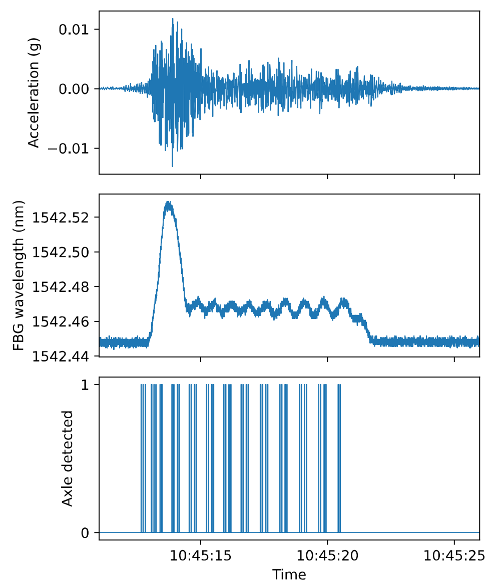

Figure 4. Initial raw data for a southbound goods train

The figure shows raw acceleration data in the longitudinal direction from the north abutment, FBG strain data from a sensor near the mid span on the east main girder (bottom) strain cable, and the axle position data from the north laser range finder.

Closer examination of the strain data shows that data from the instrumented sleepers may also be able to provide axle position data, as shown in Figure 5. However, for IB5 this would not remove the need for the laser range finders as only the northbound track has instrumented sleepers.

The laser ranger finders functioned well in good weather and were able to detect individual axles. The laser beam does however need to be aimed just above the top of the rail in order to avoid detecting the bogie structure between the axles. Further work may be needed to develop a remotely adjustable version to avoid site visits to re-align the range finders.

The bridge weigh-in-motion system has been calibrated against vehicles of known axle weight, such as the New Measurement Train and Class 70 locomotive. So far, the system shows good repeatability. Further work, such as blind testing, is needed to provide confidence that the system is functioning as intended.

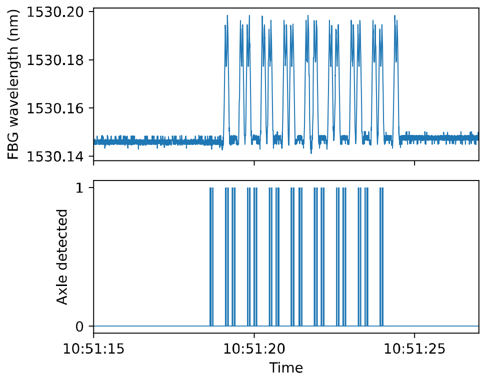

Figure 5. Data for the middle sleeper and the south laser ranger finder for a northbound passenger train

Finally, despite the low-resolution (640×480 pixels) of the videos captured by the cameras, it has been possible to use some computer vision techniques to obtain rudimentary classification of passing vehicles by type (passenger, goods, track maintenance etc.) as shown in Figure 6. Vertical strips of pixels are used to create a reference image of each train, which can then be fed to an image classifier.

Figure 6. Video processing - using vertical strips of pixels to produce reference images to be fed to an image classifier

CONCLUSION

This paper has described the installation additional sensors on and already extensively instrumented bridge. These have been time synchronized with the existing fiber-optic strain and temperature sensors using an inexpensive BeagleBone Black and some custom hardware and software. Preliminary data from the system gives confidence that the system is working as intended and will be able to meet the goal of testing a full-scale bridge weigh-in-motion system.

Data from the system is sent in near real-time to a containerized database platform which serves as the foundation of a digital twin. Open-source software has been used wherever possible, with only the data logger accelerometer sensors using National Instruments LabVIEW. The system will potentially also provide value to the asset owner by being able to provide a bridge-specific load model applicable to several bridges for use in assessments.

ACKNOWLEDGMENTS

The authors would like to thank Network Rail and particularly Kafui Klutse, Nataliya Aleksieva, George Thomson and Callum Cooper for their assistance with providing both a permanent power supply to the bridge, and for allowing trackside access in order to permit the installation of the additional sensors. We would further like to thank Dr Sam Cocking for his assistance with the sensor installation during the overnight bridge possession.

The original fiber-optic sensor installation on the bridge was carried out by Dr Liam Butler and Dr Niamh Gibbons with the assistance of He Ping and Jinlong Xu. This project would not have been possible without their previous work.

This research forms part of the Centre for Digital Built Britain's (CDBB) work at the University of Cambridge. It was enabled by the Construction Innovation Hub, of which CDBB is a core partner, and funded by UK Research and Innovation (UKRI) through the Industrial Strategy Challenge Fund (ISCF). Data supporting this paper is available from the University of Cambridge repository at https://doi.org/10.17863/CAM.82466.

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