Case Studies: Structural Health Monitoring for Real-Time Asset Management of Small Bridges

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ABSTRACT

The Smart Infrastructure group in Data61 at CSIRO has been developing new technologies for civil infrastructure monitoring and management. The main objective is to assist infrastructure owners (road and rail authorities particularly) in managing assets to support rapidly increasing traffic with an aging asset based on a limited budget. On the basis of this, Data61 has identified two small bridges in the state of New South Wales in a trial project. Both bridges have been instrumented using a variety of sensors to capture and understand the bridge behaviour. Real time monitoring data management and analysis techniques are utilised to calculate the remaining service life and remaining structural capacity, and to identify any changes in bridge behaviour over time. Several mathematical and analytical tools and algorithms have been developed and implemented to achieve these objectives. They include machine learning to identify any change in the bridge behaviour, operational modal analysis to capture the modal features of the structure, Bridge Weigh in Motion to characterise the traffic loading and to identify any overloading traffic, fatigue life analysis to count the load cycles and to estimate the remaining life of the structures. In parallel, a new system has been designed by the Smart Infrastructure group which will implement the developed algorithms and use them to monitor a number of bridges throughout Australia.

1 INTRODUCTION

Most structural and mechanical system maintenance is time-based, which an inspection is carried out after a predefined amount of time. Structural health monitoring (SHM) is a condition-based technology to monitor infrastructure using sensing systems. The potential for life-safety and economic benefits has motivated the needs for SHM, facilitating the shift from time-based to condition-based maintenance [1].

The Smart Infrastructure group in Data61 at CSIRO has been developing new technologies for civil infrastructure monitoring and management. The main objective is to assist infrastructure owners and inspectors in managing assets based on a limited budget. Our technologies have been used to monitor the Sydney Harbour Bridge, one of iconic structures in Australia. Besides, we would also like to apply the technologies to small bridges in Australia, whose fatigue life is more concerned. We have identified two small bridges in the state of New South Wales in a trial project. Both bridges have been instrumented using a variety of sensors to capture and understand the bridge behaviour. Real time monitoring data management and analysis techniques are utilised to calculate the remaining service life and remaining structural capacity, and to identify any changes in bridge behaviour over time. Several mathematical and analytical tools and algorithms have been developed and implemented to achieve these objectives. They include machine learning to identify any change in the bridge behaviour, operational modal analysis to capture the modal features of the structure, Bridge Weigh in Motion to characterise the traffic loading and to identify any overloading traffic, fatigue life analysis to count the load cycles and to estimate the remaining life of the structures.

In the following sections, these two monitored bridges and their data acquisition systems are described in Section 2. Section 3 discusses our data analysis techniques for monitoring the structures. Our software architecture for the SHM system is presented in Section 4.

2 TEST STRUCTURES

Two short span bridges have been considered and intensively instrumented to collect real data for several research purposes.

2.1 A Cable-Stayed Bridge

The first bridge is a short-span cable-stayed bridge over the Great Western Highway in the state of New South Wales, Australia (33°45'50.49"S, 150°44'31.14"E). Figure 1 shows an illustration of the bridge.

The cable-stayed bridge has a single A-shaped steel tower with a composite steel-concrete deck. The bridge is composed of 16 stay cables with semi-fan arrangement. The bridge span and the tower height are 46 m and 33 m, respectively. This bridge provides a connection between two Western Sydney University campuses over the Great Western highway and carries one traffic lane and one sidewalk. The deck has a thickness of 0.16 m and a width of 6.3 m and it is supported by four I-beam steel girders. These girders are internally attached by a set of equally-spaced floor beams as depicted in Figure 2.

(a)

(b)

Figure 1. A cable stayed bridge over the Great Western Highway NSW Australia (Ref. Google Earth), (a) side view, (b) top view.

Figure 2. Illustration of deck, steel girders and floor beams.

2.1.1 Sensor Array

A dense array of accelerometers and strain gauges along with environmental sensors has been installed on this bridge.

The measurement grid for the dynamic test consists of 29 synchronized accelerometers to measure the acceleration responses of the deck, cables and the mast. These sensors were permanently installed on the bridge in order to monitor the dynamic behavior of the bridge and to identify the modal parameters. 24 uni-axial sensors were placed under the deck at the intersection of the girders and floor beams to measure the vertical acceleration of the bridge, (see Figure 3). These sensors are low noise accelerometers with model number 2210-002 manufactured by Silicon Design, Inc (2010). The 2210-002 is a sensor that incorporates a 1210L micro-machined capacitive accelerometer. This model can detect accelerations within the range of ± 2 g with an output noise of 10 μg/√Hz and sensitivity of 2,000 mV/g. Figure 4 illustrates one of these sensors. Another four 2210-002 uni-axial accelerometers were mounted on the cables on the eastern side of the bridge. These sensors measure the acceleration response of the cables in the vertical plane orthogonal to the line of the stay. In addition, one tri-axial accelerometer (Silicon Designs 2460-002) was installed on top of the mast to measure the vertical, lateral and longitudinal acceleration responses of the tower.

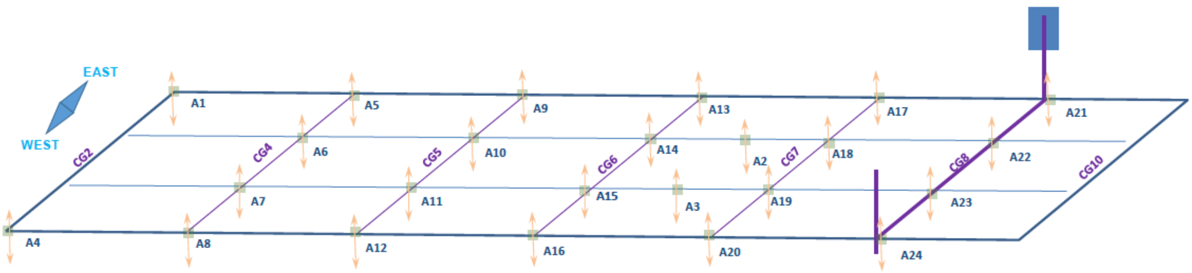


Figure 3. The accelerometer array on the deck.

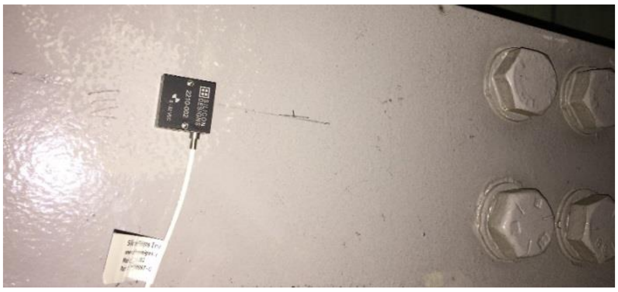


Figure 4. Illustration of the attached uni-axial accelerometer under the girder.

The bridge has been instrumented with an array of strain gauge sensors. The location of the sensors has been elaborated in Figure 5 where most of the sensors are located in between CG6 and CG7. The instrumentation array comprises of the following sensor placements,

All 8 cables have been instrumented with uniaxial strain gauges as denoted by SAi (i=23 to 30) in Figure 5. Uniaxial strain gauges SUi (i=17 to 22) have been mounted under the deck in either longitudinal or transverse directions between cross girders CG6 and CG7. The longitudinal distance between SU19 and SU22 is almost 4 m which is appropriate for calculation of speed. Strain gauges SUi (i=13 to 16) have been installed under the flange of the longitudinal girders at middle of the span between CG6 and CG7 to measure bending strains. These strain gauges are also located close to mid-span of the bridge, where large deflections are expected.

Shear rosettes have been mounted at three different longitudinal locations along the bridge; north end of the span near cross girder CG2, (north end-span of the entire bridge), bridge mid-span close to cross girder CG6 (this is also located at the north end of the span between CG6 and CG7), mid-span close to cross girder CG6, and half-way between cross girders CG6 and CG7. **Error! Reference source not found.** illustrates the sensor placements on different structural members in the bridge.

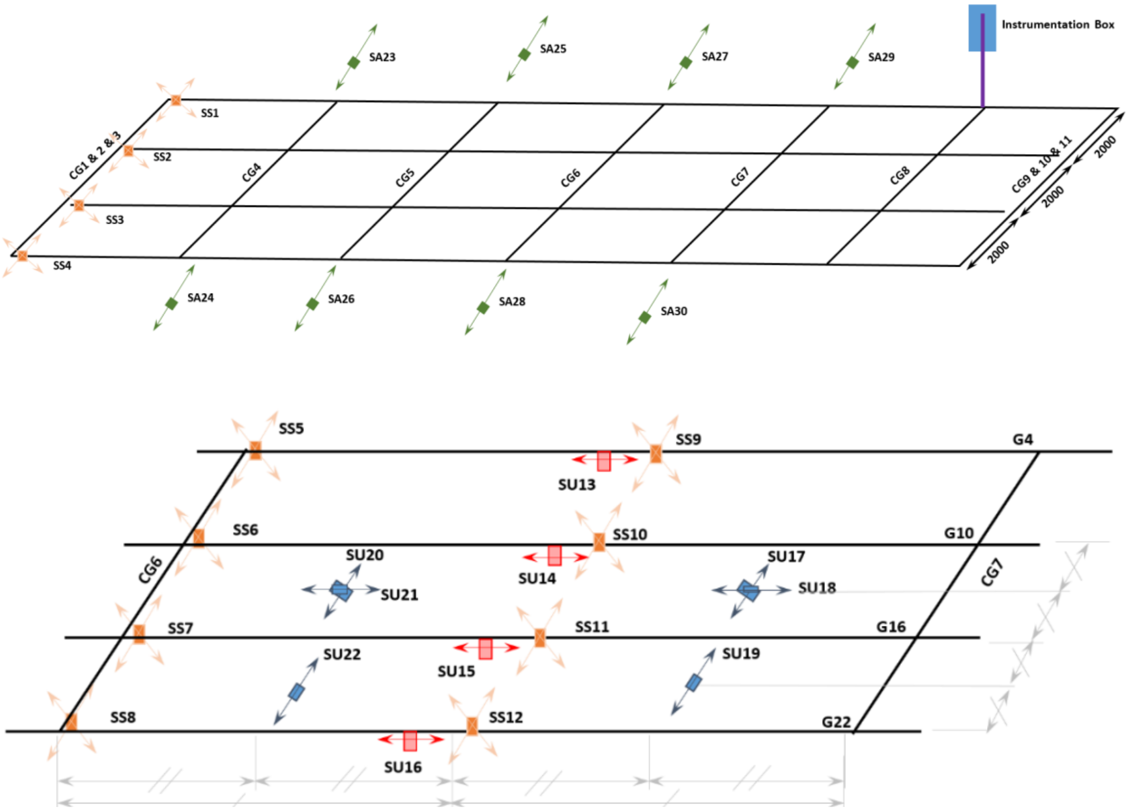
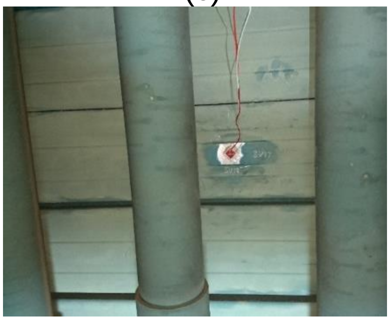


Figure 5. Illustration of dense array of strain gauges installed on the bridge.

(a)

(b) (c) (d)



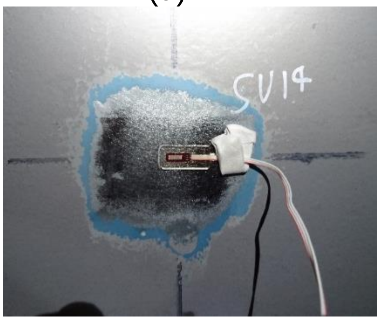


Figure 6. Sensor placements, (a) shear strain gauge on the web of the girder and magnified view of the shear sensor, (b) uniaxial strain gauge in the cable, (c) uniaxial gauges in longitudinal and transverse directions under the deck, (d) uniaxial gauge under the flange of the girder.

2.1.2 Data Acquisition

The signal conditioning and data logging software consist of an embedded PC and HBM Quantum-X data logger to record data. This system provides an integrated and reliable device to log high quality data with 24bit resolution with bandwidth capability of 0 to 3 kHz. This hardware combines instrument excitation, voltage regulation, digitization, anti-aliasing filters and data logging. The logging software is Catman. The software collects all channels at a default sample rate of 600 Hz with an anti-aliasing filter. The 3 dB cut-off frequency of the filter is 100 Hz and it is a fourth order Bessel low-pass filter.

2.2 A Culvert Bridge

The second bridge is located on Governor Macquarie Drive, Warwick Farm, NSW, as shown in the Figure 7. The bridge consists of concrete culverts with two spans and three shear walls, as shown in Figure 8. The clear spans for lane BLR (Lane 2) and BLL (Lane 1) are 4010 and 4000mm, respectively. The width of the bridge is 11240mm (9 culvert units each approximately 1.2m wide). The underpass consists of two pathways providing access for pedestrians and horses between Hope Street and Warwick Farm Racecourse as shown in Figure 8.

Figure 7. Location of Governor Macquarie Drive Bridge.

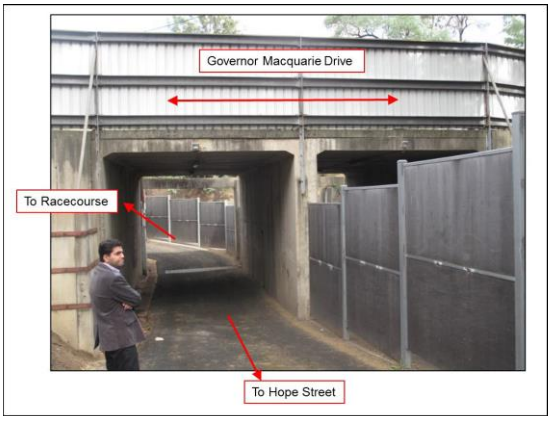


Figure 8. Illustration of double culvert in Governor Macquarie Drive Bridge.

2.2.1 Sensor Array

The sensors installed on the Governor Macquarie Drive Bridge include 22 strain gauges, 12 single axis MEMS accelerometers and 1 thermocouple. The strain gauges are used for long term strain measurements on concrete surfaces and they have been mounted at the closest location under the wheel path. They have moisture proofing over-coating and integrated lead wire in addition to the stainless steel backing. Figure 9 illustrates the sensor locations.

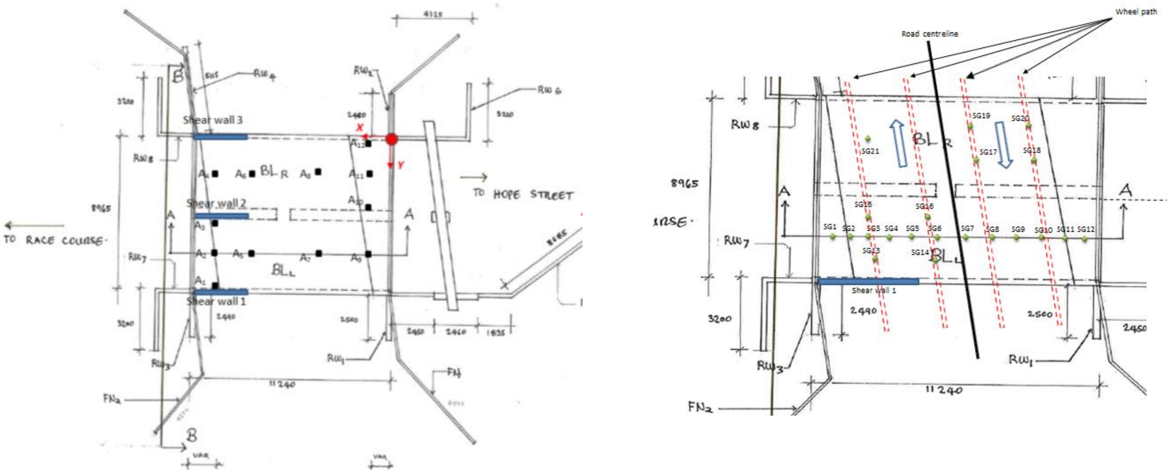


Figure 9. Illustration of the accelerometers and strain gauges on the bridge.

2.2.2 Data Acquisition

A data acquisition system from Campbell Scientific is used for this bridge, with an embedded PC running the Loggernet software connected to two CR6 data loggers, and CDM-A108 DAQ modules.

The DAQ modules and data loggers are configured to sample strain gauges at 250Hz (using three-wire quarter-bridge circuits), and accelerometers at 500Hz (using differential voltage measurement). GPS is used to synchronize clocks on the data loggers with 10uS accuracy.

While the data loggers are sampling continuously from the sensors, Loggernet software running on the embedded PC retrieves data from them every 2 minutes and makes it available via an FTPS serve (accessed via a 4G modem).

3 RESEARCH ACTIVITIES

Collection of real data from two bridges provides valuable opportunity to undertake several research activities. This section provides a summary of some of our ongoing research activities on these two bridges.

3.1 Anomaly Detection

In SHM system anomaly detection techniques have been used for damage identification (detection, localization and severity assessment) using vibration data collected from sensors mounted to the structures. Data fusion can be used to aggregate information from all the sensors to provide input for the anomaly detection techniques which involves three phases: (1) Damage detection is the technique using machine learning (ML) to build a model when the structure is healthy. When new data come in, they will be compared against the model to detect if they are associated with a heathy or damaged structure. This technique does not require a structure numerical model and is an unsupervised technique, which does not require costly data associated with damaged structures. The technique flowchart is described in Figure 10. (2) Damage localization is the technique using a data fusion approach to aggregate data from sensors at different locations in order to localize damage. (3) Damage severity assessment is the technique using a data fusion technique to aggregate data from different sensors for ML classifier. The scores returned by the classifier will be used to show the progress of damage. Details of these techniques can be found in [2, 3].

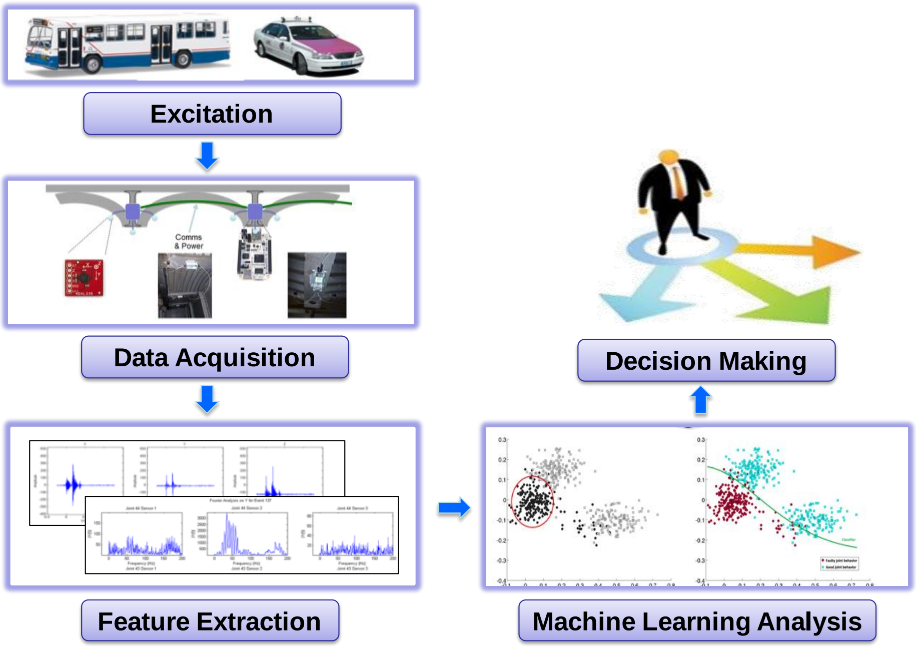


Figure 10. A ML flow chart for damage identification.

3.2 Load Cycle Counting

Fatigue life assessment of a structure subjected to a non-constant amplitude loading can be performed in the time domain using rainflow cycle counting. The rainflow method is used for counting the fatigue cycles (stress-reversals) and to obtain equivalent constant amplitude cycles from the measured strain data. This method is adopted in order to reduce a spectrum of varying stress into a sequence of tensile peaks and compressive valleys to identify the major load excursions. As a result of the counting, several cycles and half-cycles with different amplitude are obtained. With the advantage of fatigue damage accumulation hypothesis e.g. Miners rule, the algorithm gives possibility to compute the expected fatigue life under random loading conditions subject to availability of material property e.g. S-N curve. In order to achieve this, measured strain responses are analysed to identify the number of load cycles and the corresponding stress range the structure experiences. It can be further processed to estimate the remaining life of the structure [4].

3.3 Traffic Monitoring and Characterisation

Reliable live traffic data collection is crucial for effective pavement life prediction, fatigue estimation, vibration control, maintenance, and condition assessment of the bridge structures []. Bridge weigh-in-motion (BWIM) is an approach through which the axle and gross weight of trucks travelling at normal highway speed are identified using the response of an instrumented bridge. The vehicle speed, the number of axles, and the axle spacing are crucial parameters, and are required to be determined in the majority of BWIM algorithms. Nothing-On-the-Road (NOR) strategy suggests using the strain signals measured at some particular positions underneath the deck or girders of a bridge to obtain this information. Figure 11 represents schematic of a BWIM system [5, 6].

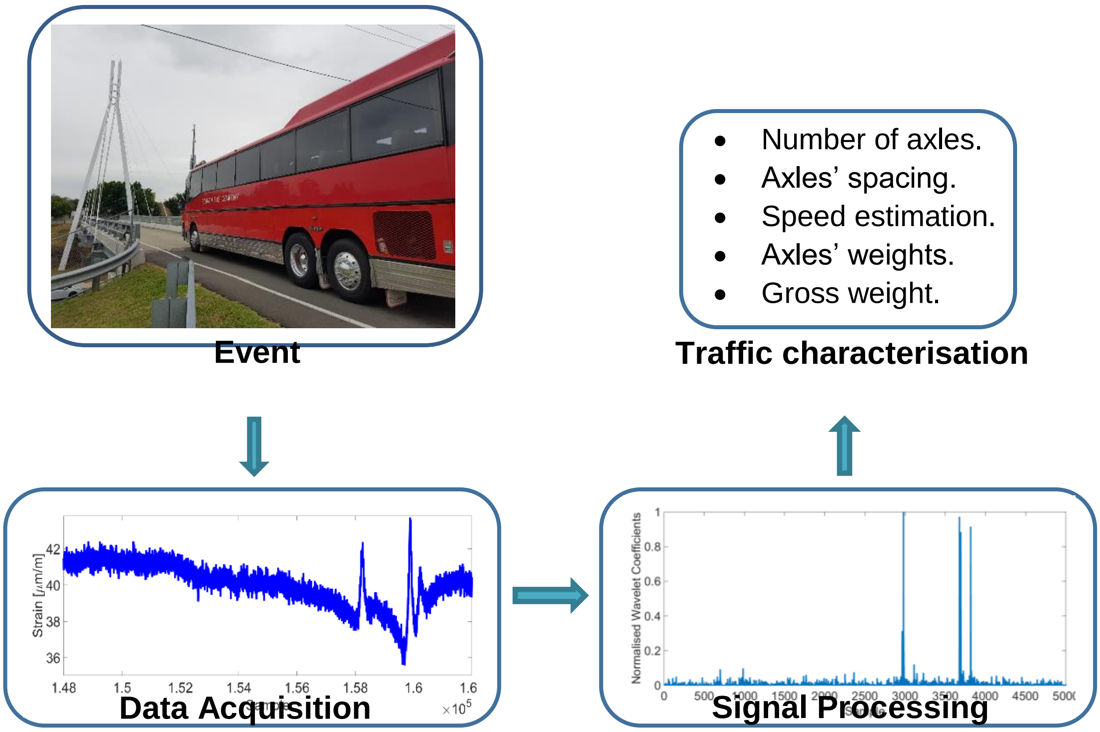


Figure 11. A schematic of a BWIM system.

3.4 Operational Modal Analysis (OMA)

Operational Modal Analysis (OMA) methods are widely used in the extraction of structural modal features such as natural frequencies, damping ratios and mode shapes. These parameters represent the characteristics of the structure and are widely used as key indicators for damage detection, damage-severity determination, damage localization and tracking the damage evolutions of a structure over time. OMA is a generic approach and is mostly suitable for studying the dynamic behaviour of large-scale civil structures such as bridges without disruption to traffic. The results from OMA not only is beneficial for SHM application but also it provides important ground truth information for numerical analysis i.e. finite element analysis [7].

4 SOFTWARE ARCHITECTURE FOR THE SHM SYSTEM

A cloud-based software system has been designed as in Figure 12 to process and display sensor data from the two bridges, focusing on modularity and scalability.

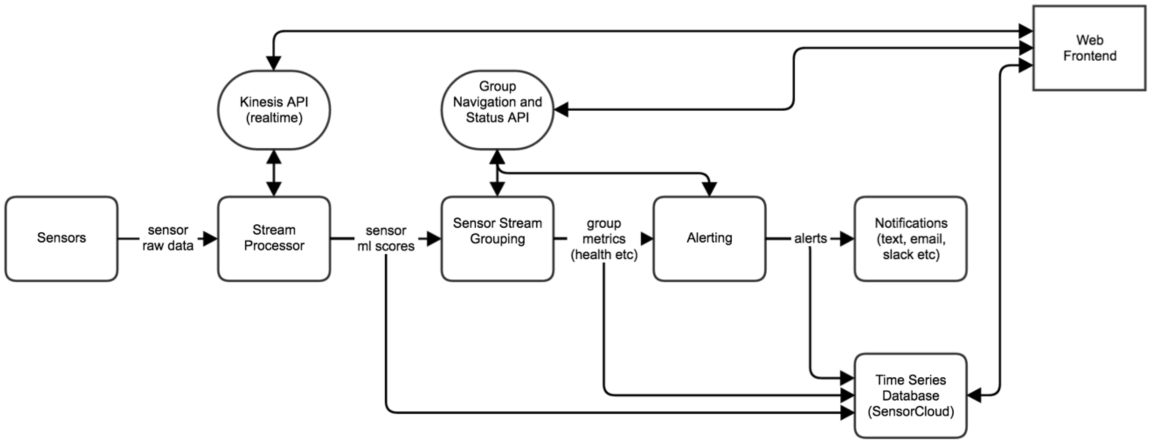


Figure 12. Basic architecture of the SHM system.

Real-time data processing is based around a Stream Processor component, which performs signal processing and machine learning to detect anomalies in each sensor. Machine learning scores flow to a Sensor Stream Grouping system, which contains a database to model the structural hierarchy of each bridge, relating the data from each sensor to a specific point in the hierarchy. Streaming SQL queries are used to update the hierarchy with readings from each sensor, enabling the health of the overall structure, or any component to be determined. Results are stored in a time series database for future queries, as well as made available to end users via an interactive dashboard as shown in Figures 13 and 14.

Figure 13. Dashboard for the cable stayed bridge.

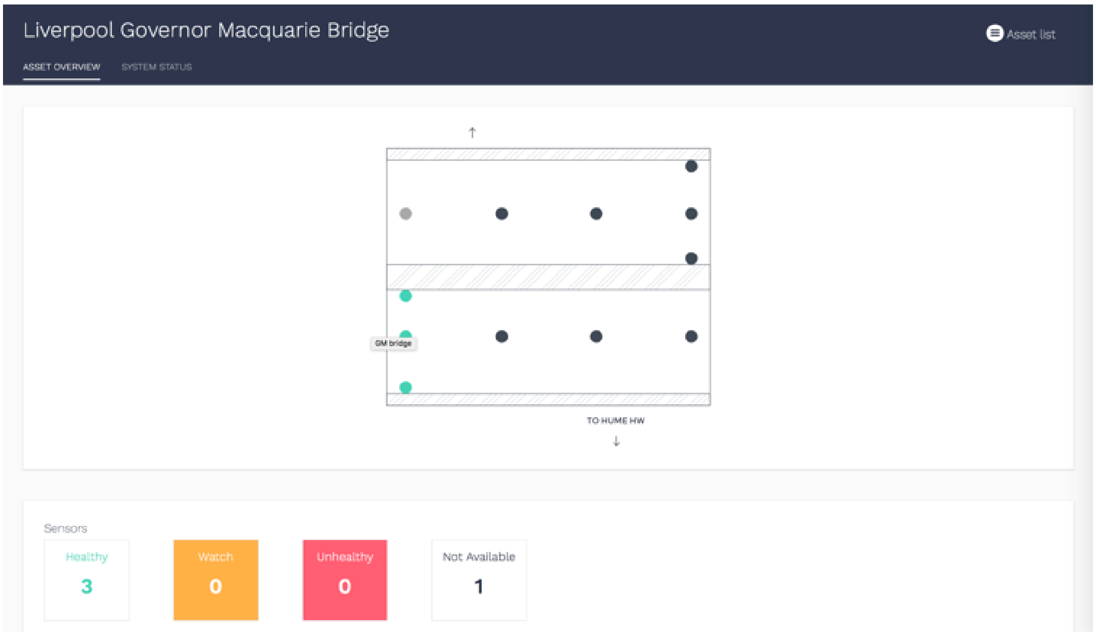


Figure 14. Dashboard for the culvert bridge.

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