A discussion on the uses of smart sensory network, cloud-computing, digital twin and artificial intelligence for the monitoring of long-span bridges

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ABSTRACT

This paper discusses what are the smart sensors that are currently available to be used for real-time monitoring of long-span bridges, how to develop an effective and efficient data strategy for collecting, processing, managing, analysing and visualising data sets from monitored assets to support decision-making, and how to establish a cost-effective and smart sensory network according to the objectives set up through thorough communications with asset owners. Due to high data rates employed and dense monitoring sensors installed the traditional processing technique will not fulfil the monitoring functionalities and is not secure. Cloud-computing technique is widely used in processing and storing big monitoring data sets. Using the experience attained by the authors in the establishment of long bridge monitoring systems in the UK and China this paper will compare the pros and cons of using cloud-computing for long-span bridge monitoring. It will further explore how to use digital twin (DT) and artificial intelligence (AI) for the extraction of relevant information or patterns regarding the health conditions of the assets and visualise this information through the interaction between physical and virtual worlds to realise timely and informed decision-making in managing essential road transport infrastructure.

I. INTRODUCTION

A very recent statistics carried out by the RAC Foundation reveals that 3,211 bridges in the UK are substandard by the end of 2021, a 3.4% increase compared with those of 2020 (RAC 2021a). In the UK a substandard bridge means those are unable to carry the heaviest vehicles on the road network, including lorries of up to 44 tonnes, and a weight restriction must be applied. As most of 2021 were under the COVID-19 pandemic lockdown in the UK and this rapid structural deterioration must be caused by their natural degradation process. It is estimated the cost to bring these substandard bridges back up to a perfect condition is £1.16 billion and to clean up all the maintenance backlog on 70,944 bridges in the UK would be £5.44 billion (RAC 2021b).

There are much higher bridge inventories both in China and the US. By 2019 China has built more than 878,300 highway bridges and 87% of them are medium and small size bridges. More than 10% of these bridges are categorized as “structurally deficient” which means that immediate retrofitting is required. Most of the long-span bridges in China (single span > 500 m for a suspension bridge and > 300 m for a cable-stayed bridge) are constructed in the past 30 years and bridges built in the past 10 years usually have a built-in structural health monitoring (SHM) system by the regulations or laws. Zhao *et al*. (2020) give a very comprehensive introduction on the recent research and practice of China in SHM of bridges.

The American Road & Transportation Builders Association (ARTBA) 2022 Report points out that 7% of its total 619,588 highway bridges are “structurally deficient” and 167.5 million daily crossings are on the total 43,578 structurally deficient U.S. bridges in poor conditions (Black 2022). The estimated cost to retrofit all 224,000 bridges that need major repair work or replacement, including the 43,578 structurally deficient bridges, is $260 billion. Recently, the US has passed its long-waiting Bipartisan Infrastructure Law (www.whitehouse.gov/bipartisan-infrastructure-law/) and it announced to invest $1tn for clean energy, internet, its ageing road networks including bridges, etc. Ironically, just before President Biden delivering his first infrastructure speech at “US City of Bridges” Pittsburgh in Pennsylvania on 28 January 2022, a bridge collapsed and injured 10 people. This is an apparent evidence of how serious the shared challenges are for the bridge maintenance and safety around the world.

From 2005 the first author of this paper had participated and then led a series of episodic monitoring campaigns to one of the longest bridges in the UK, the Forth Road Bridge in Scotland (Roberts *et al*., 2012). With the support mainly from the European Space Agency (ESA) a phased installation of a permanent monitoring system called GeoSHM started from 2014 (Meng *et al*., 2018a). The Forth Road Bridge was opened to traffic on 4 Sept 1964. The total length of the bridge is 2.5 km with the main span of 1,006 m (Figure 1). It was the world longest bridge outside the US but now it ranks 44. The Forth Road Bridge is essential for the Scottish/UK economy. According to the former bridge master closing one of its four lanes per day will cost £650K. The structural responses are dominated by temperature and traffic loadings and the bridge is susceptible to wind effects which cause excessive lateral movement and predicted over-stress under design wind loading. Regular repairs to the main components were carried out during its service lifetime of 58 years (www.theforthbridges.org/forth-road-bridge/maintenance).

Figure 1. The Forth Road Bridge with the Queensferry Crossing as background (from: Edinburgh News).

This paper uses the Forth Road Bridge in Scotland as an SHM example and the experience attained from the SHM systems erected on the bridges in China contributes enormously to the concepts and contents of this paper. The overall focuses of this paper include:

- How to establish a cost-effective and smart sensory network for monitoring long-span bridges.
- How to develop an effective SHM data strategy to handle large quantity of monitoring data from high-rate sensory network.
- Analysis to the pros and cons of cloud-computing technique for an SHM system.
- Discussion on the integrated uses of Digital Twin (DT) and artificial intelligent (AI) for smart monitoring of bridges.

II. SMART SENSORY NETWORK FOR SHM

The monitoring objectives by the bridge owners, available budget, timeline and most importantly the user demands together govern the overall design and configuration of a structural health monitoring (SHM) system. This requires the SHM developers sit down with bridge owners and listen to their burning pains in managing their assets. Selection of the right sensor types, determination of their optimal placement locations on the structure and design of the data transmission approaches are all essential factors to be considered in the initial stage of setting up a sustainable SHM system. To make this system adaptable to accommodate the changing demands of bridge owners and survive the harsh operational environment smart sensors and the network to connect them into an effective and efficient monitoring system are widely used in the current SHM systems. The smart level of the sensory system depends on the advance of many key impact parameters (KPIs) or affecting factors such as core chipset design, advanced materials and manufacture skill, computing power, wireless or cabled communications such as 5G/6G and fiber optic cables, etc.

In general, the monitoring parameters to be considered in a practical bridge monitoring system include the environmental parameters such as wind speed and its direction, temperature, humidity, rain, snow, ice, etc., the spatial-temporal displacements (four-dimensional, 4D) of the structure such as deflection and deformation, crack, fatigue, corrosion, etc., and the forces on the structure, such as strain and stress and their 4D distributions. Since different bridge owners have their specific monitoring priority agenda and the size and complexity of each individual structure are different therefore the determination of the number and types of the sensors and their placements on the structure is unique. According to Xu and Xia (2012) and Campbell *et al*. (2016) the sensors used to measure these above three types of parameters include loading sensors for wind, earthquake and traffic applied on the structures, the sensors for measuring structural responses such as displacement, strain, stress etc., and the environmental sensors for measuring temperature, humidity, rain, ice, snow, corrosion, solar radiation etc.

Nowadays due to their unique advantages such as higher bandwidth, longer transmission distance, lower latency and stronger security optical fibres are extensively used for large quantity of monitoring data transmission in the bridge SHM systems and various fibre optic sensors are developed to measure strain, temperature, dynamic and static vehicular weight, pressure, image etc. Furthermore, the advance and application of the micro-electromechanical system

(MEMS) sensors makes bridge monitoring more accurate and affordable and hence significantly improve the density of the sensory network on the structure. The use of optical fibres, and fibre optic and MEMS sensors have paved the way for integrating a digital twin (DT), analytic models such as finite element model (FEM) and other advanced data sciences such as big data analytics and machine learning, etc. into daily operation of the SHM systems.

Clearly, bearing this above development trend in mind and considering the affordability of the Forth Road Bridge owner's, GeoSHM was designed as a phased, open and scalable system (Meng *et al.*, 2018a; 2018b). The first phase was to proof the GeoSHM feasibility of fusing the satellite InSAR regional inspection and in-situ point-based monitoring with GNSS positioning and laying an optical fibre-based communication network to form high spatial-temporal monitoring (Meng *et al.*, 2018b; Psimoulis *et al.*, 2017). The demonstration phase of the GeoSHM development was more focused on densifying the existing monitoring footprint and developing a deep learning method to implement effective data mining, interpretation and structural diagnoses (Nguyen *et al.*, 2019). The GeoSHM system consists of the online and offline processing modules which play different roles: the online one for structural condition evaluation and the offline one for health and safety assessment. Figure 2 shows the main components of the GeoSHM sub-systems and how the GeoSHM *in-situ* sensors are linked to the processing centres with the optical fibre network on the bridge and via the TCP/IP protocol through the Internet. The cabled based network has been further upgraded using hybrid communication techniques.

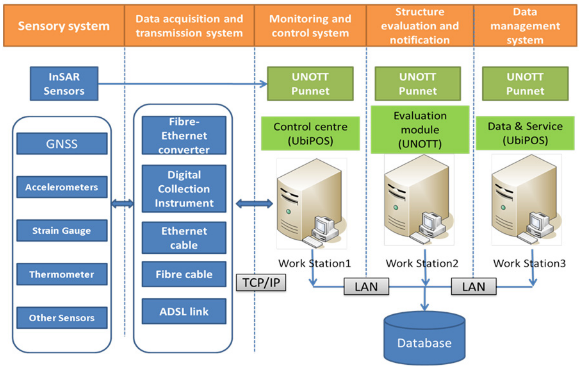
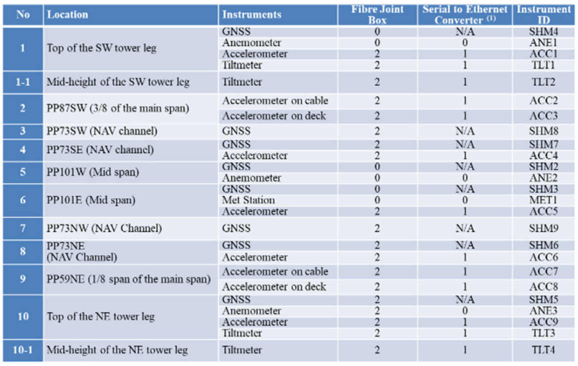


Figure 2. GeoSHM Sub-systems and Data Flow.

In the GeoSHM system, different high-rate sensors are installed at different locations of the structure to gather the digital or analog signals of interest. Figure 3 is a list of the sensors intended to be installed during its demonstration phase. Up to now most sensors have been successfully installed and running on the bridge but due to the pandemic replacing two corroded sensors at two quarter-span locations (SHM8 and SHM9) on the west side of the bridge was delayed. Figure 4 illustrates the current sensor types and locations.



No	Location	Instruments	Fibre Joint Box	Serial to Ethernet Converter [1]	Instrument ID
1	Top of the SW tower leg	GNSS	0	N/A	SHM4
		Anemometer	0	0	ANE1
		Accelerometer	2	1	ACC1
		Tiltmeter	2	1	TLT1
1-1	Mid-height of the SW tower leg	Tiltmeter	2	1	TLT2
2	PP87SW (3/8 of the main span)	Accelerometer on cable	2	1	ACC2
		Accelerometer on deck	2	1	ACC3
3	PP73SW (NAV channel)	GNSS	2	N/A	SHM8
4	PP73SE (NAV channel)	GNSS	2	N/A	SHM7
		Accelerometer	2	1	ACC4
5	PP101W (Mid span)	GNSS	0	N/A	SHM2
		Anemometer	0	0	ANE2
6	PP101E (Mid span)	GNSS	0	N/A	SHM3
		Met Station	0	0	MET1
		Accelerometer	2	1	ACC5
7	PP73NW (NAV Channel)	GNSS	2	N/A	SHM9
8	PP73NE (NAV Channel)	GNSS	2	N/A	SHM6
		Accelerometer	2	1	ACC6
9	PP59NE (1/8 span of the main span)	Accelerometer on cable	2	1	ACC7
		Accelerometer on deck	2	1	ACC8
10	Top of the NE tower leg	GNSS	2	N/A	SHM5
		Anemometer	2	0	ANE3
		Accelerometer	2	1	ACC9
		Tiltmeter	2	1	TLT3
10-1	Mid-height of the NE tower leg	Tiltmeter	2	1	TLT4

Figure 3. A full list of the sensors planned in the Phase Two development of the GeoSHM system.

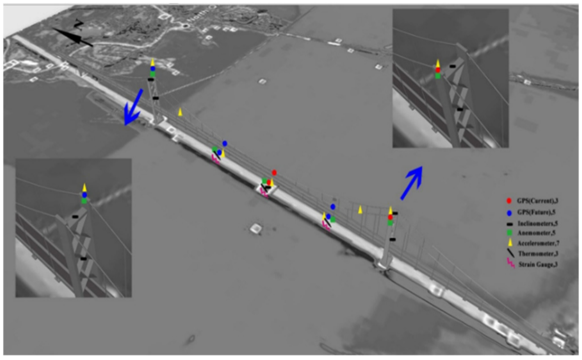


Figure 4. The sensor locations on the Forth Road Bridge.

Traditional sensing systems are mostly cable-based systems with monitoring nodes being installed at essential locations of the structures and these systems are usually sparse and expensive. Great efforts are required to maintain the communication systems since the communication cables are more vulnerable to the environment than the sensors. With wireless communication large quantity of sensors could be installed flexibly and the overall monitoring systems could be more scalable and cost-effective.

Current SHM systems extensively use cable-based communications for data transmission due to the drawbacks in power supply, communication bandwidth, effective ranges and signal interference due to complicated operational environments in wireless based monitoring. Some wireless sensors operate on unlicensed transmission frequency bands such as 2.4 GHz and hence there are output power limitations imposed in different countries. For instance, it is one watt in the US and 0.5 watts in the UK. This affects both data transmission throughput and a valid range.

When the optical fibre connection failed to transmitting data due to the installation challenge and long transmission range limitation for a remote monitoring node in the GeoSHM project wireless communication method was tried and it turned out to be a very reliable and cost-effective solution. Therefore, the communication network used in the GeoSHM project is a combination of optical fibre for most sensory sites and paired long-range Wi-Fi devices for a remote northeast (NE) supporting tower site. The NE monitoring node is the furthest point in the whole GeoSHM system and consists of a GNSS receive, an anemometer and a tri-axial accelerometer. Figure 5 is the wireless communication setting-up of SHM5 which sits atop the NE tower of the Forth Road Bridge.

Figure 5. A TP-Link Wi-Fi transceiver point (CPE510) installed atop the NE tower of the Forth Road Bridge.

In this case a pair of TP-Link's Outdoor Wireless Base Station 510 (WPS510) and Access Point 510 (CPE510) are used to receive and transmit monitoring data. CPE510 is linked to the remote sensors of SHM5. WPS510 is installed on the roof of the FRB control centre and linked to the Internet to stream the received data to the GeoSHM server to be processed. The nominal transmission range of these TP-Link devices is 5 km.

Figure 6 is the time series of the SHM5 lateral movement and 100% transmission rate is achieved in a period of three months during the peak of the COVID-19 pandemic which reflects the reliability of wireless communication for SHM.

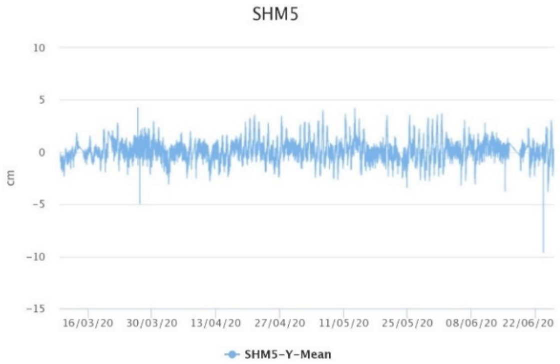


Figure 6. The time series of the lateral movement at SHM5 in three months.

III. DEVELOPMENT OF AN SHM DATA STRATEGY

Data strategy refers to the tools, processes, and rules that define how to manage, analyse, and act upon data. A data strategy helps different practitioners to make informed decisions based on the available data. It also helps to keep the data safe and compliant. According to Gartner's definition a data strategy is a highly dynamic process employed to support the acquisition, organization, analysis, and delivery of data in support of business objectives (Maguire 2019).

Using the data-driven approach for the establishment of an SHM system as illustrated in Figure 7 the aim of the development of an SHM data strategy is to provide the bridge owners and operators or service providers with appropriate bridge performance data and derived information to make informed bridge management decisions. The focus of the SHM data strategy should cover the procedures for data pre-processing and cleansing, real time data acquisition, data fusion from different sources, comparisons among real time data, historical ones and those from models, detection of extreme events and identification of system changes. As digital twins, big data analytics, IoT and AI are more and more applied into SHM of large infrastructure efforts should be made in how to seamlessly plug these into an updated SHM data strategy. As an example, the developed GeoSHM data strategy that has been utilized in guiding the development of the GeoSHM system comprises five interlinked components:

1. Data acquisition and pre-processing. All the raw measurements and the corresponding derived time series should be referred to a common spatial-temporal datum such as those defined by the Global Navigation Satellite System (GNSS) and using multi-GNSS including BDS becomes indispensable when a precise spatial-temporal datum is required for life-cycle infrastructure monitoring (Yang *et al*., 2020). Data acquisition rates and smart triggers for sensor controls should be determined, validated and operational. Also, an appropriate bridge coordinate system (BCS) should be defined, where its X-axis coincides with the main axis of the bridge (longitudinal), Y-axis is perpendicular to the X-axis in the horizontal plane (lateral) and the Z-axis points to the vertical up-direction. All the global, local and body-framed coordinate systems of the monitoring sensors should be linked to the BCS through rigid coordinate transformations. Outliers and gaps in the acquired data sets should be detected and removed before further processing.
2. Data architecture and integration. A data architecture is devised and used to guide data archive and storage process. Immediately after data pre-processing the cleaned data sets will be pushed to the dedicated SHM Cloud. Further data processing including data fusion and mining from summary statistics of whole data sets will be performed on a dedicated processing engine. A heterogeneous database structure is used to store all the data in the same Cloud.
3. Data storage and technology. The GeoSHM users have access to the layered live data stream, historic data, structural health status report and so on, according to their roles which include

bridge masters, engineers, researchers and general public. This part of work is to set data storage and access rules (raw data vs processed ones, and duration in keeping this large quantity of raw measurements) and what kinds of media for storing these data. Solutions are compared against KPIs such as cost, performance, ease to access, etc.

4. Data insight and analysis. Direct comparison of short-term statistics with historical data will be made using statistical control charts. Bridge performance data will be presented on a chart relating maximum displacement (or other variables) to incident loading (traffic, wind, or combined). Live bridge performance data will be presented as a time series with the thresholds which are based on historical data analysis. These will include how to use finite element models, AI and DT to enhance structural health condition assessments.
5. Data governance, privacy. Setting up the rules regarding who is the owner and responsible for the data, who and how can access the data.

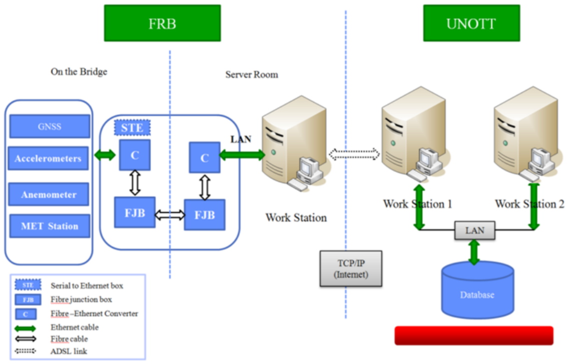


Figure 7. Data storage and technology.

IV. CLOUD-COMPUTING TECHNIQUE FOR SHM

As defined by Ray (2018) cloud-computing is the on-demand availability of computer system resources, especially data storage, which is called cloud storage, and computing power, without direct active management of the IT facilities by the users. The advantages and disadvantages about using cloud-computing for an SHM system are listed below.

The advantages in using a cloud-computing platform are:

1. Much lower processing cost. There is no need to purchase expensive hardware equipment, network equipment, and most software systems are also provided by the cloud-computing service providers for free.
2. Scalable computing performance and storage capacity. For the GeoSHM system, less resources need to be purchased at the initial stage, and the computing performance and storage space can be gradually increased as the amount of data increases in operation.
3. Significantly improved data storage security. Generally, cloud platforms provide corresponding data storage protection or backup strategies which reduces the risk of data loss at the server ends.

The disadvantages in using cloud-computing include:

1. Data security and privacy. Service providers have the opportunity to directly access to the data, which poses potential risks to data security and privacy.
2. Migration of data and services. Transferring large quantity of data/services from an old provider to a new one can be very painful and cumbersome if the SHM user wishes to switch to another provider.

The traditional way to build a structural health monitoring platform starts from purchasing computer workstations and servers, routers, gateways and other hardware equipment, software tools, etc. Due to the lack of maintenance facilities, such as UPS backup power supply, dual network devices, standard air-conditioning room, 24/7 professional maintenance personnel, etc., it may cause data loss because of power failure, network disconnection or even system failure, etc. Data loss statistics with the traditional data storage method in a server at the University of Nottingham (UNOTT) from 2017-2019 is listed in Table 1.

Table 1. Data loss statistics from 2017-2019

Reason	Time frequency	Days of data loss
Network disconnection	5	23
Power failure	6	9
System failure	5	20
Total	**16**	**52**

From July 2020, the architecture of the GeoSHM system has been changed and the same data were sent to the Cloud which is located in London and provided by Alibaba Cloud Ltd. Figure 8 is the current hybrid computing architecture of the GeoSHM system. After a period of debugging and optimization, the entire system has been completely transferred to the Alibaba Cloud. There is no data loss caused by the Ali Cloud server.

The Ali Cloud SHM server includes the following three running software modules:

1. The data receiving and management software module. This is used for data receiving, cleaning, and pre-processing and storing relevant statistic data and original observation measurements according to the designed SHM data strategy.
2. Data processing and analysis management software modules. It is used for estimating the SHM parameters and model update driven by AI,

dynamic adjustment of thresholds, real-time health assessment of bridge structures, and warning services.

3. Web-based network client system. It provides real-time data query and statistics, historical data comparison and analysis, real-time health status query and other related SHM functions.

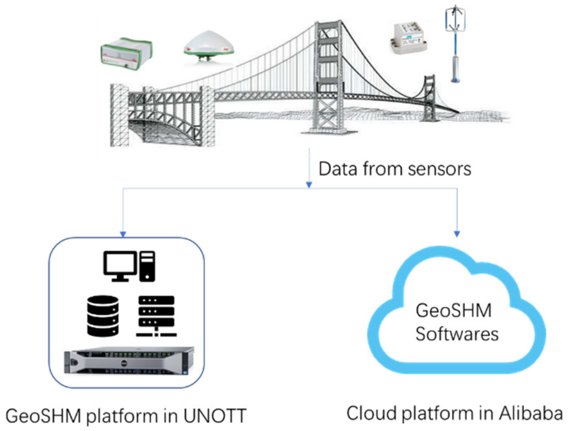


Figure 8. Hybrid SHM processing platform using Ali Cloud and a local server UNOTT.

V. DIGITAL TWIN (DT) AND ARTIFICIAL INTELLIGENT (AI) FOR SMART MONITORING OF BRIDGES

In SHM of bridges, a digital twin intends to build a virtual model that uses the real-world heterogenous data sets gathered from an operational bridge as its input for enhancing asset management process. Once precisely constructed the DT can be used to simulate and predict the possible impacts for certain environmental and loading effects using monitoring data sets as the DT inputs. Linking the DT and artificial intelligence, especially using deep learning and transfer learning, is essential and a current development trend in implementing the smarter, safer and higher-quality infrastructure inspection regime. It is extremely useful while seeking timely, robust, accurate and cost-effective solutions to address much overdue bridge inspections around the world. This new way of inspection includes the integration of smart sensors or other field data acquisition, secured data transmission via cabled and 5G/6G or even LEO satellite broadband comms, building high definition (HD) 3D or 4D models of the assets with DT technique and uses of both AI and analytic models such as FEM to process, analyse and visualise huge monitoring data. Pairing a DT with AI that uses the data from smart sensory system on the structures as its inputs and the high-speed data communications provide great opportunities to conduct instant interaction among the physical world features with the cyber world models to maximize monitoring effects (Liu *et al.*, 2022).

Artificial Neural Networks (ANNs) have been successfully applied in many fields including pattern recognition, connected and autonomous vehicles, civil engineering, public security, etc. (Goodfellow *et al.*, 2016). In the area of SHM, ANNs are one of the most common methods to study the relationship between the bridge responses and loading factors. Bayes is used to determine conditional probability which is the likelihood of an outcome occurring, based on a previous outcome having occurred in similar circumstances. Compared with other AI algorithms Bayes-based Neural Network (BANN) has the following characteristics:

- A single-layer feed-forward neural network.
- Quicker learning process.
- Better generalisation.
- Quantification of uncertainty of predictions.

The last character is extremely important since sensors on the structures bear errors or outliers which are detrimental to the success of structural condition assessment. In the GeoSHM data analytics toolbox, the BANN is employed to generate a non-linear regression model to estimate time-dependent lateral and heaving responses with respect to variation of wind, temperature, and traffic. Inputs and outputs of the regression model are 10-minute average statistics and the use of BANN for monitoring data analysis is described in Figure 9.

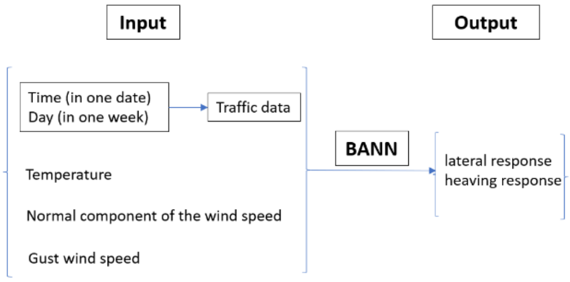


Figure 9. Input and output of the BANN algorithm.

The formula of the Bayesian inference is (Eq. 1):

$$p(\theta|D) = \frac{p(D|\theta) \cdot p(\theta)}{p(D)} \tag{1}$$

where $p(\theta)$ = prior probability of a parameter ϑ before having seen the data
$p(D|\theta)$ = called the likelihood and is the probability of the data D given θ
$p(\theta|D)$ = posterior probability of ϑ given the data D

Instead of considering a single answer to a question, Bayesian methods allow us to consider an entire distribution of answers which can solve the issues like regularisation (overfitting or not), model selection/comparison and cross-validation data set separation.

Empowered with the BANN, a new rolling assessment and updating approach is developed for the GeoSHM project to detect structural changes of the Forth Road Bridge as shown in Figure 10. The first row in this figure is the time series comparison between the measured mean lateral movements and those of predicted with the BANN. The second row includes the difference of the two time series in the comparison (called as residual), the upper and lower thresholds determined using at least one year monitoring data (loading and response) and daily mean residual which is used to assess the structural changes. It is apparent that after 13 February 2017 the daily means are either close to or moved out of the set thresholds. Further investigation reveals that on this date the maintenance team had completed the truss end link repair at the north east main span which changed the dynamic characters of the bridge (www.theforthbridges.org/forth-road-bridge/maintenance/major-projects/truss-end-links-repair).

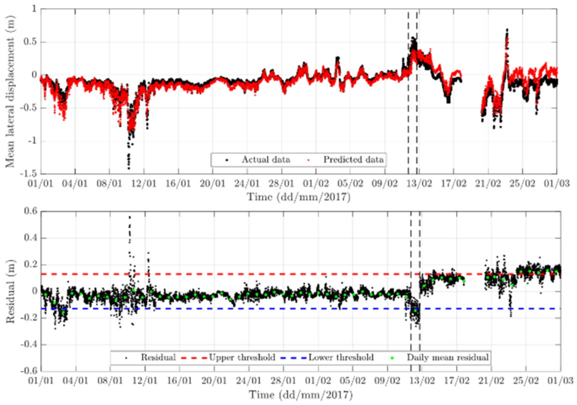


Figure 10. Detection structural changes in the Forth Road Bridge.

VI. Conclusions

In this paper the authors discussed four aspects in establishing the structural health monitoring systems of long-span bridges. There is a wide range of smart sensors could be used to monitor loading, response and environmental factors but under the journey to establish digital twins to support timely and informed SHM decision-making both the sensors' quality and density need to be improved. Wireless communication might be a good option when other means of data transmission fail to work, and authors have demonstrated how a long range Wi-Fi could bridge this gap. Large and high-quality monitoring data are the basic requirement for an SHM system and to manage these data a data strategy is essential for building a successful and long lasting SHM. Using the GeoSHM project as an example the authors presented in detail what should be covered in the data strategy development. This paper also analysed the pros and cons of cloud-computing technique for an SHM system and according to the experience of the authors' cloud-computing is a great progress in the SHM system architecture design. Finally, the authors introduced their efforts in successfully using the BANN for the structural change detection of the Forth Road Bridge and discussed the benefits in the integrated uses of Digital Twin (DT) and artificial intelligent (AI) for smart monitoring of bridges. In summary, integrating smart sensory system, IoT, cloud-computing, DT and AI will greatly benefit the monitoring and inspection work of long-span bridges.

VII. Acknowledgements

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