IBMS2016

1st Biennial Conference On Bridge Sustainability

Leveraging Cloud Computing Services for Economical and Cost Effective Remote Online Monitoring of Bridge Health

Amod Gujral[a]*, Arushi Bhalla[b]

[a]MD, Encardio-rite Electronics Pvt. Ltd., A-7 Industrial Estate, Talkatora Road, Lucknow-226011, India
[b]Director Exports, Encardio-rite Electronics Pvt. Ltd., No. 17, Yusuf Sarai Main Market, New Delhi-110016, India

Abstract. A very large number of old bridges whose condition is deteriorating would benefit greatly from continuous real time health monitoring. Even smaller bridges can be important because of their logistic or strategic importance. Invariably most of these bridges do not have any sensor network installed for monitoring their health. These bridges first need to be retrofitted with a number of sensors and then the data collected needs to be monitored continuously in real time, preferably remotely. For a country like India the number of such bridges are in thousands. Using Cloud Computing Services together with suitable choice of low power sensor network can make remote online monitoring of bridge health very affordable. Even bridge owners with a single small bridge to those owning thousands of smaller older bridges can use this approach to economically monitor the health of their asset remotely over the internet in near real time.

Keywords: *Bridge health monitoring, Bridge rehabilitation, Real time bridge monitoring*

1. Introduction

Owners of bridges that are a decade to more than a century old are today concerned about the health of their bridges as the traffic over the bridges have increased many fold than anticipated at the time of their design. Many of these bridges are also in a very dilapidated condition or are showing signs of stress that would lead to serious damage over time if not taken care of. However, it may not be economically possible to replace such bridges with new bridges in the near future. Some such bridge owners are regularly employing specialist agencies to assess the condition of their bridges and chart out a rehabilitation program for each bridge. Subsequently the bridge health needs to be monitored continuously to ensure that the bridge is safe for its intended traffic.

New or old, the greatest problem faced in long term monitoring of bridges is to collect data from all the sensors, whose number can often exceed a hundred for large bridges, and log it in near real time. This data needs to be analysed in the shortest possible time and any problem area identified so that proactive or remedial action can be taken to avoid further damage to the bridge or stop traffic from becoming a victim of any catastrophic failure of the bridge.

* Corresponding author. Tel.: +91-522-266-1044; fax: +91-522-266-2403.
E-mail address: encardio@gmail.com.

Most of the real time bridge instrumentation monitoring activity in the past required the sensor data to be collected through centralized [1, 2] or distributed sensors and data loggers [3] that sent the data logged from the various sensors to a central computer generally housed in a cabin close to the bridge location. The central computer after collecting the data would archive the data in a database. Specialized software was then used to display the monitored parameters in suitable graphical form for easy interpretation by human operators.

For each bridge the owner needed to maintain a team of trained manpower for operation and maintenance of the computers and other infrastructure like a control room, redundant power supply to power the computers and the sensor network itself, air-conditioning, telemetry links etc.

2. The disadvantages of past individual control room for each bridge approach

In the past approach the cost of maintaining a control room for each bridge turns out to be very expensive for owners who own a large number of bridges. For bridges at relatively remote locations maintaining a manned control room is in itself an expensive proposition.

The computer hardware and software employed in the control room is required to be upgraded continuously with time due to obsolescence or discontinuation of support by the vendor of the hardware, software or even just plain incompatibility with advances in technology.

Another disadvantage of the above approach is the difficulty in transmission of bridge health information simultaneously in near real time to all stake holders who may be located far away from each other and the bridge itself.

Owners of only one or a few bridges (that are being monitored) also find it difficult to maintain a control room manned by suitably trained and experienced staff and would generally prefer to outsource the job to any competent agency if available.

There are many small bridges with structural problems that too need to be monitored in real time as they may be carrying significant traffic or are part of a critical or strategically important link. The number of parameters that need to be monitored would be relatively small and the cost of having an individual manned control room for each such bridge is not economically feasible.

Considering the above disadvantages, a bridge owner who needs to monitor a large number of smaller bridges would also like to have a much more economical but reliable solution.

3. The cloud computing approach to data monitoring

Cloud computing services are generally provided by commercial entities who maintain clusters of highly reliable and powerful servers (computers) with matching infrastructure like redundant power supply, air conditioning, redundant broad band internet connections and a team of experienced manpower with different levels of experience who man these centers round-the-clock. The client's data is kept at redundant locations so that in case of data loss due to any reason the data can be fetched from the backup location.

The specialized software for data monitoring function (in this case bridge health monitoring) is provided as a service. This model is known as SaaS or 'Software as a Service'. Online data monitoring service provided by these service providers collect the sensor data, either directly from the smart sensors or collected and logged by local data loggers, over the internet. Depending on the type of smart sensors or data loggers used the data can be collected using two modes, the push and pull modes. In the push mode the smart sensor or the data logger pushes the data to the cloud server at predetermined intervals. In the pull mode the cloud server requests data from the sensors or the data loggers at prescheduled times or intervals.

As the data coming from different types of sensors or data loggers may have different formats (even for products from the same manufacturer) a data reformatter software converts the received data to an uniform format. Each data record generally consists of a time stamp (i.e. at what date and time the data was collected) and the parameter values returned by the sensors. Data loggers often return parameter values from a number of sensors connected to it with a single time stamp as a data record.

A proprietary database management software stores the reformatted data record in a database on the server. Currently employed database/storage cloud servers have huge storage space and can store and process a very large amount of data at a very high speed.

The database management software fetches the historical (including the most current) data from the database and sends it to the end users, on demand, in a suitable graphical or tabular format as a web page using a web server. The end user has a lot of flexibility in choosing how and over what period the data is to be displayed.

End users do not have to install any special software on their device. The end user can use any device like a laptop, tablet, smart phone with any type of operating system running on their system. As long as the device has a standard web browser the end user can access the bridge data as well as perform many administrative tasks provided he/she has the necessary privileges to access the bridge data.

Fig. 1.

Fig. 1 shows the schematic diagram of a typical very low power sensor network being used with a cloud data monitoring service. A typical SDI-12 data logger can interface from 1 to 180 sensors with SDI-12 interface. A large number of commercially available sensor types can be connected to such a network. Many conventional sensors can also be connected to the network using a SDI-12 interface unit.

4. Track record of cloud based data monitoring service

The cloud based data monitoring service has matured a lot over the last few years and have proved their reliability, economy and cost effectiveness in many large and critical projects or applications worldwide. These monitoring services are not specific to bridge monitoring service only and are being used for monitoring many types of civil engineering project or structures like hydro-electric projects, rail, road or sewerage tunnels, underground caverns and deep excavation sites, very tall buildings, heritage structures like centuries old churches, monuments and forts, airports, seaports, land remediation and reclamation areas, land slide prone areas like hill slopes, etc.

In India such systems are currently also being used by central and state government agencies for monitoring thousands of ground water monitoring borewell dataloggers, river, sewage and effluent treatment plant water quality monitoring stations spread all over the country for the past few years.

The authors of this paper are, however, not aware of any large scale use of cloud based services for bridge health monitoring application in India.

5. Advantages of using cloud based data monitoring systems as a service

The greatest problem faced in monitoring a large number of bridges owned by a single owner is in quick identification of bridges and the parameters that have either crossed the preset alert levels or are likely to do so in near future. It is a mammoth job for human operators to look at each and every bridge parameter individually for all the bridges being monitored for signs of alert every day.

The latest cloud based data monitoring systems have automatic report generation facilities for spotting only those bridges whose any measured parameter value is either approaching the alert threshold or has crossed the alert threshold. Automatic report generation also alerts the user about those sites that have stopped sending data to the cloud server due to failure of telemetry link or problems with the data logging system or non-working sensors.

Cloud based data monitoring system also have provision of sending out email and SMS alert messages to any number of persons who are responsible for monitoring the condition of a particular asset (bridge) for taking pre-emptive or remedial action.

Manual operators who are given the task of monitoring a large number of sites daily, due to sheer workload, often miss alert events specially those events in which any monitored parameter had crossed the alert threshold due to any reason but had again come back below the alert level after a short time before the operator could spot the alert condition.

Available cloud based monitoring systems are able to "raise a red flag" whenever an alert condition is detected, even if the event persisted for a relatively short duration. A list of all such sites together with the parameter involved is maintained and displayed by the monitoring software. Until the time a human operator checks the alert event and acknowledges the alert, the alert flag is kept pending. This ensures that no alert condition, including even short duration ones, can go unnoticed.

Users can also generate a report, on demand, of all or selected sites where any of the measured parameter had crossed its alert level between two specified dates and the number of times the alert level had been breached within that time period.

Cloud based data monitoring service frees the user from having to invest in expensive infrastructure, high reliability servers and associated peripherals, software licenses and trained manpower and maintenance of the same. The data monitoring service is provided by very sophisticated and powerful software suites running on the cloud server.

The end users need not invest in any special device or software for monitoring the health of their asset. As long as they have access to any device that has a web browser and connectivity to the internet they can check out the health of their asset from anywhere in the world. A number of authorized users for any particular bridge can simultaneously access different parameters or reports remotely from different geographical locations.

6. Cost effectiveness and economy

The general payment model for cloud based data monitoring service is an initial set up fee for configuring the site (like a bridge) and a monthly subscription fee for using the service. The fee is based on the amount of computational resources required by the user and can be scaled up any time by paying a higher fee. These systems can cater to small users who need to monitor a single site with less than 10 sensors to large users who need to monitor thousands of sites with more than a total of hundred thousand sensors. The subscription can be cancelled any time freeing the user from making any long term investment.

This payment model allows even very small bridge owners to take advantage of the sophisticated features of powerful cloud based data monitoring systems at a very low cost.

Due to the low overall cost of monitoring using cloud services, even in India, some owners of large houses, on hill slopes that have been declared as showing signs of instability, have installed two or more sensitive biaxial tilt sensors with battery operated data loggers and a subscription to cloud based data monitoring service to keep a tab on any excessive movement or tilt in their house so that they can take proactive action in case of an alert condition. Buildings that have developed cracks are also fitted with crack meters to keep a tab on widening of the crack with time to detect any hazardous development. The battery used in the data loggers require replacement after around 7 years of continuous operation and so these sensor network systems can be considered as a maintenance free 'fit and forget' installation.

7. General access and security features of cloud based data monitoring service

The cloud based data monitoring service allows the user agency to specify which of their personnel would have what level of access to the data monitoring system and whether they want to share the data with other agencies.

At the highest level an end user with administrator level privileges has complete access to the configuration, alert settings, monitored data and various reports for any bridge assigned to the user. At the lowest level an end user with only viewing rights can only view the monitored data but cannot do any other task. In between there can be users with varying degree of access to different features of the monitoring software.

Each end user is provided with a unique login credential for logging on to the data monitoring system. After logging in the end user can only access the data and privileges allotted to that particular user.

The data monitoring software can also provide hierarchical access to monitored data if so desired by the owner. For example, a national agency can have access to data from all the bridges being monitored in the country. State level agencies or divisions can have access to bridges in their state. District or subdivision level personnel can have access to data only for bridges falling in their jurisdiction. Maintenance staff responsible for a particular bridge can have access to data and alert messages related to their allotted bridge only.

An issue of serious concern for any system connected to the internet is from different kinds of cyber-attacks with serious consequences. A cloud service provider is able to allocate a higher budget, hardware and software security systems and trained personnel to guard their systems against such attacks. Such level of protection would be very expensive for individual bridge owners who maintain their own individual data management servers.

8. Reliability of cloud data monitoring service

To use a cloud data monitoring service, the data collected from the sensors and sensor systems on the bridge need to be transferred over internet to the cloud server. In general data from all the sensors installed on the bridge is sent through a central device that is connected to the internet using copper wire, optical fibre, cellular phone network, point to point radio frequency link or radio frequency satellite link.

One major problem with cellular phone telemetry link, which is the lowest cost radio frequency link, is their unreliability. This unreliability can be reduced to some extent only by using services of two cellular operators simultaneously. Though less often, other types of telemetry links can also be subject to failure due to a variety of reasons. For example, in the authors' experience, fibre optic cables mostly get damaged due to unsupervised excavation work. The data loggers currently used with cloud based systems generally have a large internal non-volatile data memory. Even if the telemetry link is down for days as soon as the link is restored all the stored data is transmitted to the cloud server without any data loss.

Fortunately, depending on bridge design and health and the parameters being monitored, most of the bridge health monitoring systems will not require data to be collected more than a few times a day. Transmission of logged data once or twice a day is considered sufficient. Short duration telemetry link failure is generally not an issue in these cases.

However, any critical parameter that requires to be monitored continuously and remedial action taken in the shortest possible time, especially to guard against loss of life, is not suitable for monitoring and alert generation using a cloud based data monitoring service because of the latency of the alert generation process and the unreliability of the telemetry link. Such alerts are best processed by suitable systems at or very near the bridge location.

9. Low budget sensor network design for monitoring health of small old bridges

Using a cloud based bridge health monitoring system will reduce the overall cost of bridge health monitoring. However, the other major cost is the actual health monitoring sensor network and cloud compatible data logging systems.

A discussion of all the available sensor types, data loggers and networking topologies that are available is beyond the scope of this paper. This knowledge and information is very essential to find the most cost effective but reliable bridge sensor network design when using cloud data monitoring service. It is suggested that bridge owners should work closely with safety instrumentation providers to find the most economical and reliable solution.

Bridge owners who would like to monitor the health of a very large number of small old bridges would benefit from low cost solutions available discussed below.

Health monitoring of small old bridges would generally require only a few tens of sensors like crack gauges, surface mounted strain gauges, sensitive tilt, settlement and displacement sensors, water level/piezometric pressure, etc.

Today such sensors are available with SDI-12 bus interface and very low power requirements. These days commercially available relatively low cost SDI-12 sensor interface compatible data loggers can be used with sensors with SDI-12 interface to form a bridge sensor network.

A brick sized data logger for use with sensors with SDI-12 interface can practically be connected to a maximum of 180 sensors. These data loggers can be powered by a couple of lithium batteries. If the data from the sensors need to be collected a few times a day and transmitted once daily to the cloud based data monitoring system, the batteries will last for more than two years. For very low number of sensors a set of batteries can last from 5 to 7 years. A cellular service provider's data SIM card is all that is required to connect to the internet. The data logger generally spends its time sleeping, waking up at scheduled times of the day to collect data from the connected sensors and transmits the collected data to the cloud at programmed times. The bridge location should, however, be covered by any cellular service network for this to be possible.

Fig. 2

Fig. 2 shows application examples of typical low power sensors deployed for monitoring civil engineering structures. Picture A – shows a sensitive biaxial tilt sensor monitoring a road over-bridge pier that is suspected of developing a tilt. The little black box near the base contains a battery powered data logger with cellular network connectivity. This is an example of an user monitoring isolated problem areas spread over a large area with a few autonomous sensors together with cloud services. Picture B – shows a strain gauge that is monitoring the stress on a structure. Picture C – shows water level/piezometric pressure sensors used to monitor the water level in a river or piezometric pressure in the ground on which the bridge is built. Picture D – shows a crack meter monitoring a crack in a structure that has started showing signs of movement.

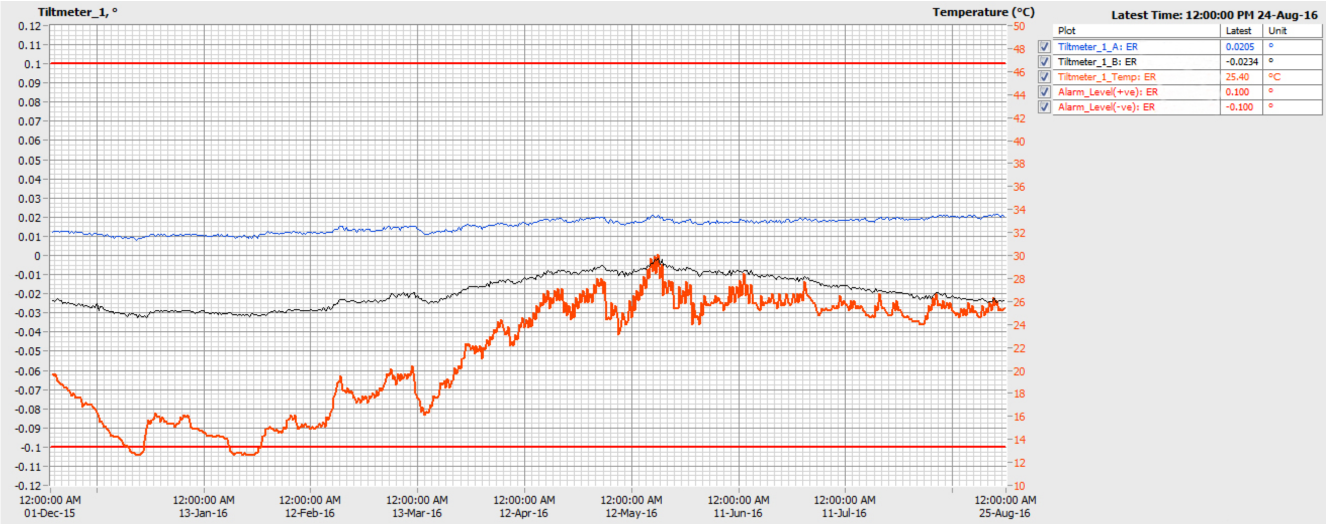

Fig. 3

Fig. 3 is screen shot of graph presented by a cloud based data monitoring service showing 8 months' data of a biaxial tilt sensor sampled once a day at a fixed time. The trace in red showing larger variation is of ambient temperature variation. The other two traces are magnitude of tilt in degrees along two orthogonal axes. The difference between the maximum and minimum value of tilt registered is approximately 0.02 degrees. The two red lines at the top and bottom are alarm limits set for the biaxial tilt sensor.

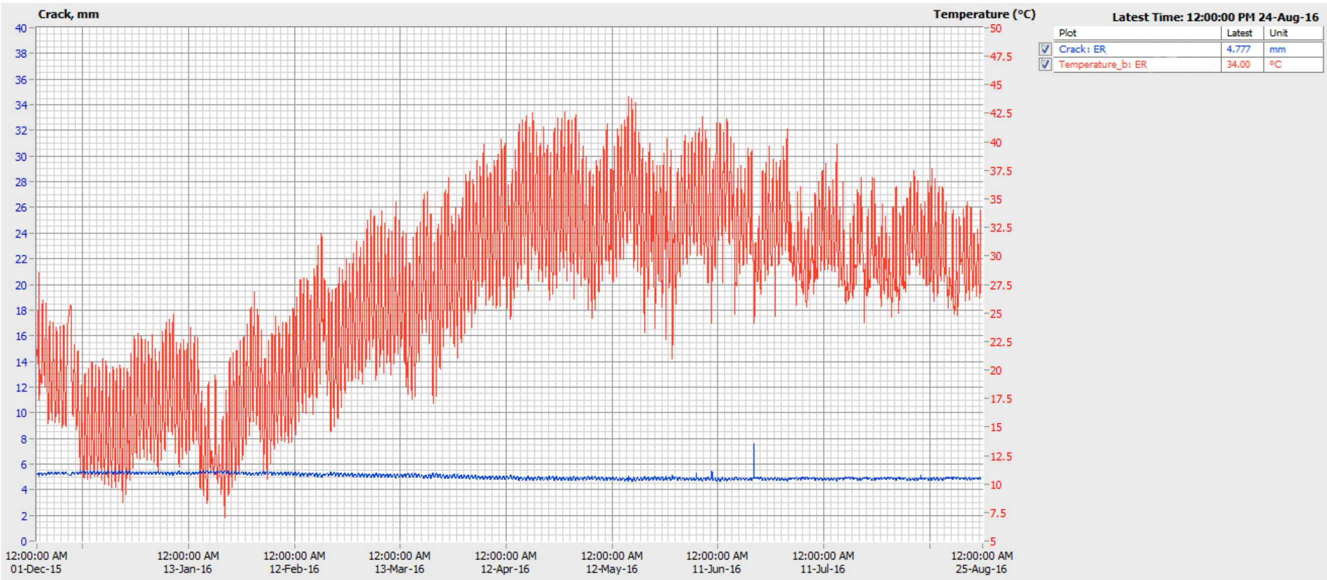

Fig. 4

Figure 4 shows 8 months' data from a crack meter monitoring change in crack width over time. The crack meter was initially set at 6 mm to register both closing and opening of the crack with time. The data is being sampled every 30 minutes. The band like trace is the ambient temperature as measured by the sensor. Because the sensor is being sampled every 30 minutes it is tracking the variation in ambient temperature over the whole day unlike Fig 3 in which the sensor is being sampled only once a day.

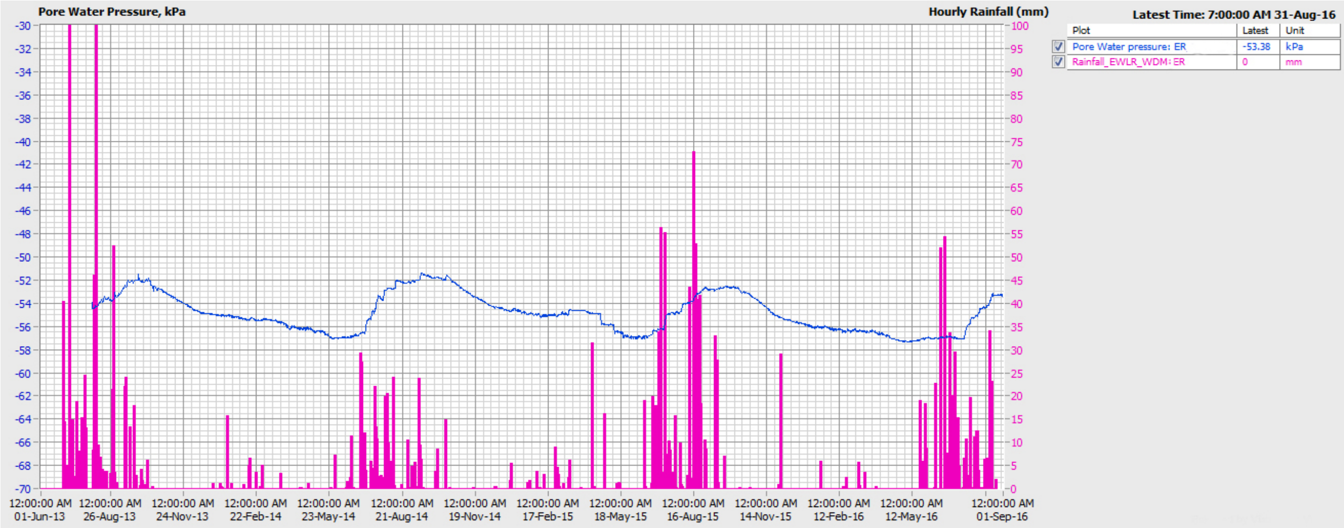

Fig. 5

Figure 5 shows 3 year's data of changes in ground water table and rainfall at a particular site. The ground water level is logged four times a day, the rainfall is logged continuously and the data is transmitted once a day to the cloud server. Co-relation of variation in ground water level with rainfall can be seen on the graph. Similar instrumentation is used for online automatic monitoring of river water level and rainfall with time.

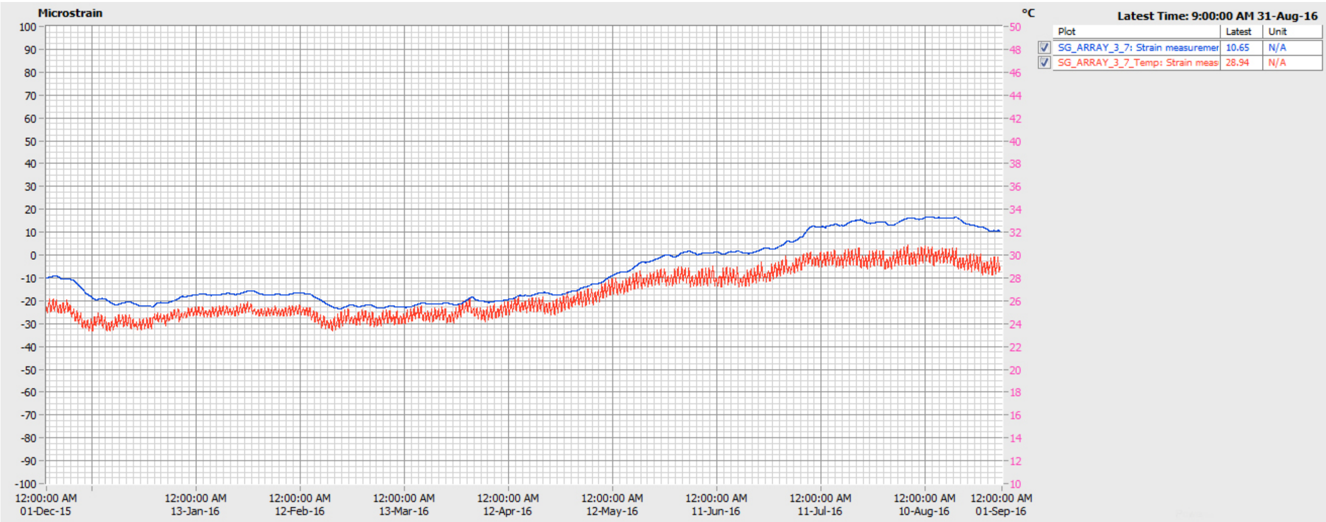

Fig. 6

Figure 6 shows 8 months' data of variation in strain levels on a structure. This gives important information on changes in strain/stress in the structure with time at that point. The strain values are also affected by changes in temperature so the temperature variation is also plotted for correlation on the graph.

10. Conclusion

Cloud based data monitoring service provides a very economical, cost effective, highly scalable and reliable solution that also provides sophisticated monitoring and alert capabilities for online bridge health monitoring. When combined with a low power, low cost sensor network it allows monitoring of large number of much smaller older bridges, that need or have undergone rehabilitation, at a low initial and recurring cost.

The cloud based online data monitoring systems have proven their reliability and effectiveness in many different types of large and critical civil engineering projects worldwide over the last few years and can without hesitation be used by bridge owners owning from a single to a very large number of bridges.

Acknowledgements

This paper is based on the authors' experience over the last eight years in the field of remote online monitoring. The authors are closely involved in providing internet/cloud based data monitoring services to a large variety of civil engineering and structural health monitoring projects. A majority of the project sites are located in India or the middle east region and range from a single building on hill slope, heritage churches and forts to very large projects like railway, metro rail, road and sewerage tunnels with cumulative length of hundreds of kilometers, large excavation sites, landslide zones, etc. However, the commercial nature of the products and services described in this article and the reluctance of the asset owners (mostly government organizations) to put the safety instrumentation scheme and vast amount of data of their asset in the public domain did not allow including references to them in this paper.

The authors would like to thank the various asset owners who gave them the opportunity to work for them and the many engineers who worked with them over the years in developing, deploying, maintaining and refining the remote online structural health monitoring systems using internet/cloud based data monitoring and alerting services.

Reference

1. Sumitro,S.,Matsui,Y.,Kono,M., Okamoto, T., and Fuji, K. (2001), "Long Span Bridge Health Monitoring System in Japan," Health Monitoring and Management of Civil Infrastructure Systems, Proceedings of SPIE, vol 4337, pp. 517-524.
2. Park, C. M., Park, J. C. (2003) "Seo-Hae Cable Stayed Bridge Behavior Analysis Using Sensor Data," KSCE Conference proceeding, KSCE, pp. 571-576.
3. M. Chae, H. Yoo, J. Kim, M. Cho, Bridge Condition Monitoring System Using Wireless Network (CDMA and ZigBee) ISARC 2006, 2006, pp. 332–334, IAARC, 3–5 October 2006, Tokyo, Japan.