SHM DATA – Management, Treatment, Analysis and Interpretation – a Solution for Permanent Monitoring Systems

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ABSTRACT: VCE as commercial monitoring service provider has gained considerable experience in the topic from more than 600 projects worldwide. Data management, processing, analysis and interpretation are always a challenge especially in case of permanent monitoring. Monitoring systems with hundreds of sensors produce gigabytes of measurement data every day. Full automatic operation and analysis is required to provide the results in time especially in case of alert systems. The challenges for these systems are:

- Elimination of noise
- Reliable detection and removal of monitoring errors
- Data management (transfer, storage, archiving)
- Data pre-analysis
- Detection of events
- Correlation analysis and cross checking
- Statistical analysis
- Data analysis and diagnosis
- Triggering of action (alerts, automatic traffic management)
- Access to data
- Data presentation
- Support of systems operators and engineers for decision making

1 INTRODUCTION

Over the last 15 years numerous permanent structural health monitoring systems for bridges and structures have been installed. At the beginning a site visit for picking up measurement data and carrying it to the office was necessary due to the lack of data transfer possibilities. There was not even a possibility to get informed remotely if the system was running properly.

The rise of wireless standards like GPRS and UMTS paired with steadily decreasing costs for data transfer offered the opportunity to implement remote control as well as remote monitoring capabilities. Likewise internet access was simplified and got more and more widespread thus developing web based remote monitoring and assessment of bridges and structures was just a logical consequence of this development.

Permanent monitoring systems for bridges and structures are varying in shape, size, components, etc. substantially but in fact they do have some features in common. Although some of them consist of multiple subsystems, they are mostly realized with one central node which could be a PC or some kind of central DAQ-Unit that produces enormous amounts of monitoring data day after day and year after year. Data-management, data-transfer, data-analysis and the interpretation of the results with regard to structural performance, structural condition and structural safety over the service lifetime is a huge challenge.

2 REQUIREMENTS TO SATISFY THE END-USERS' NEEDS

Asset owners are interested to manage their structures, e.g. bridges with optimal cost-benefit ratio. This implies to match the goals which are minimization of maintenance effort and maximization of service lifetime, safety and availability for users. Permanent structural health monitoring can help to reach these goals. Asset owners and asset managers are not interested in the huge amounts of monitoring data produced by such systems (except for scientific purposes in some cases) but they are interested in the monitoring results and the interpretation of these results with regard to structural performance.

Advanced tools for data-management are needed to keep the personnel efforts low and to get out of the data as much as possible. In particular the following problems have to be addressed:

(1) Reliability of the monitoring system:
Tools which ensure the reliability of the monitoring systems. Operation interruptions and malfunction of system parts (e.g. sensors) have to be fully automatically recognized and the system operator has to be informed.

(2) Data archive:
The huge amount of measurement data has to be structured and archived in a redundant data library. Tools are required which allow easy access to the measurement data. This includes intuitive search functions.

(3) Measurement data quality control:
Measurement data could contain errors due to various reasons. These errors can impact the data analysis and lead to misinterpretations of the data. Tools are required which can detect and eliminate measurement data errors such as high signal noise, abnormal signal drift, spikes, breaks, jumps or saturation for example.

(4) Event notification:
Regular events (e. g. passing vehicles on bridges) or irregular events (e. g. earthquakes, storms) have to be detected and classified fully automatically. The result has to be transferred to the system operator.

(5) Analysis tools:
Many sensor types require calibration and analysis tools to retrieve useful information from the monitoring data (e.g. stay cable force from vibration data). Automatic analysis with reliable software tools is required.

(6) Alert functions and triggering of actions:
Tools for the management of alerts are necessary. If predefined threshold values are exceeded, fully automatic detection, alert and action triggering (e. g. influence on traffic flow) are required.

(7) Statistical analysis:
Statistical tools like auto-correlation or cross-correlation could provide valuable information on the quality and reliability of the measurement data but also on the behavior and performance of the structure. Tools for fully automatic and permanent statistical analysis are required.

(8) Data reduction:
In many cases the transfer of all raw monitoring data from the structure to the office of the system operator or the asset owner is not possible or not reasonable. Wireless communication often limits the amount of the data transfer. Tools for data selection and data reduction are required prior to the transfer.

(9) Data transfer:
Reliable data transfer plays a major role in many monitoring cases. Wireless communication via cell-phone network and internet is a common technology now. Software tools which manage the continuous data transfer without data loss also in case of network interruptions are required.

(10) Data presentation:
User interfaces which are simple and intuitive to operate are required. The user-interface is installed at so-called control rooms or monitoring rooms in some cases, especially for huge structures like cable-stayed bridges. But for most cases, especially for small structures such facilities are not available. Therefore web-based solutions like web-user interfaces are required.

(11) Support of system operators:
System operators are responsible for the permanent day-to-day operation of the monitoring system but also for the monitored structure in many cases. Sometimes one person is responsible for a number of structures. System tools are required which support the operator with their daily business but also help them with the handling of special events (e. g. accidents, earthquakes, storms).

3 DEVELOPMENT OF A WEB-BASED SOLUTION FOR THE REMOTE OPERATION OF PERMANENT STRUCTURAL HEALTH MONITORING SYSTEMS

In 2007 VCE started the development of a web-based solution for the operation of a structural health monitoring system. The development was triggered by the increasing number of permanent monitoring systems installed and operated by VCE. The development addressed all the above mentioned requirements and is still ongoing. The systems can be divided into software tools installed at the master station of the monitoring system on the bridge, software tools installed at the home office of VCE (or the headquarter of the asset owner) and tools installed at the computer (or smartphone, tabled PC) of the system operator.

3.1 *Tools at the master station*

The monitoring master station at the bridge collects the data from all sensors and from optional monitoring substations at high frequency in real time. The recorded measurement raw-data are initially stored at the monitoring computer in the master station on site. For high data integrity and safety the storage is carried out on two mirrored hard disks for permanent operation or on SSDs (solid state disks). This measure prevents data loss caused by single disk failure. The monitoring computer and other equipment are placed in a locked steel cabinet to avoid unauthorized access.

The monitoring computer is fully remotely maintainable via secure VPN connection. This connection may be established via an existing dedicated line or via mobile UMTS-based internet connection. The bandwidth of the UMTS-network is perfectly suitable for monitoring tasks. All monitoring results can be transferred to the server, at the same time remote control tasks can be performed without any limitations. Usually the data volume does not exceed 2GB/month.

The monitoring computer is equipped with sophisticated monitoring software. The software is capable of checking the function of the sensors, of quality control of the measurement data and of data analysis (e.g. analysis of the stay cable force from vibration data; traffic analysis).

The quality control function eliminates measurement data errors such as high signal noise, abnormal signal drift, spikes, breaks, jumps or saturation.

All measurement results that have already been transferred to the database-server are backed up regularly at short intervals and archived at a separate position. Additionally these results are also stored on the monitoring computer on site.

All measurement raw data that are stored on the monitoring computer but cannot be transferred automatically (e.g. high-frequency acceleration measurements) may be copied onto an external USB-drive, USB-pen or notebook and afterwards inserted into a structured data archive inside the VCE headquarters. This archive is organized according to structures and timestamps and is database-administrated. This method allows explicit assignment of monitoring data to the corresponding structure/project and works as a basis for later evaluation or more profound investigations.

3.2 *Tools at the head office of VCE*

The monitoring computer compresses the analyzed data and writes the results into the centrally administrated monitoring database via a secured VPN-link. The monitoring webserver and the database server are located in a safe datacenter environment at the VCE headquarters in Vienna, Austria. All measurement data are stored on two separate servers located in two separate buildings in order to prevent data losses.

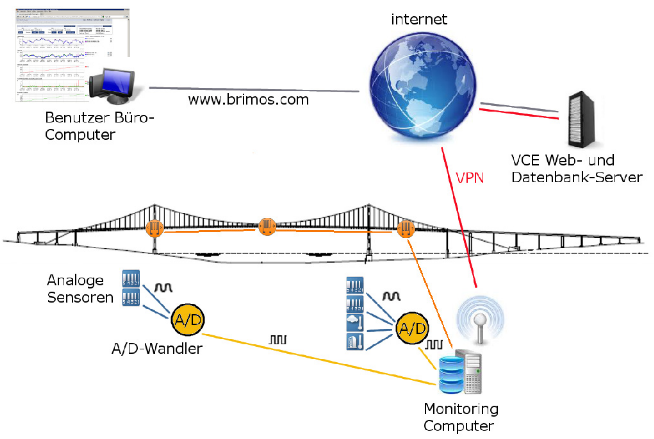

Figure 1: Data flow scheme of permanent monitoring systems with web-user-interface

The web-service and database servers are supervised by monitoring experts and IT-staff together at the VCE headquarters. Both servers are redundantly designed, high availability may be expected. Both, database schemata and web-service architecture have been completely developed by VCE and are continuously expanded. Therefore exceptional demands of monitoring projects can be easily considered and required additional features are implemented on short notice. Extensions may be also applied on a running system without suffering data loss.

3.3 *Tools at the device of the system operator – the web user interface*

The user side of VCE's monitoring systems is completely designed as internet based service, therefore no additional software programs have to be installed on the user's desktop or mobile computer. The access is done via widely-used web-browsers (like Internet Explorer, Mozilla Firefox).

The user interface can be seen as front end of the monitoring system, providing the interface for the operator and feeding the graphical display with condition and event-values and - if necessary - instructions for the personal. The operator chosen information is presented in a user friendly and simply understandable form. High frequency data is displayed in clear graphics (e.g. mimic panel format).

The web-user-interface offers the following features:

- Password secured user authentication for any number of users.
- Access of single users to features and monitoring data can be accurately scaled. Thus it is possible to grant different users within one organization different rights with full or restricted access. Every client has strictly restricted access to his own projects.
- General view of the monitoring project including a summary of all relevant information (monitoring dashboard)
- Display of time histories for any number of measurement channels. In addition to a complete view of all channels views for groups of channels may be arranged in order to increase the legibility of the monitoring results.
- Arbitrary time interval selection of measurement data for display and download (zoom function with different preset values for current week, current month, etc.)
- Different types of charts allow optimal visualization of monitoring data: line and bar charts, scatter

plots, special types for presentation of meteorological data.

- Automatic execution of mathematical operations and analytical processes enables calculation of measurement channels, correlation analysis, trend evaluation, limit-state criteria, classification, cycle-counting, pattern recognition, etc.
- Alarm messages or notifications may be sent via e-mail or SMS in case of exceeding or shortfall of static or even dynamic limits, missing data input or malfunctions like interruption of power supply. The notifications may be provided with an internal priority in order to separate “warnings” or “alarms”.
- Logbook function: The user has the ability to journalize events in relation to the monitored structure. In this way it is possible to oppose the monitored data to recorded impacts e.g. from construction works, extraordinary traffic events, etc.
- Real-time display of selected measurement channels allows the presentation of continuous data streams of dynamic high-frequency acceleration signals or other, rapidly changing parameters.
- Embedding of webcams on monitored structures
- Data export in common comma-separated ASCII-text-format for easy import into e.g. Microsoft Excel and other scientific software programs.
- Import of external data sources via different interfaces (web-forms, e-mail attachments, ftp- upload and download, database-replication mechanisms, etc.).

The internet service “Monitoring Measurement-Data-Treatment” is designed in a highly user friendly way. The login is carried out at www.brimos.com

Figure 2: Login area

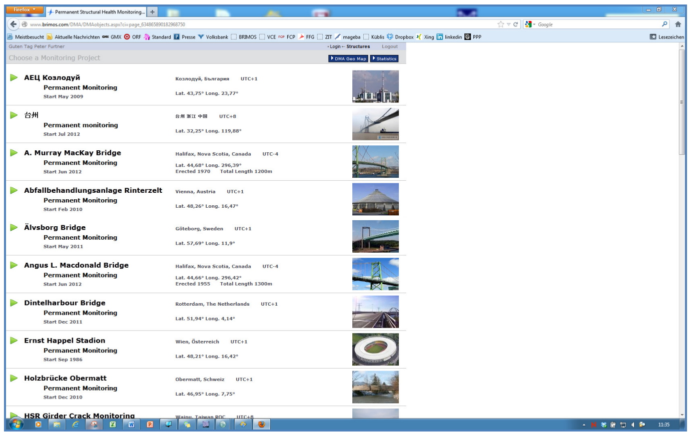

Figure 3: Project selection list

The project dashboard provides an overview of the structure, the monitoring task and also possibly existing notifications. Additionally pictures from webcams or contents from other webpages in relation to the monitored structures may be embedded. A list allows fast and accurate navigation to grouped time histories of adapted measurement channel selections.

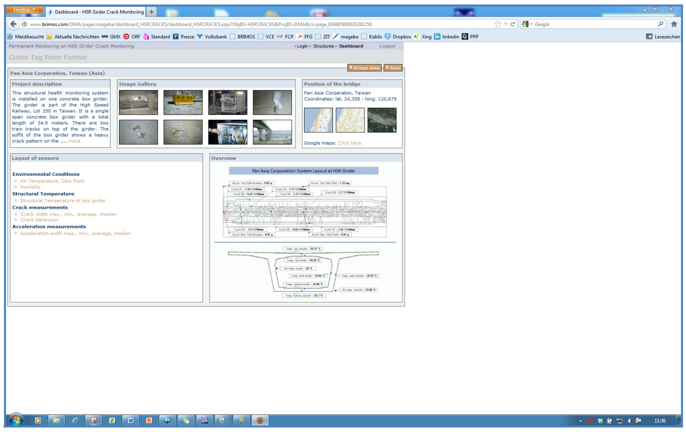

Figure 4: Project dashboard

The monitoring cockpit gives an overview of the structure together with the sensor positions and their instantaneous values. The notification module is shown below: A list of notifications (pending and/or historic) gives evidence about their source, the colored tag on the right edge indicates the severity of the message.

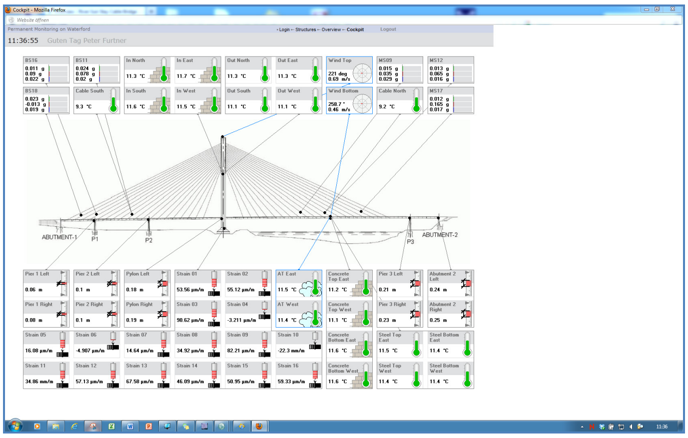

Figure 5: Monitoring cockpit

Figure 6 shows typical time history charts of multiply monitored parameters. The navigation area is positioned at the top of the page and allows the accurate selection of the time period to be displayed as well as the display of events and/or logbook entries. Specific kinds of diagrams allow detailed analysis of monitoring results. Figure 8 shows a correlation between two variables.

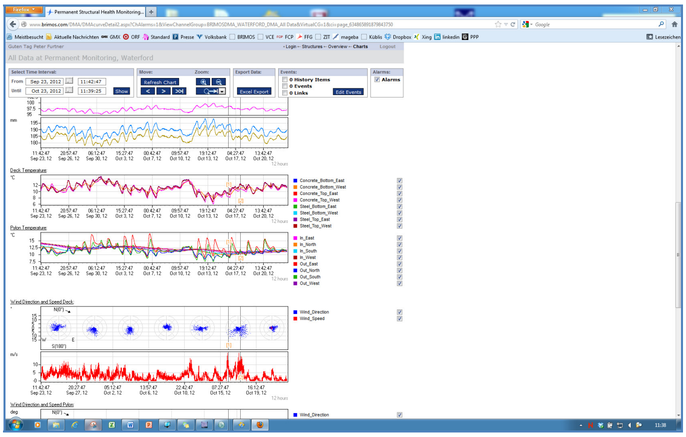

Figure 6: Typical time history charts

Figure 7 shows event-based evaluation combined with video analysis. This tool allows identifying the relation between significant effects on the structure (e.g. erratic displacement, extremely high deformation) and actual traffic load. The traffic camera is triggered by strain gauges installed in the center of the bridge.

Strain gauges and vibration measurement can also be used for automatic traffic analysis like vehicle weight analysis and speed classification. After some calibration runs with different vehicles the analysis is done fully automatically. The result is shown in Figure 8.

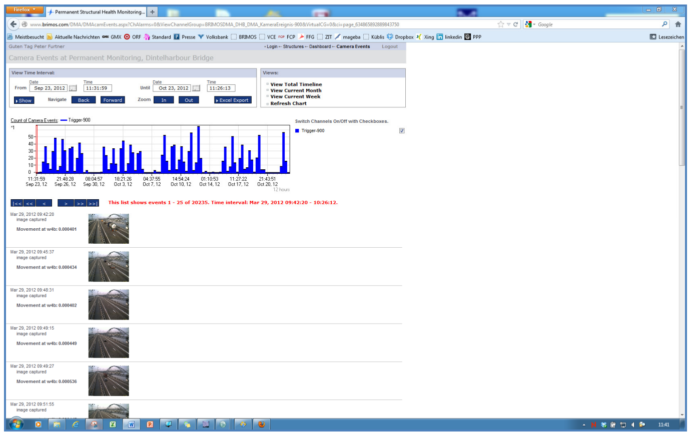

Figure 7: Event-trigger

Figure 8: Traffic analysis

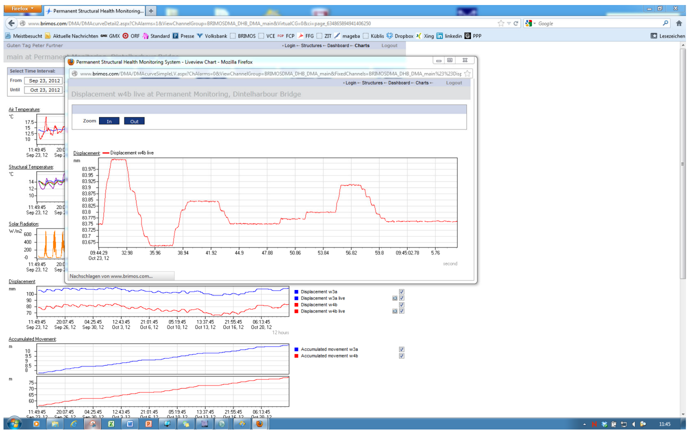

Figure 9: Live-view function (real-time continuous data-stream)

All monitoring data shown at the web-user-interface may be downloaded and subsequently imported into common software programs (e.g. Microsoft Excel, Matlab, etc.), if activated for the specific user. Additionally access to the raw-data can be disposed.

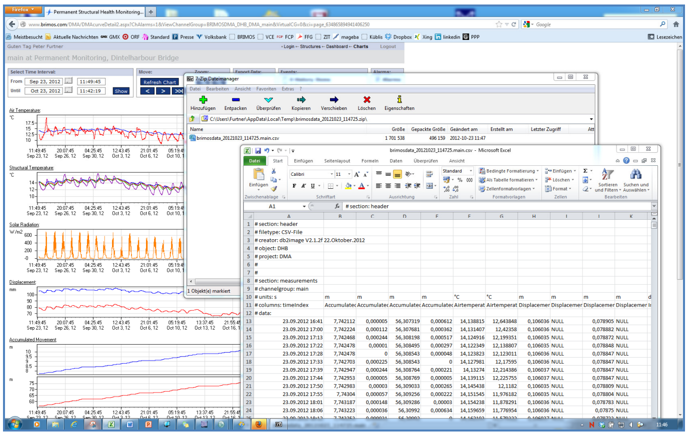

Figure 10: Data download in comma-separated ASCII-text format

The statistics toolkit of the web interface is one of the most important functions. Especially the auto-correlation and cross-correlation functions provide a lot of additional information on the condition and function of structural components as well as on the data quality.

Figure 11 and Figure 12 show typical examples. Figure 11 shows the correlation of the longitudinal movements of 2 bearings of one bridge. Figure 12 shows the correlation between wind speed and stay cable vibrations.

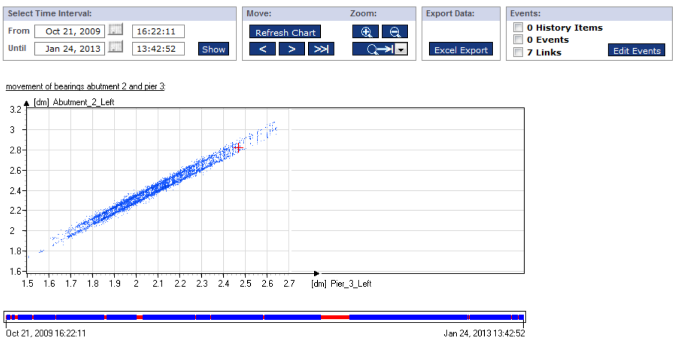

Figure 11: Correlation analysis – bearing movements

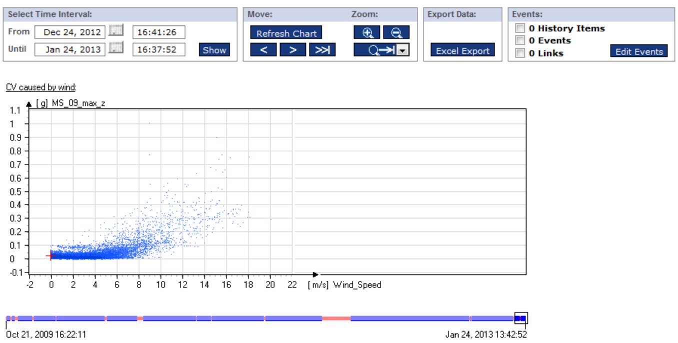

Figure 12: Correlation analysis – wind and cable vibration

Other functions, which are not described in detail here, are the automatic generation of reports which are presented in PDF-format. The reports can be provided on a weekly, monthly and yearly basis. The system is able to generate such reports when defined threshold values are exceeded. The reports are provided to the client via e-mail.

4 SUMMARY

The operation of permanent structural health monitoring systems can be a challenge. Especially the handling and analysis of the huge amount of measurement data requires sophisticated software tools. This paper describes the solution developed by VCE during the last 5 years within many monitoring projects all over the world. The main features are monitoring data quality assurance, automatic data analysis, data transfer and data presentation. The system will be further developed within monitoring projects in the next years.

5 REFERENCES

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