A Structural Health Monitoring Data Management System for Instrumented Cable-Supported Bridges

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ABSTRACT:

Three cable-supported bridges in Hong Kong, namely Tsing Ma, Kap Shui Mun and Ting Kau Bridges, have been instrumented with a sophisticated long-term structural health monitoring system. Massive high-dimensional data are continuously collected from this monitoring system, which are managed with a file-based approach. In order to handle the data for damage detection studies, a database system for current monitoring data management and an indexing system for history raw data management have been developed in the Hong Kong Polytechnic University. The database system consists of three modules: (i) an Oracle database of the 4D bridge model to maintain the spatial-temporal information about the bridges such as the bridge general information, structural information, sensor information, current raw data, analysis results, and inspection, maintenance and repair records; (ii) MATLAB-based structural health evaluation software package with an automated data swap mechanism which facilitates advanced data analysis; and (iii) a web interface for communication between the database and end-users through virtual reality 3D bridge models. The indexing system has two modules: (i) a MySQL database to maintain the information about the sensors and history raw data; and (ii) a web interface for displaying bridge and sensor information, querying data, and presenting query results.

INTRODUCTION

Over the past decade, the implementation of structural health monitoring systems on long-span bridges (with spans of 100 m or longer) to monitor their operational and structural conditions has been increasingly accepted in bridge engineering community. Structural health monitoring systems have been implemented on bridges in Europe [1], Canada [2], United States [3], Japan [4], Korea [5], and Hong Kong [6]. The first-generation bridge health monitoring systems were implemented in 1990's. They have

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evolved from traditional field testing or inspection to go far beyond intermittent data collection and limited data processing to include several subsystems such as sensory system, data acquisition and transmission system, data processing and control system, and structural health evaluation system. They accomplish continuous, real-time and long-term operation. Massive high-dimensional data are acquired and a file-based approach is usually adopted in the management of monitoring data. In the operation of these systems over the past years, it is found that the file-based approach often makes the data probing tedious, time-consuming and formidable because of massive quantity and high dimensionality of the monitoring data. It in turn impedes the data analysis to extract maximum useful information and finally impedes the bridge owners to benefit from the systems. The importance of a data management system capable of effective storage, query, visualization, swap and retrieval of the monitoring data, has recently been recognized [7]. In the development of a structural health monitoring system for the Stonecutters Bridge currently being constructed in Hong Kong, a structural health monitoring data management system has been designed [8]. This paper describes a structural health monitoring data management system developed in the Hong Kong Polytechnic University for managing the monitoring data from the Tsing Ma, Kap Shui Mun, and Ting Kau Bridges intended for damage detection studies.

STRUCTURAL HEALTH MONITORING SYSTEM IN HONG KONG

The long-span cable-supported bridges so far built in Hong Kong are the suspension Tsing Ma Bridge with 1377 m main span, the cable-stayed Kap Shui Mun Bridge with 430 m main span, and the cable-stayed Ting Kau Bridge consisting of two main spans of 475 m and 448 m, respectively. The three bridges constitute a major part of the transportation network connecting Hong Kong Island to the airport. The bridges were designed to serve 120 years and to satisfy stringent criteria resulting from Hong Kong's typhoon wind climate. After completing construction in 1997, the three bridges were instrumented with a sophisticated long-term structural health monitoring system called WASHMS (Wind And Structural Health Monitoring System) by the Highways Department of Hong Kong SAR Government [6].

The WASHMS comprises six subsystems, i.e., sensory system, data acquisition and transmission system, data processing and control system, structural health evaluation system, portable data acquisition system, and portable inspection and maintenance system. The sensory system consists of over 800 sensors including anemometers, temperature sensors, weigh-in-motion sensors, level sensors, global positioning systems, displacement transducers, strain gauges and accelerometers. The WASHMS accomplishes continuous, real-time and long-term running. Massive high-dimensional data are acquired from the system (the raw data are acquired at a rate of 140 MB per hour for the three bridges). The current practice of the WASHMS adopts a file-based approach in the management of the monitoring data. Because of the massive quantity and high dimensionality of the monitoring data, the file-based approach makes the data management a labor-intensive task.

MANAGEMENT OF CURRENT MONITORING DATA

In the WASHMS, there is no automated data swap between the data processing and control system and the structural health evaluation system. The current monitoring data are managed by the data processing and control system with a file-based approach and manually fed to the structural health evaluation system for advanced data analysis. Due to complexity of the data analysis and massive quantity and high dimensionality of the monitoring data, many pre-processing and post-processing efforts (e.g., the data format conversion, data file renaming, data file localization, and data swap between subsystems) have to be made to handle and organize the monitoring data and analysis results. In the analysis of data acquired in the past years, it is found that pre-processing and post-processing may greatly impede the data analysis if the data are not properly addressed. Hence, utmost care must be taken to these seemingly trivial pre-processing and post-processing work. To improve the effectiveness and efficiency of data analysis and the accessibility of analysis results, a database system is developed for the three instrumented bridges to manage the current raw data, analysis results and other information. The core of the database system is a 4D bridge model that integrates the spatial-temporal information covering the lifecycle of the bridges to the 3D models of the bridges. It consists of three modules: (i) an Oracle database of the 4D bridge model to maintain the bridge general information, structural information, sensor information, current raw data, analysis results, and inspection, maintenance and repair records; (ii) MATLAB-based structural health evaluation software package for advanced data analysis; and (iii) a web interface for communication between the database and end-users. The framework of the system is shown in Figure 1.

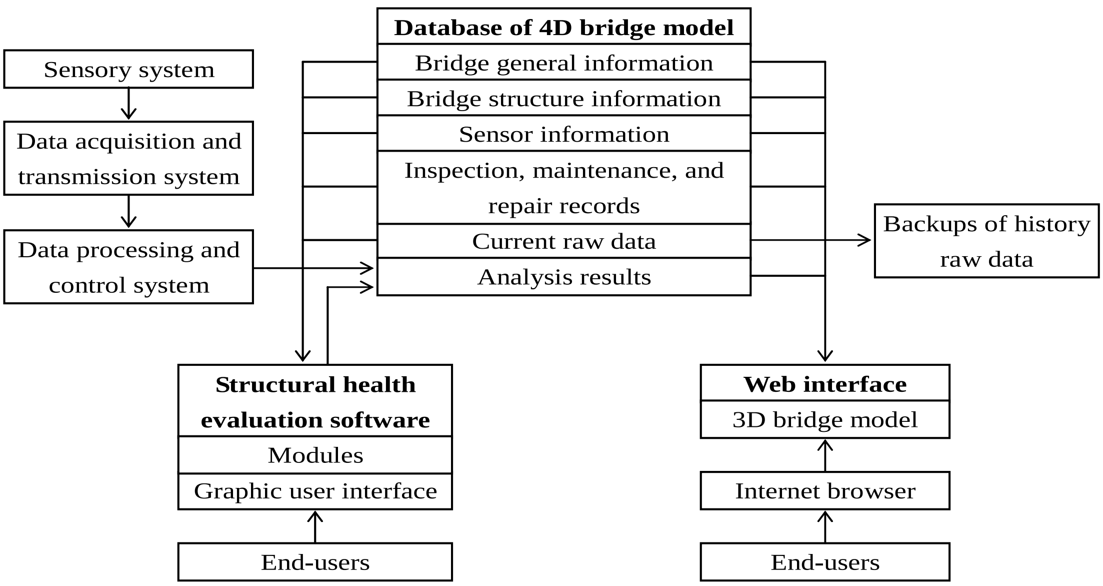

Figure 1: Framework of database system.

Database of 4D Bridge Model

Database is a shared collection of logically related data and a description of these data [9]. The main advantages of the database approach over the file-based approach are: (i) control of data redundancy; (ii) improved data consistency; (iii) improved data integrity; (iv) more information from the same amount of data; (v) sharing of data; (vi) improved data accessibility and responsiveness; (vii) improved productivity; (viii) improved maintenance through data independence; and (ix) economy of scale. Various database management systems have been developed since its root in 1960's. Among them, the relational database management system is the most widely used one. The database of the 4D bridge model is not excepting. It is designed with the relational database management system Oracle.

The database of the 4D bridge model is designed to retain: (i) bridge general information; (ii) structural information; (iii) sensor information; (iv) raw data acquired from the WASHMS in a recent period; (v) analysis results; and (vi) inspection, maintenance and repair records. The former three types of data are static information about the bridges and sensors stored for long-term use. The latter three types of data are dynamic information about the bridges which are either automatically updated at regular intervals or manually updated by end-users. The bridge general information includes the bridge name, type, static and dynamic characteristics, baseline model, etc. A bridge relation/table with attributes/columns of bridge ID, bridge name, bridge type and others is created to store the bridge general information. The bridge structural information includes the bridge components and their design parameters and physical properties, monitored members, etc. An element relation with attributes of element name, location, monitored members and others is created to store the bridge structural information. The sensor information includes the sensor layout, sensor specification information, etc. A sensor relation with attributes of sensor ID, sensor type, sensor channels and others is created to store the sensor information. The raw data are pre-processed, including data classification, data filtering, etc., before being reorganized into the database. Several raw-data relations are designed to store the raw data, each with attributes of time, data of channel 1 to channel *N*. The data analysis results, such as the safety index of bridge components, the rating levels, etc., are gradually created and accumulated in the database as the WASHMS running. The last part included in the database is the inspection, maintenance and repair records of the bridges.

Structural Health Evaluation Software

MATLAB-based structural health evaluation software package has been developed for advanced data analysis. It includes nine modules: (i) serviceability assessment making use of wind speed, deflection, expansion joint displacement, acceleration, etc.; (ii) analysis of wind characteristics, including mean wind speed and direction, turbulence intensity, gust factor, spectra of wind speed, etc.; (iii) correlation analysis between deflection and wind speed and model-based secondary analysis such as the prediction of extreme wind speed and maximum deflection; (iv) correlation analysis between expansion joint displacement and temperature and model-based secondary analysis such as the estimation of thermal expansion coefficient, prediction of extreme temperature and maximum displacement, calculation of accumulative displacement, etc.; (v) characterization of temperature-caused modal variability using neural network technique; (vi) damage detection using auto-associative neural network technique; (vii) damage localization using probabilistic neural network technique; (viii) analysis of fatigue life expectance; and (ix) safety index evaluation of bridge components based on reliability analysis.

Graphic user interface of the structural health evaluation software package is devised with MATLAB GUI. Two means of data analysis is provided in the interface, i.e., batch analysis and single analysis. In batch analysis, end-users need only set requisite parameters and the rest is done by the software. It enables end-users to accomplish data analysis in a fast way. However, end-users may fail to detect the abnormal raw data because of being not displayed in batch analysis. In single analysis, end-users should specify the time of the data to be analyzed. Raw data are visualized in single analysis, which enables end-users to catch closer insight into the raw data. However, single analysis is tedious because the data are analyzed one day/hour after another. Therefore, combined use of the two analysis means is recommended. Batch analysis is performed on all raw data first. Susceptible results are found and the corresponding raw data are pinpointed, if any. The selected raw data are then analyzed individually.

An automated data swap mechanism between the database of the 4D bridge model and the structural health evaluation software package is devised with MATLAB Database Toolbox. With this mechanism, the structural health evaluation software can acquire data by direct access to the database of the 4D bridge model and organizing analysis results in datum or figure format to the analysis result database.

Web Interface

Traditional computer applications in civil engineering mainly focus on analysis, design and construction of buildings and other structures. By using information technology, efforts have been devoted in this study to creating a web interface for authorized end-users acquiring information about the bridge structural health condition. The core of the web interface is the 3D models of the bridges. With the 3D bridge models, end-users can interact with the database system in a virtual reality mode. End-users can query the database by picking a specific element, and can obtain results as visual feedback in the 3D bridge model.

The 3D model of the bridge is created by converting the CAD drawings of the bridge into DXF (Data eXchange Format) and VRML (Virtual Reality Modeling Language) files. Different levels of details (LoDs) are designed in visualizing the 3D bridge model. The basic idea of LoDs is to use simpler versions of an object to meet different precision needs and improve the image rendering performance. Each LoDs group uses different referential center points and distance range and operates only on objects related to that group. For example, when the viewer is far from the object, a simplified model can be used to speed up the rendering. Due to the distance, the simplified version looks approximately the same as the more detailed version. End-users can navigate the 3D bridge model and select an element of the bridge by picking that element. Upon selection, the element will be highlighted and the related information about the element will be displayed. Several navigation behaviors are provided including drive, fly and orbit. Each button on the pointing device generates a different type of motion while the button is pressed.

MANAGEMENT OF HISTORY RAW DATA

Due to the limited storage capacity of database system and host computer, an indexing system has been developed to manage the history raw data. The WASHMS stores raw data in a propriety data format which is not directly compatible with data analysis packages. To facilitate the data analysis as well as save the storage space, a data format conversion application has been developed to convert the raw data into MATLAB binary format data. Besides the converted raw data, their pertinent information such as the channel name, unit, sampling frequency is also saved. Backups of these data are packed into labeled DVD disks according to the sensor type and sampling frequency.

The database of history raw data is designed with the database software MySQL. Two relations each with many attributes are created to hold information about the sensors and raw data, respectively. A client/server architecture running on the internet is adopted for the communication between the database and end-users. The web interface is designed with the web server software Apache and Tomcat. Figure 2 shows the home page of the indexing system. It presents a briefing about the three bridges and the WASHMS. End-users can link to the home page of the indexing system for a specific bridge by clicking its image as shown in Figure 3 for the Ting Kau Bridge. In Figure 3, a briefing about the bridge is introduced and the instrumented sensor types are listed. More detailed sensor information like the sensor layout, installation location, and sensor ID can be found through the hyperlink on the home page. Figure 4 illustrates a query interface of the indexing system, where the users can search for desired data by specifying sensor ID and time period. The time period can be input using a calendar or sliding bars. The sensor picture and ID, label of DVD disk, and time period associated with each searched file are displayed to the users for retrieving data from DVD disks as shown in Figure 5. The indexing system greatly facilitates the data probing work and provides a good way for the management of history raw data because of the limited storage capacity of a database system.

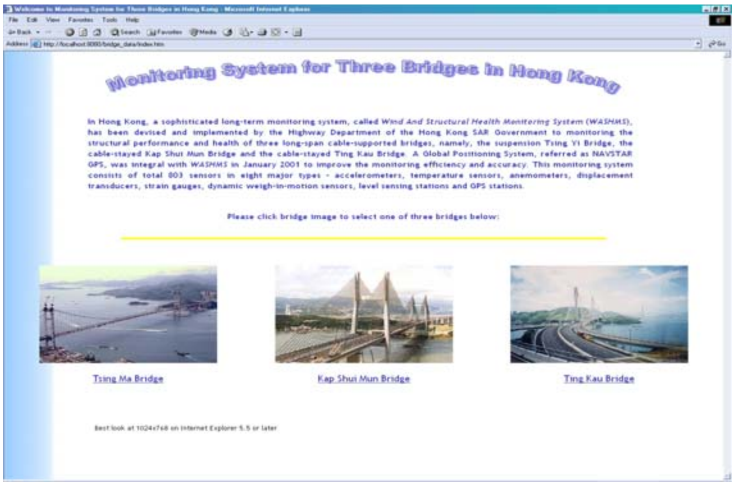

Figure 2: Home page of indexing system.

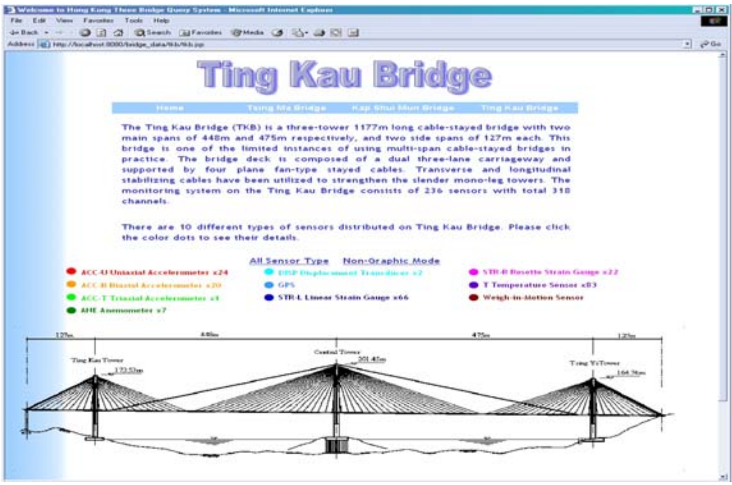

Figure 3: Indexing system for Ting Kau Bridge.

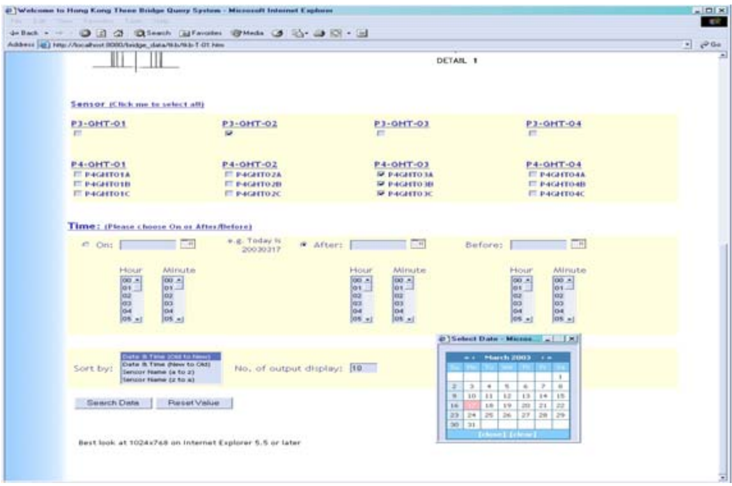

Figure 4: Query interface of indexing system.

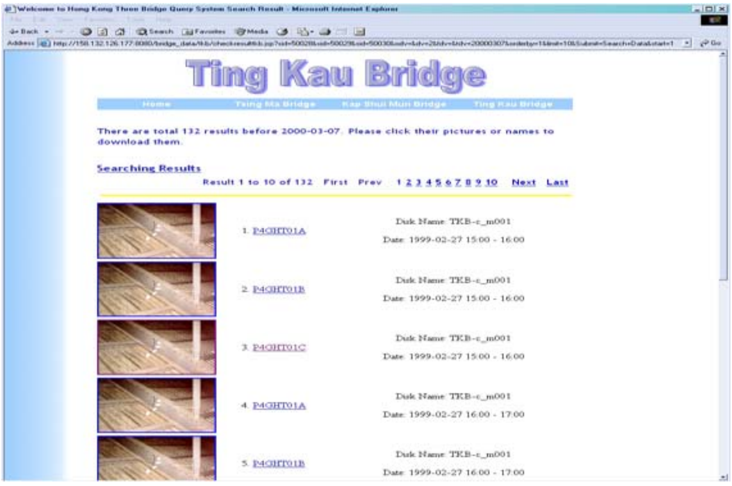

Figure 5: Result display of indexing system.

SUMMARY

This paper describes a structural health monitoring data management system for managing the long-term monitoring data stored in the Hong Kong Polytechnic University from the Tsing Ma, Kap Shui Mun and Ting Kau Bridges, including a database system for current monitoring data management and an indexing system for history raw data management. It has been shown that (i) developing a data management system is imperative for storage, query, retrieval, and visualization of huge volumes of measurement data from a sophisticated monitoring system; (ii) a database system for current monitoring data management in conjunction with an indexing system for history raw data management can greatly facilitate the data probing work and overcome the problem of limited storage capacity of both database system and host computer.

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