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ViBest SHM: an information system and data repository for structural health monitoring

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ABSTRACT: This project has been motivated by the need to standardize, preserve, and share the data sets of the Laboratory of Vibrations and Structural Monitoring (ViBest, www.fe.up.pt/vibest) of FEUP, produced by several long term projects individually managed. The solution presented is meant to support the process of Structural Health Monitoring, offering features to catalogue the projects, their goals and components, to store and visualize their acquired and processed data through time, and to preserve the data in a standardized form for all the research unit and extensible to future applications. The result is a digital archive with automatic ingestion of new data files and a Web interface with access control and tools for information management. There is a batch export functionality to deal with large data transfers. It is being used on monitoring data related with different kinds of structural health monitoring applications. The standardization and preservation of all data sets acquired in multiple applications will be certainly a solid basis for further research, either at a local basis or in the context of international joint cooperation.

KEY WORDS: Structural Health Monitoring; Scientific Data Repositories; Digital Archive.

1 INTRODUCTION

Vibration-based Structural Health Monitoring (SHM) implies the study of behavioural characteristics of a system through time. It implies the analysis of long time series and the detection of damages in the structure based on statistical pattern recognition [1]. It is a process divided in four different stages: an operational evaluation, data acquisition and cleansing, feature selection and data compression, and statistical model development [2].

Creating a standardized platform with all the tools that researchers need to perform their analysis in Vibration-based SHM would be a very hard task. Each research project may require different tools and configurations for each step of the process and each project manager must have freedom to choose the best tools, routines and configurations for his projects. In many cases, the documents, data, tools and information related to each project is managed by the corresponding researchers and is stored in their work computers. The result is that the information becomes difficult to share and hard to preserve, once the project ends.

Nevertheless, typical projects in this research area share a common setup: there is a structure to be monitored, a project to frame the work, a data acquisition system, one or more data streams, data processing, and project reports. So it should be possible and profitable to build a digital archive to gather the information of all the projects from a laboratory along with their data streams, thus granting integrated access to their characteristics, goals, instrumentation and configuration, as well as to data visualizations and statistics. Besides, storing data in such a platform eases the establishment of preservation procedures.

There is a growing trend for research funding agencies to require not only the dissemination of research projects results but also the publication of the data acquired under the project context upon which the results are based [3]. Research centres and laboratories have interest on granting controlled access to this stored data, in order to allow cross-checking of their results by other researchers and also to foster reuse of, so often, unique data to create new knowledge. The cost and expertise required to set up the experiment and assemble reliable data sets, justify sharing them through the Web, for further research initiatives. This new research paradigm where scientific data sets are curated and made available to other research groups is being called e-Science.

The goal of this paper is to propose a scientific data repository adequate for SHM. It must guarantee the storage and preservation of large data sets; allow easy data access to analysis tools; support the research process core requirements for SHM research centres; and possess a Web interface with access control. The next section presents the research centre, its activity and its goals. Section 3 discusses some descriptions and paradigms of the Structural Health Monitoring Process. Section 4 presents the proposed system and its modules. The system integration in the SHM research process is the object of Section 5. The final section presents some conclusions and points to aspects for further development.

2 VIBEST LABORATORY

ViBest – Laboratory of Vibrations and Structural Monitoring is a facility / research unit of the Civil Engineering Department of FEUP that conducts experimental and numerical works in the context of the development of research, consultancy and teaching activities in the field of Structural Dynamics, aiming in particular at the experimental characterization of vibratory phenomena, and the analysis, identification, monitoring and control of the structural behaviour under different types of dynamic loads.

2.1 *Activity Domains*

The main areas of activity of ViBest are the following:

- Experimental characterization of vibratory phenomena;
- Analysis and identification of dynamic properties of structural systems;
- Finite element modeling and updating of large Civil Engineering structures;
- Numerical and experimental assessment of traffic induced vibrations;
- Aeroelastic analysis of slender structures;
- Long term monitoring of the dynamic structural behaviour;
- Vibration based damage detection;
- Passive, active and semi-active control of vibrations.

Special attention has been given to the study of dynamic problems in bridges and special structures, such as:

- Dynamic behaviour of cable-stayed and suspension bridges;
- Modal parameter identification based on forced vibration, ambient vibration and free vibration tests;
- Evaluation and control of dynamic effects of traffic loads in railway and roadway bridges;
- Analysis of fatigue;
- Buffeting and aeroelastic instability analysis of long span bridges;
- Design and tuning of vibration control devices in footbridges and cable structures;
- Construction and long-term monitoring of bridges, dams, turbine towers and special structures;
- Dynamic analysis of large stadia and cable roofs.

ViBest Lab's activity is spread around the globe, having participations in projects of several structures, from bridges (railway, roadway or pedestrian), stadia and other constructions, encompassing researchers with several academic grades [4][5][6][7][8][9][10].

2.2 *A Repository for ViBest's Projects*

The way different monitoring projects have been configured and managed by different researchers is one of the main concerns of the proposed system.

Several monitoring projects have been developed during the last ten years, managed by several project managers, each one with a specific configuration. Different dynamic monitoring systems have also been used to perform accurate measurements in several points of the structure under analysis. The raw collected data is kept in data files, stored and subjected to several processing operations by algorithms developed by the researchers. The way files are structured has some variations among different projects (depending on the project's team). The meaning of each data value in data files is not always clear because the information about each project is scattered through several documents and files.

The increasing number of projects and the new requirements on data availability and reuse raised the issue of building a data repository to overcome those shortcomings. The data files should be standardized and information about their structure and meaning must be readily available. Also information about the data production environment and about the project and its team is required, in order to assign credibility to the data and to convey enough information to make it understandable and usable by other researchers. Search and visualization functionalities are important for the practical use of the system, including the possibility of displaying at least some MATLAB data files, a relevant tool in this context. The goal is to build a common tool to manage and visualize the laboratory's research data in a user-friendly and flexible enough way.

3 STRUCTURAL HEALTH MONITORING

Structural Health Monitoring (SHM) is a process to detect and characterize damage in engineering structures. These damages are associated to changes of the structures' materials or properties, as well as changes in the surrounding conditions (such as wind or traffic) which have influence on the structure's performance.

According to Dawson [11], SHM involves the following steps:

- System's observation through time, with periodical readings from sets of components deployed on the structure;
- Extraction of features on those measurements;
- Statistical analysis of those readings to determine the current status of the structure's health.

This process interacts with a structure's day-to-day exposure to the surrounding conditions and several events that may expose it to wearing conditions (e.g. storms, floods or earthquakes), which may give interesting information to researchers.

Sohn, Farrar, Hemez, & Czarnecki define some topics on statistical pattern recognition for SHM [2].

3.1 *Operational Evaluation*

There are some questions to be answered before setting up the monitoring system related to several bounding variables and the way they may cause any influence on the readings acquired from the system. A goal must also be defined for the system monitoring:

- How damage is defined for the monitored structure;
- The boundary conditions of the activity and the environment, which will surround and have influence on the monitoring operations;
- The limitations on the data acquisition;
- The goal of the monitoring, in terms of safety and economical savings for the future.

3.2 *Data Acquisition, Fusion and Cleansing*

This part involves the selection of the components to deploy in the monitoring system and their location on the structure. The planning of all the schematics of the monitoring system and its hardware components, linked together to acquire, process and store data is related to this topic of data acquisition and fusion, which also requires a decision on the best way to integrate all measurements from the several sensors in order to better detect the damages to be traced.

Data cleansing has the purpose of cleaning the acquired data, requiring the researchers to decide which data to accept or reject from the acquisition system.

3.3 Feature Extraction and Information Condensation

This topic requires the identification of data that may provide useful information concerning the damages being tracked.

One has to process that data, in order to make it more readable and easy to track for relevant information on the structure's behaviour and health. This may sometimes require some processing and compression routines, as the acquired measurements come in large volumes. Some other processing may include noise reduction and error tracing and deletion.

4 VIBEST SHM

ViBest SHM is a digital archive with some specialized features for data acquired in ViBest Laboratory's structural monitoring projects. The data files mostly come regularly (once every 15 minutes, for example) from the data acquisition system deployed in the monitored structure, through a communications network, and are stored in the repository server file system. Then they are pre-processed to remove garbage and possibly produce some normalization. The pre-processed data files are stored, too. The specific analysis algorithms, often developed by the ViBest researchers, may still produce result data files, for example with the structure's spectral evolution, which are also added to the repository.

The metadata describing the data files and the project creating them is stored in a relational database, according to a specifically developed metadata architecture.

To record and query the metadata, a Web interface has been developed (see Figure 1). This interface controls access by visitors and by registered users to the acquired and processed data streams of each project, offering features for graphical visualization of the data and statistical analysis.

Figure 1. Web interface home page

These several components shall work together, in order to provide an easy access to the data for the researchers, analysis tools to ease the creation of new knowledge from the information stored in the system and a set of mechanisms to allow the researchers to work on their data.

4.1 Metadata Model

The digital archive metadata model is structured in three different levels: context, system and data (see Figure 2; for a more detailed description, see [12]). Some model elements, like person and document, will be linked to all the levels, allowing the creation of associations of documentation and authorship of any element in the database. The main goal of this architecture is to record information to characterize each one of the projects and their systems, according to the topics described below in the process of SHM.

4.1.1 Context

Context information refers to all the relevant objects in the project's environment. It includes information about people, documents and entities related to the context, the structure on which the project is implemented, related events and the information describing the project itself.

4.1.2 System

This level encompasses the configuration and deployment information about a monitoring system. It contains more technical data about elements that integrate a project's data acquisition system, such as hardware (computers or sensors) and software (acquisition and processing routines) components. This level records the components' choice and configuration, their location and deployment on the structure, the specific purpose and the behavioural patterns to analyse.

From this module, it shall be possible to understand the disposition of the system on the structure, the way the data is acquired and the location and role of each component in that operation.

4.1.3 Data

The data module describes the data files generated in the data acquisition process by the monitoring system. A data set defines the common characteristics (variables under analysis, sampling periods, type of data – raw, pre-processed or results –, file structure) for all the files in a data stream.

Figure 2. Metadata model

These data sets group several data files according to the defined characteristics. Each data file contains data acquired in a time period. The database will keep the information to identify and allow access to the object stored in the repository, allowing the application to access the latter and to retrieve the information it contains to the several visualization options.

4.2 Interface

The interface was developed using the Vaadin framework, a tool to develop rich Internet applications, using the Java programming language, providing features to design the interface and to implement a data architecture and access [13].

It has an access control, using a login feature, controlling which users have access to which elements at each project, differentiating project managers, researchers and external collaborators (as well as the administrator role – lab director – common to the whole system). It comprises features like parameterization – people, entities, structures, projects, data sets and documents –, search and visualization (see Figure 3).

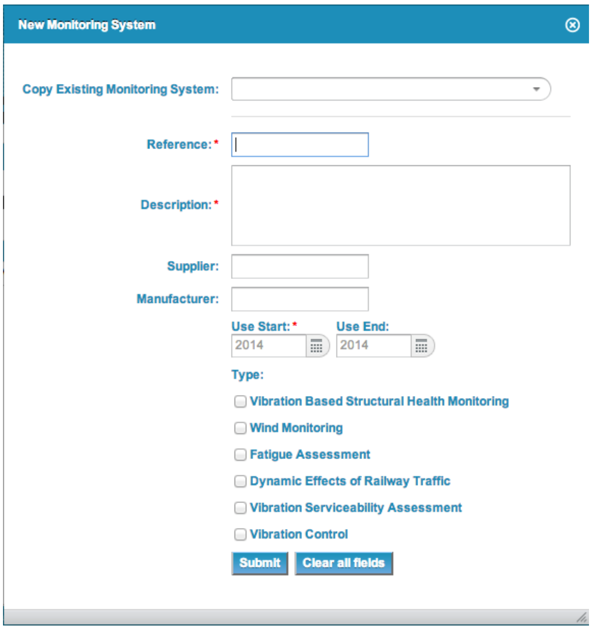

Figure 3. Form to create a new monitoring system record

Due to the large quantity of data files, some cautions must be taken when using the data visualization features, to limit the size of the data to a reasonable value. A user with the proper permissions may access the information about the project's monitoring systems or its data sets. By accessing a data set, a user can perform a search of its data files (Figure 4), where one of the fields allows a selection of a time period. Accessing a data file, one can select the option to download the file or to generate its graphical visualization and statistics (Figure 6), being able to choose which columns to plot. This plotting option is also available in the fetched data files list, plotting the data in the selected time period, even if it is a result set from more than one data file.

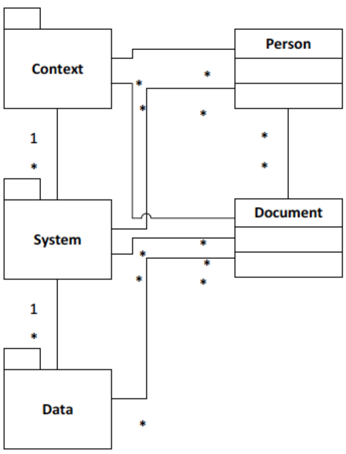

Figure 4. Form to select a set of data files in a time period

4.3 *Digital Archive*

The digital archive uses the file system to store the acquired data files. The root directory is divided into sub-directories for each project and monitoring system, which store the data files from each data set, organized by their sampling start dates. This information is also available in the file's own name, which is supposed to identify the project, the sampling date, its data type and the file extension. The naming format is

PROJ_SUByyyyMMdd_hhmmss[mili]_typ.ext

where PROJ_SUB identifies the project and its monitoring system, yyyyMMdd_hhmmss[mili] identifies the sampling start date, _typ identifies its data type (raw, pre or res) and .ext identifies the file type (.tab, .csv, .prn, .mat). This file name, with common structure and standard for every project, will help in another routine installed in the system, which will periodically synchronize the repository with the database, to create the records of newly stored data files. This organization and interaction between the repository and the database allows the latter to be lighter and to keep just a record of every file, with which it is possible to the application to access its location in the file system and fetch its content to be read and used for visualizations.

5 INTEGRATION WITH SHM PROCESS

One of the main concerns during the development of the digital archive has been to find standards to handle the laboratory's information. The metadata architecture with detailed contextual information on the projects associates institutional, contractual, authoring, and technical information to the data, thus transforming the repository into a digital archive. Visualization tools implement the structure analysis step of the SHM process. Being available on the Web, the information is easy to share, providing potential to scientific and pedagogical collaboration.

5.1 *Standardization*

Before the digital archive development, the information on the several projects and related components was dispersed and limited to the project researchers. Currently, the project teams have compiled all the information relative to the projects' characteristics to feed the database. In a project's page, one can find its operational information, including a full description of the monitored variables and the operational conditions of the monitoring system together with a detailed description of its components, their organization and distribution along the structure (Figure 5). Complementary documentation, schemas and images are easily integrated.

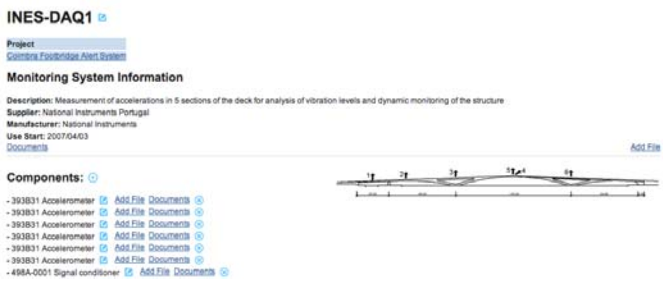

Figure 5. Monitoring system information and components

Each data set will describe the data it represents, its type and time period and reading configurations, such as the sampling interval, frequency and the trigger (continuously or by trigger events), as well as the structure of each acquired set of data, describing the meaning of each time series and its measured variables and units. This metadata is systematically recorded by the project manager when creating a new data set. It is enough to give any other visitor, with the proper permissions, a complete picture of the project ant to enable him to understand and use any data set.

Using data crossing tools, it is also possible to perform a search for other data sets with common attributes, opening a path to information exchange and comparative analysis between projects on different structures and contexts.

5.2 Visualization and Analysis

Each researcher must have access to the system's stored data, so as to be able to visualize and work on it. The system implements the main services of a data digital archive. The data files acquired on the monitoring systems are kept in the laboratory's server and made available through the Web interface or directly in the file system to other tools. There are also visualization and analysis tools that complete the support of the SHM process.

For each data file, the interface provides options to visualize the signal produced by its acquired data, in the time series of the file's sampling period (see Figure 6). The user may analyse the signal and, from there, extract the relevant characteristics to his work. The user is also able to visualize the file's statistics: the maximum, minimum, average and standard deviation values for each measured time series. If the user wants to work over these files, with other tools available on his desktop, in order to execute other operations and to generate other visualizations not supported, there is a file download feature.

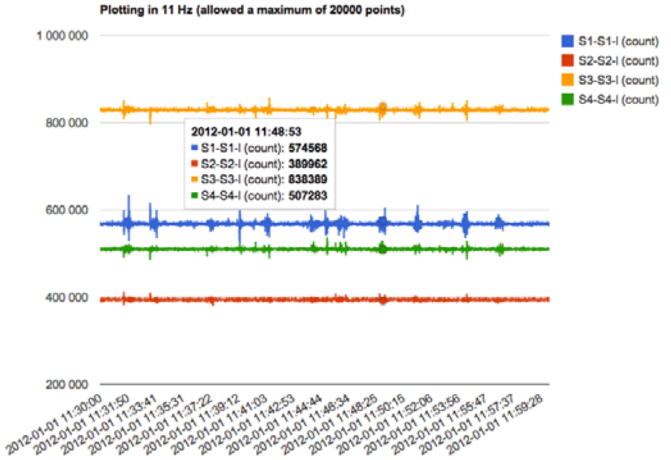

Figure 6. A chart generated from a datafile

5.3 Online Availability

The graphic interface that allows a user to access the projects and monitoring data information is available in any Web browser. Access to the generic project description is provided to any visitor, for the access restrictions are controlled through the user authentication.

There is an export utility that has been developed to support batch assembly of large collections of data files in a single compressed (zip) file. Successively downloading single files is not feasible. Online assembly in a compressed file takes too long and causes time out errors. That's why a batch assembly routine has been prepared which upon completion sends an email to the requester with the relevant link to download the result.

The potential to controlled data sharing is in place, opening way to future cooperation with other teams contributing with new analysis and new knowledge. Data from the different monitoring projects may contain new material for further research elaboration which may be disclosed to selected researchers or open on the Internet.

6 CONCLUSIONS

ViBest SHM brought a new organization to ViBest Laboratory, when it required a standardization of all data sets and files, organized their storage and access and provided means of documenting and storing information about every projects' characteristics, monitoring systems, components and configurations.

It is possible, now, to access a web interface and fetch information on several details of any of the SHM projects, retrieving the information on their characteristics and setups, such as sampling frequencies and periods, components configuration, deployment and use and several other features. With this, the laboratory has now an interface for visitors to be shared with the achievements and work of the ViBest's researchers.

The measurements acquired and processed on each project are stored in data files kept on a digital archive accessible through this Web interface, which enables the final step of this information storage and visualization: to gather the results of the monitoring systems procedures.

The implemented features are able to support the main steps of the SHM process: it is possible to store and find information on the several phases of a project, starting with its goals and characteristics; it is possible to directly inspect raw data as well as processed results that display behavioural patterns and to detect and monitor damages on a structure, through the graphical and statistical visualizations; technical documents, reports and papers are easily associated in the appropriate places highlighting the research results; establishing preservation procedures for the collected data becomes feasible.

ViBest SHM doesn't aim to be a tool for the researchers' processing operations. As said in previous sections, the set of tools used in research is very dynamic and a framework to consolidate all such tools would be systematically outdated. Instead, this system comes as a tool for observations and information archiving on the research work. It is a system to manage a dynamic digital repository of scientific data files and to allow researchers to get and share graphical visualizations and statistical analysis.

This way, the activity of the laboratory has a proper archive to share its projects and knowledge with the rest of the scientific community.

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