FRAMEWORK FOR INFORMATION MANAGEMENT IN MONITORING OF THE CONFEDERTION BRIDGE

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ABSTRACT

Monitoring of structural health of the Confederation Bridge began, with issues related to ice as the most prioritized ones, right through its construction phases and involved several actors and clients amongst the government bodies and Canadian universities. In course of evolution, however, the prodigious volume of the data so generated and the extensive customization leading to significant loss of the meta-data would consequence in an acute lack of agility and efficacy. Analyses of a global scale, thus, seemed to be heavily inflicted.

In an attempt to reestablish due agility and efficacy while also paving the path to integrate all the incongruities hitherto, a framework for management of the information, namely the IGLOO Framework, has been designed and deployed. The framework, besides adequately meeting the demands of agility and efficacy sought therein, also provides an example of a modular but inter-communicative architecture that could potentially be used as a model for similar undertakings. Furthermore, the ROLAP-based database system avails a promising template of managing disparate SHM data within a flexible, scalable, and homogeneous framework for routine and DSS-processing.

KEY WORDS

Structural health monitoring, database management, system architecture, information system, Confederation Bridge, ice force

1. BACKGROUND

The construction of an infrastructure unit also entails the efforts undertaken to assure it to be structurally, economically, and environmentally safe, sound and serviceable. In this suit, Confederation Bridge was constructed to provide a permanent link across New Brunswick and Prince Edward Island in Atlantic Canada. In the probability-based design work-out, lack of sufficient understanding of the phenomenon of interaction of drifting ice against an intercepting structure ultimately resulted in ice-forces dominating the lateral load spectrum besides convoluting the entire design and construction as well (Buckland et al. 1997), (Brown et al. 2001). Eventually, an exhaustive monitoring program, namely the Confederation Bridge Monitoring Program (CBMP), was conceived to monitor for the effects of ice forces, structural deformations, temperature, traffic loads and combinations, wind, earthquake and other transient load effects, and corrosion. The monitoring would be

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complemented by an additional comprehensive research program as a partnership between several Canadian universities and government bodies (Cheung et al, 1997).

In the course of evolution, the requirements and methodologies of the several receptor ends would impart considerable incongruity in the face and form of the data they seek for, besides of the data they themselves create- the latter being rather obvious. The consequence was trivial – formidable inconsistency in the dataset which was known to exist but never clearly understood. Some of the factors that contributed in the meta-data being mired, if not perished, include changes in the layout and format of the data-files, un-administered renaming of the variable-names, extensive adjustments in the measurement bases (datum, rates, baselines, and benchmarks), ambiguous nuances in the processing algorithms, and above all, no systematic and unified record of the changes being made. Furthermore, the prodigious volume of data effectively inundated just any other effort of further objective analyses. It became next to impossible to base the analyses on a larger set of data as in "looking at the bigger picture".

Monitoring makes the best sense only when it comes with due agility and efficacy, which was seriously lacking in the context of the CBMP. As a means of extrication, at least for the case of monitoring for ice-issues, an information management system has been architected, constructed, and commissioned which makes the substance of this paper. The information management framework (Tiwari 2006) is also readily scalable to accommodate all other dimensions of monitoring of the bridge, in fact, even to other Structural Health Monitoring (SHM), or Infrastructure Behavior Monitoring (IBM) schemes of the kind. And the database solutions founded thereupon avail a promising template of global data-management of typical SHM undertakings and assist the subsequent Decision Support System (DSS) applications.

2. SYSTEM ARCHITECTURE

In a pragmatic outlook drawn from the popular software design methodologies (Somerville 2001), management of information essentially embodies the processes that seek the synergistic combination of the so-called *twin-pillars* of the *data* and the *processing technologies* to enhance speed, reliability, and efficacy. In practical colloquialism, as the level and amount of intellectual interpretation ascends, the system of understandings is represented by the hierarchy *Data-to-Information-to-Knowledge-to-Decision*. Keenly, the term *data* itself is rather relative – anything can be *data* if it is likely to be subjected to further intellectual interpretation of any kind and any order. For holistic reasons, the features, capacity, and popularity (read support-base) of the *processing technologies* do tend to govern the overall modeling perspective despite whatever is prescribed in textbook rhetoric. Nevertheless, the management of information can be edified in terms of the following process elements – (1) Generation, (2) Storage and Access, (3) Processing, and (4) Dissemination.

An *architecture* is a framework for disciplined introduction of change. Simply because no explicit prescription is made does not imply no architecture exists, but might well imply a lack of standards; and the efforts expended can still be abstracted in terms of the process elements, in fact, it is procreative to do so. In the same lineage, requirement analyses are carried out by analyzing what already exists and what the desirables can reasonably be, as discussed in the following sections.

3. ASSESSMENT OF THE EXISTING ARCHITECTURE

As in a typical SHM scenario, the trail of the data itself begins with the data first sampled by instrumentation in the infrastructure unit, commonly known as the *field-data*. For semantic reasons, the field-data can be termed as **sensor-traces** which collectively represent the variables of external *stimuli* and the corresponding *responses* of the bridge (Tiwari and Brown 2004). Such a data-set would then be funneled through several strata of intellectual interpretation, or analyses, such as rectification by correction and filtering in the initial stages to statistical as well as core-engineering analyses in the intermediate stages to what-if analyses, simulations, and surrogate modeling in the later stages. The level and order of interpretations and analyses on the data are of a perpetual kind and so is the process of generation of data and thus the management of information as well.

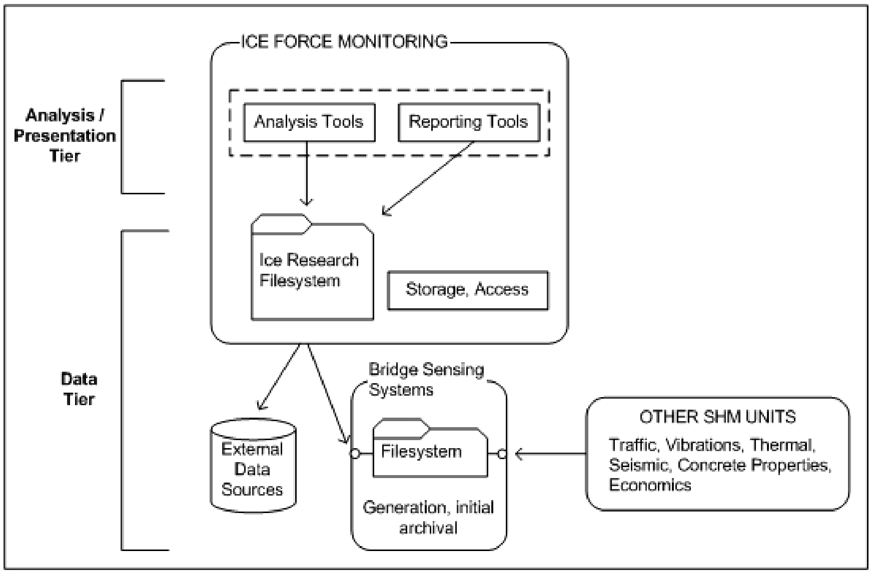

Figure 1: Layout of the initial system architecture. Source: (Tiwari 2005).

A landscape of the existing "chores" is reflected in Figure 1. A detailed treatise is presented in (Tiwari 2005). The following discussions elaborate some of the prominent particulars.

3.1 GENERATION

On the first hand, the sensor-traces are sampled, at different modes and sampling rates, as time-histories of the relevant variables, i.e., each recorded instances are *keyed* with the timestamp of happening. All such regular tabular character-data or the more esoteric data requiring ad-hoc software for a meaningful interpretation such as imagery and documents or the data/information generated after further intellectual interpretations can always be associated (keyed) to a particular time-of-interest. Such data are saved in the form of disk-files and archives of compressed files.

3.2 STORAGE AND ACCESS

As shown in Figure 1, as a crude usage of the filesystem, the files are simply saved in different forms and formats within a directory structure which has created a considerable dissimilitude. As such, it demands remarkable time to locate a particular band of information.

3.3 PROCESSING AND CURATION

Typicality has it that even to complete a single sequence of meaningful processing, the feed data have to be channeled through a number of tools (built on purpose) in different modes, environments, and platforms, often with discourses in the natural sense of sequence and with extensive reformatting and realignment to suit the input-requirements of the host system. In terms of coverage too, at times, new tools have to be developed or intensive human labor has to be expended in popular application suites to complete an analysis job. Typical processing jobs include calculation of loads due to ice followed by in-depth analyses of dynamics and stimuli-response spectrum, further characterization of the events, to name a few. Often, the results of one analysis lead to additional analyses back on the parent dataset, sometimes even the curation of the dataset itself in cases of identified mal-reporting of the sensors.

The tools developed so far also vary in terms of the structure and execution, some are implemented as extension of popular applications, some are in the forms of scripts, and some as compiled binaries, executable in different platforms. Even the algorithms have been nuanced, without any record, thus generating outputs with significant recondite inconsistencies. Lack of configurability forces one to invest considerable efforts on altering the source code while the shape of the program keeps morphing. Usage documentation also seems to lack in the existing tools.

3.4 DISSEMINATION

Traditionally, dissemination has been accomplished in the form of files and documents. The downside is that one or several documents with a lot more contents than the one sought for have to be disseminated even when only a particular band of information is sought, which is typical of an unstructured data-source. For sure, this also creates considerable confusion and waste of resources.

4. THE DESIRABLES

Because the ice issues monitoring is a sub-system within the entire SHM of the bridge, it is obviously affected by the inductions from the overall SHM policy of the bridge operations which implies that the stipulated objectives will be more of “carve” than “design” in some initial levels of the data administration. This leads to a modular design with task-orientedness and loose-coupling amongst the modules which can most easily be implemented in terms of a client-sever architecture, the server part primarily responsible for the data regime. The following discussions demarcate some of the prominent specifics.

4.1 GENERATION

Keeping untouched the process of generation and logging of sensor-traces, enhancements can be introduced in terms of web-based remote administration and collaboration functionalities for prompt notification, contents-exchange, and decision-making.

4.2 STORAGE AND ACCESS

By far, this is the most important process element in terms of the efficacy and reliability of the entire information system. It has been proposed that while maintaining the existing filesystem-based means, especially for reasons of back-compatibility and archival, a new system of database management based on Relational Database Management System (RDBMS) and eXtensible Mark-up Language (XML) be deployed.

4.3 PROCESSING AND CURATION

The foremost objective of reform is to have new tools created and existing tools re-engineered for mutual integration and compatibility so as to cater for the need of a homogeneous and uninterrupted processing environment. Effectively, when processing involves a flow through sequences, the output from one sequence should be readily amenable to be piped into another sequence with none or minimum of re-formatting and realignment required and also with the maximum possible automation. There should be ample room at the disposal of the user for any desired customization, configuration, and branching of the algorithms while the information after processing should be rich in terms of the relevant meta-data. The tools should also be intuitive enough for the user.

From a bird's-eye-view, then, the tools would be of two broad categories. For one, the *database management tools* would interface with the user and the data-stores, both of the traditional filesystem as well as the proposed structured DBMS. Owing to the heterogeneity in the raw data files, especially the issues of dispersion of congenial variables across and throughout logger stations, files, and archives, the issues of the health of the files, and the issues of formats, the database management tools should be able to diagnose, report, rectify, unify, and eventually populate the contents into the records of the database system, and that too without any error which otherwise will adulterate the dataset. For two, the actual analysis tools will assist in processing of the information for routine and other sophisticated engineering analyses. These include numeric computations and modeling, besides analysis of graphics, video, and geographic information. Such tools will interface with the database as well as the database management tools to save and retrieve the information.

4.4 DISSEMINATION

Dissemination of information, timely and accurately, is one of the most important aspects, especially when the objective is monitoring of some behavior. For this part, reporting tools and web-tools will be developed. Reporting tools, in general, will interface with the database to automatically publish reports within a prescribed scope and theme. Web-tools will best enhance the dissemination of information and prompt collaboration amongst the human actors, for instance, as with content-exchange, online (real-time) monitoring of instruments –

preferably as charts or graphs, online discussion forums etc. Being "web-based" ensures universality of client-side access (such as with web-browsers).

5. CONCEPTUAL MODELING

It thus turns out that the ultimate architecture would be aimed at availing a homogeneous bed of information management while accommodating all the existing legacy incongruities and also being able to scale up for any seen or unseen future requirements. These objectives can be best fulfilled with the formation being a conglomeration of specialized software systems, units, and tools that are mutually compliant and inter-communicative on the *processing side* while the communication of the processes and activity chains should be focused to a single database system on the *data side*.

5.1 DATA-MODELLING

Any SHM is predominantly a data-centric undertaking and an exhaustive knowledge of the meta-data is a pre-requisite for just any data-modeling process. Accordingly, to get over the incongruity in the shape and size of the data and thus begin the task of modeling for an organized system, a separate relational database system was first developed to rebuild the meta-database which now remains as one of the "smart" modules assisting in trafficking of the contents from the raw data-files to the structured database system (Tiwari 2005). Detailed derivations of the entire modeling process are also outlined in (Tiwari and Brown 2006).

Drawing from the concepts of the Entity-Relationship (ER) approach, the Geographic Information Systems (GIS) approach, and the Rational Unified Process (RUP), a **snap** class is derived as the unit of information carriage of any process time-history. The proposed *snap* class depicts a 3-dimensional data-set, namely in the taxonomical dimensions of time, theme, and space. The *member elements* of state and association in an RUP model-space, or the variables of *space* and *theme* in a GIS model-space, would be modeled as *theme* – which would map to the *fields* of the *table* in a relational model. The *unique identity* (primary/candidate) keys would be furnished by the timestamp. However, implementing the same as a *table* – a 2-dimensional data-structure, in a *relational* paradigm will necessitate some transformation from the state of 3-dimensionality into a state of 2-dimensionality. To accomplish the same, Relational OnLine Analytical Processing (ROLAP) methodologies have been adopted.

Let us define an **event**, declarable with any arbitrary *granularity*, as the *grain* of the ROLAP schema. *An event is anything that has happened, or is projected or imagined, that has been recorded*, hence also a *synthesis* of the analytical interpretations made on the process. The objective is to provide an *associative entity* (or a bridge table) to relate the various seen and unseen taxonomies of the dataset. In the lineage of the *fact*, then, an event is qualified by a *begin-snap* and an *end-snap* for basic identification while for *grained* (aggregated) relationships such as further objective **analyses**, an event could be assigned an identifier, say an *eventID*. The Snap-Event-Analysis (SEA) model is shown in the Figure 2.

In overall, the SEA model represents the entire ontology of the SHM process within a relational framework. In the SEA model, the S (snaps), the E (events), and the A (analyses) are only generic classes that represent generalized super-classes at the root level. There might be any number of *relations* (tables) corresponding to the specific classes inheriting from the root generic classes. For example, the members of the *snap* class would be the pressure sensors, the kinematics sensors, the ambience sensors and so on. Even the exact same sensors but sampling at different rates would constitute different derived classes. Examples include data correction events, wind events, ice load events, and so on. Any perceivable event can thus juxtapose any other event and/or instances of snap and/or analysis amongst each-other.

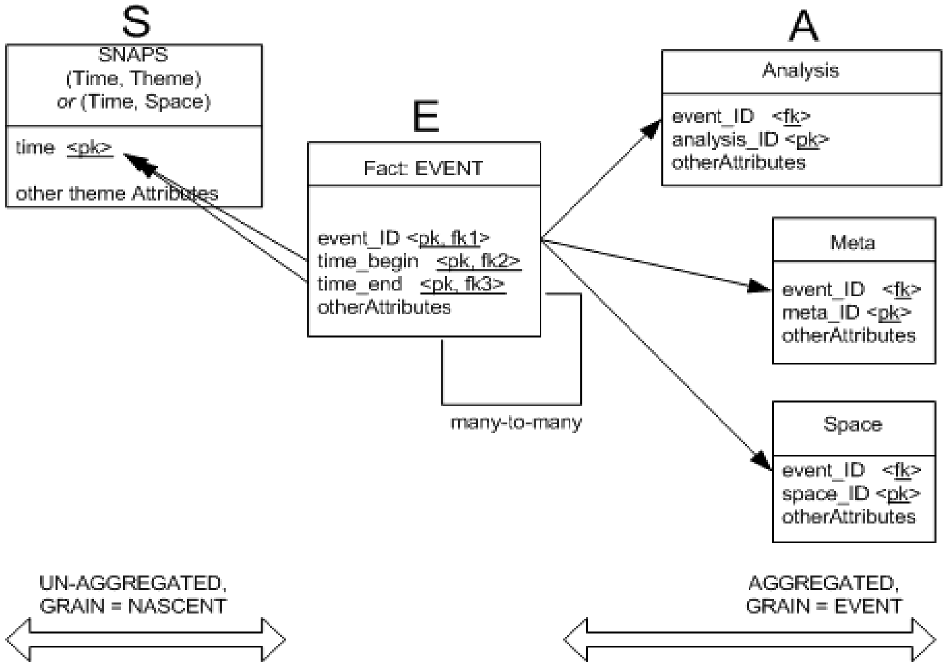

Figure 2: ROLAP-based SEA-model of data-keeping. Source: (Tiwari 2005).

5.2 DELINEATION OF USE CASES

In the stipulated pedigree, the conceptual model of the framework has been designed as the upshot of thorough and iterative requirement analyses, as shown by the use-cases in Figure 3.

Thus, as seen from Figure 3, the IGLOO Framework indeed represents a software system with sufficient task-oriented modularity, loose-coupling amongst the units, and flexible and compatible interactivity amongst the modules of any hierarchical order, besides others.

6. CONCLUSIONS

The SEA-model of database management can potentially serve as an excellent model of data-keeping and data-integration for the spatio-temporal data of SHM activities and relevant DSS applications, and also to provide a supporting avenue for ambitious futuristic projects such as the eCOGNOS and the Semantic Web. It is believed that given the importance of the ability to share the data and derivations from SHM applications and the lack thereof of a comparable model till date, the availability of a robust and scalable data-housing scheme, and hence unified formats and standards, has immense potential for the benefit of the relevant community.

The entire architecture can be an exemplary template for similar undertakings, especially in those cases which also demand for an efficient information management system while also inclusively integrating the legacies of mutual inhomogeneities and incongruities. As such the entire data, information, and synthesis are stored and managed within a single stage and it can be readily scaled to future requirements of the expansion of volume as well as scope.

Figure 4 illustrates the usage of a few features through the web-gateway (IGLOO Framework Web Gateway 2006) of the framework. As a proven accomplishment, the desired levels of agility and efficacy of the monitoring process have been duly established; in fact, also extended a lot beyond thus also opening a vista of opportunities for further research and analyses.

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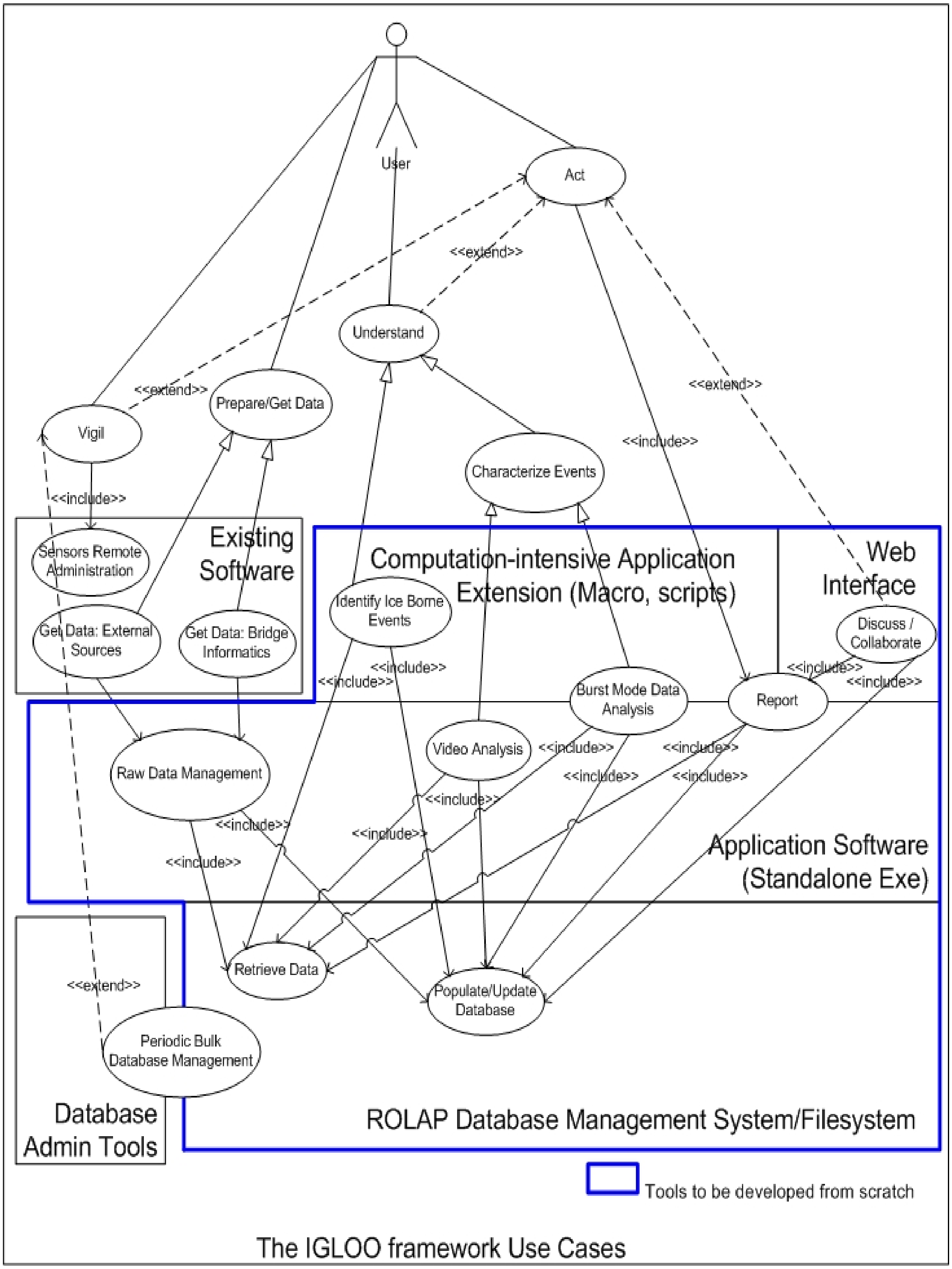
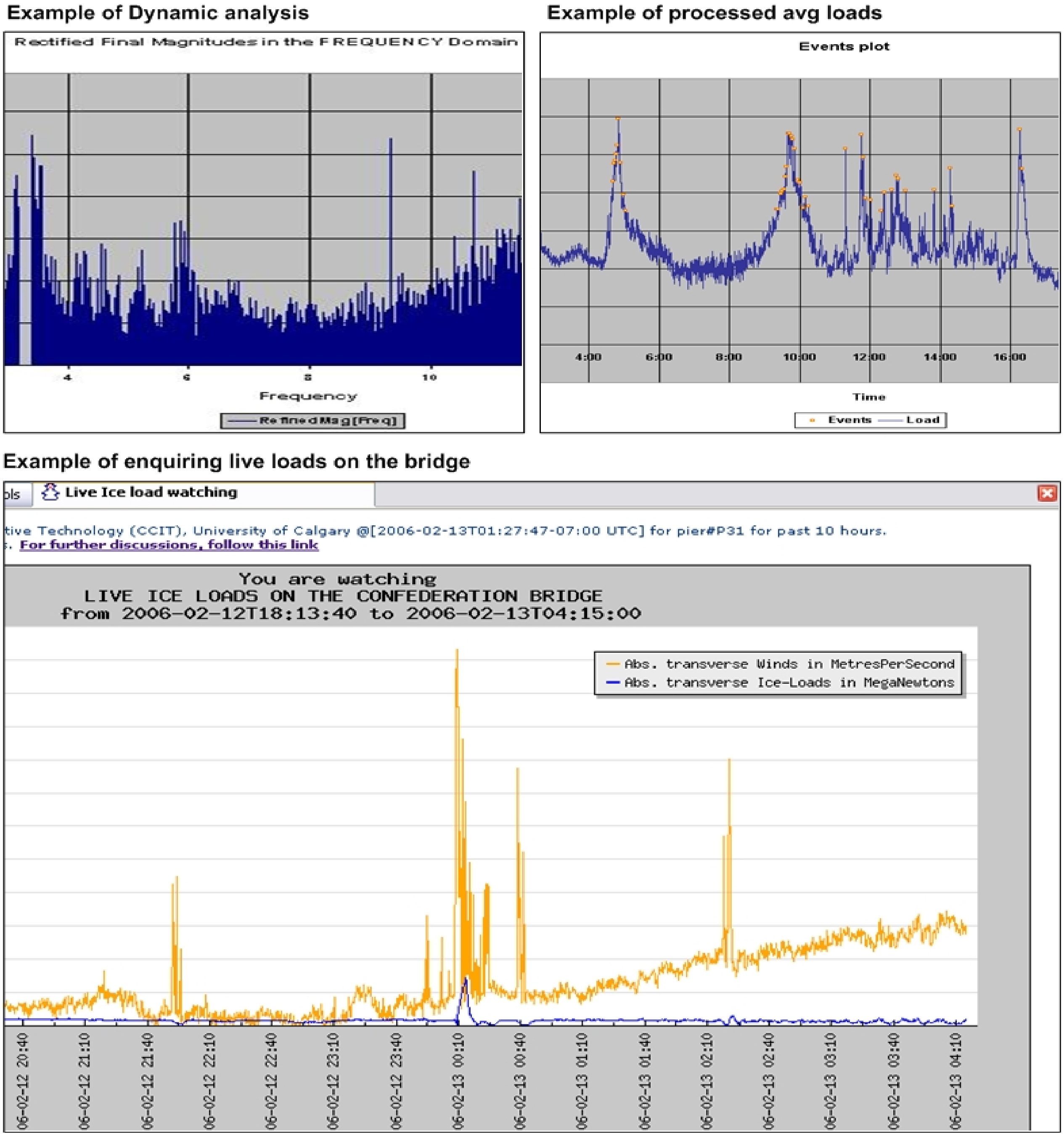


Figure 3: Prominent Use Cases for the IGLOO Framework. Source: (Tiwari 2005).



Example of Dynamic analysis

Example of processed avg loads

Example of enquiring live loads on the bridge

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You are watching
LIVE ICE LOADS ON THE CONFEDERATION BRIDGE
from 2006-02-12T18:13:40 to 2006-02-13T04:15:00

Figure 4: Few examples of the IGLOO Framework in action. (1) dynamic analysis done on the data from the sensors- that would be related to data-curation events and load events (2) ice load events determined from processed data and reported on a daily basis, and (3) live winds and ice-load feeds. The real gracefulness is demonstrated in the fact that the activities are carried out with just an internet browser on the client-end which provides unsurpassed flexibility in terms of personnel, time, and location. Source: http://www.ice.ucalgary.ca/