Integration of Knowledge-based Approach in SHM Systems: A Case Study of Force Identification

Fazel Ansari, Yan Niu, Inka Buethe, Claus-Peter Fritzen, and Madjid Fathi

Abstract—**This paper discusses the potentials for integration of knowledge-based techniques in Structural Health Monitoring (SHM). Knowledge-based techniques and methods reinforce health assessment and influence on predictive maintenance of structures. Using the case study of force identification, a concept of the knowledge-based approach is developed. In particular, a toolbox for force reconstruction in Canton Tower is implemented. The case study deepens the insight into identifying needs in the field of SHM to employ knowledge-based approaches, especially in the reasoning process.**

The proposed concept lays the ground for future research in the field of SHM for utilizing knowledge-based methods in correlation with SHM algorithms and analysis of feedbacks accumulated with/from sensors, engineers or customers. The foresight is to develop a decision-making component for supporting SHM systems, and in turn to foster the detection, localization, classification, assessment and prediction.

Index Terms—**SHM, Knowledge Based Systems, Force reconstruction, Reasoning process, Integration.**

I. Introduction

TODAY a variety of structures coming e.g. from civil, aeronautic, astronautic or, mechanical engineering sector need to be monitored. According to [1], approximately one third of all bridges in the US national inventory need either be repaired or replaced. The monitoring is not only expensive but also – depending on the structure – hard to be realized at all times e.g. after an earthquake or a typhoon. The emerging research area Structural Health Monitoring (SHM) assesses the state of structural health continuously or periodically in an automated way via direct measurements and through appropriate data processing and interpretation in a diagnostic system. SHM also allows the prediction of the remaining useful lifetime of the structures. The automated SHM system involves the sensors and their integration, the signal conditioning unit and data storage as well as data evaluation unit and automated diagnosis (see [1] and [2]).

SHM features a variety of sensing and data evaluation techniques, based on different physical principles and mathematical approaches. In general, it can be separated into passive and active methods. Active methods always introduce some sort of excitation into the structure. The sensing of its interaction with the structure is used to gain information about the diagnosis object. In contrast, passive methods do not require an additional excitation like active methods, but use ambient excitation like wind or traffic load. This way these methods investigate operational parameters and accordingly reveal the structures' state. Additional information is then needed to predict the remaining useful lifetime. SHM systems therefore can also be categorized into five subsequent levels: Detection, Localization, Classification, Assessment and Prediction [3].

Usage monitoring is the process of measuring responses of, and in some cases the inputs to, a structure while it is in operation [4]. The damage prognosis (DP) process attempts to forecast system performance by assessing the current damage state of the system (i.e. SHM), estimating the future loading environments, and predicting through simulation or statistical models as well as past experience, the remaining useful lifetime of the system, see [5] and [6].

An example of a technique used in SHM is the force identification. In many practical cases, it is difficult or not possible to directly measure the external force applied to the structure. One solution is to reconstruct the external force from the measured structural responses, e.g. acceleration. This process is often an ill-posed inverse problem, in the sense that small noise in the measurements may cause large deviation in the reconstruction result. Force identification is the process of solving this type of ill-posedness and provide the stable estimate of the external force.

Already the general overview on SHM, DP and usage monitoring reveals the potentials for developing and integrating knowledge-based approaches in the context of these kind of systems. The knowledge-based approach for

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SHM requires effective deployment of knowledge sources, and therefore uses semantics to establish the relation between entities and to create a Knowledge Base (KB). Here, the common attribute is "Knowledge" for reasoning (i.e. reasoning under uncertainty). The knowledge-based approach is derived from the principles of Knowledge Based Systems (KBS) [7], [8]. KBS consists of four core components: (1) Knowledge acquisition, (2) Knowledge representation, (3) Knowledge modeling, and (4) Dialogue system (User interface).

"Knowledge acquisition is the extraction of knowledge from sources of expertise and its transfer to the knowledge base"[9]. Knowledge acquisition methods are classified into three categories as: (1) Manual e.g. by means of interview, analysis of protocols, observation, case studies, brainstorming, etc. (2) Semi-automatic by direct support and influence of domain experts, (3) Automatic by minimizing or eliminating the role of experts or knowledge engineers. The automatic method to knowledge acquisition is ideal. However, the realization of an automatic solution depends on the advancement of the algorithms for transferring all required knowledge into the system. Therefore the semi-automatic method is the most used one.

In the context of KBS, the knowledge engineer is responsible to construct the system. The knowledge engineer contributes to domain experts who hold expertise in the problem domain (e.g. SHM). Using manual or semi-automatic methods, the knowledge engineer has a considerable role to be in contact with domain experts to submit questions, data and problems and to receive knowledge, concepts and solutions to be delivered to KB. KB is a warehouse which contains the required knowledge for formulating and solving problems with formalized structure [8], [9]. It provides the means for collection, organization, and retrieval of knowledge through establishing semantics between entities.

Knowledge representation includes two major forms, declarative or procedural [7], [8]. In declarative representations, knowledge stored as facts that must be interpreted, and it is accessible for a variety of purposes,while in procedural representations, knowledge stored as algorithms (program code), and it is usable only within specialized problem-solving contexts [7],[8]. In comparison, procedural representation is highly efficient in the correct context. Knowledge representation methods are e.g. predicate logic, rules, frames and scripts, or semantic networks.

Knowledge modeling are procedures for working with the knowledge stored in the KB, and mapping of the knowledge to fulfill certain tasks. It supports the acquisition and structuring of knowledge, formalization of knowledge for building KB, processing for solving a problem e.g. using inference engine, visualizing of the knowledge and so on [7], [8].

Moreover, a dialogue system utilizes a variety of knowledge sources and models. It is the main communication interface between users and system. The dialogue system is realized in the form of a graphical user interface which encompasses a structure and mechanism in the back-end for interpreting the entries of the user, matching them with the representation structure, and accordingly to provide an understandable output to the user.

In the context of SHM, reasoning is a critical endeavor due to reliability and safety requirements of the structures. Some SHM studies already consider advanced decision making components including a variety of factors and combining them e.g. via votes [10]. Nevertheless many SHM applications use algorithms of damage detection isolatedly, which is not an optimal solution and could not consider all influential factors of decision-making in a right time and place. To this extent, knowledge-based approaches to SHM can improve the situation through utilizing and integrating various knowledge sources, combining SHM algorithms, and deploying knowledge acquisition, representation and modeling methods.

In the area of fault detection and isolation of automatic control systems already various approaches taking into account knowledge based systems, existing examples can be found in e.g. [11] and [12].

In this paper we adopt the knowledge-based approach in the field of SHM by focusing on modeling rules. It reflects the first results on the conception of knowledge-based approach for a SHM system. Thus the primary objective is to develop the concept for reasoning in the context of SHM especially health assessment. In this way, the case study of force reconstruction is employed. The secondary objective is to foreground and highlight the promising potentials of this merging in future research.

II. KNOWLEDGE-BASED APPROACH IN SHM SYSTEMS

In this section, a case study of force identification is first presented. Secondly, the conception for the integration of knowledge-based approach for reasoning is proposed. The concept is developed based on the Need Analysis through discussion with the SHM's domain experts.

A. Case study of force identification

The knowledge of external loading condition is crucial for both SHM and future loading estimation. For high-rise structures, e.g. offshore wind turbines and tall buildings, wind load is a major concern in SHM. Even though an anemometer can provide information on the wind speed and wind direction at a specified height, the wind load is not only stochastic in amplitude and direction but also distributed in space, which makes a direct measurement not economical or not feasible. A potential solution is to reconstruct the loading history information from the structural response measurements, i.e. displacement, strain, velocity or acceleration.

The 600 meter tall Canton Tower is located in a typhoon active area, and a long-term SHM system has been designed and integrated into this tower [13]. These two points make the Canton Tower an ideal test-bed for the wind load reconstruction study using the field measurement data from the SHM measurement system. Figure 1 schematically

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shows a methodology adopted for the wind load reconstruction study [14].

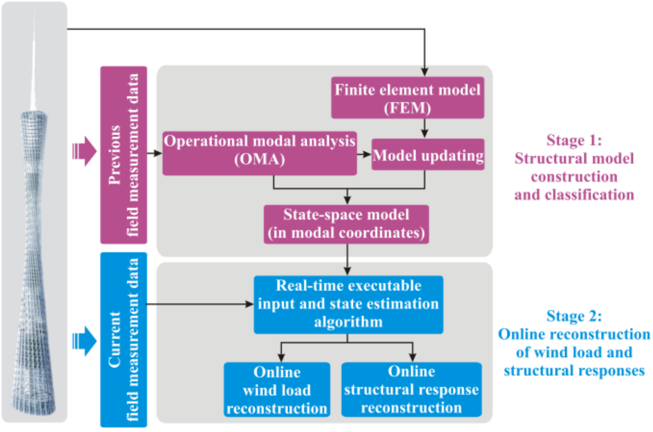

Fig. 1. Online simultaneous wind load and structural response reconstruction methodology for high-rise structures [14]

In the stage 1, an operational modal analysis (OMA) for the Canton Tower can be performed using the previously recorded field measurements. According to the obtained OMA results, the finite element model (FEM) of the Canton Tower can be updated to better represent the dynamics of the real structure. Based on the updated FEM of the Canton Tower, a state-space model in the modal coordinates can be constructed.

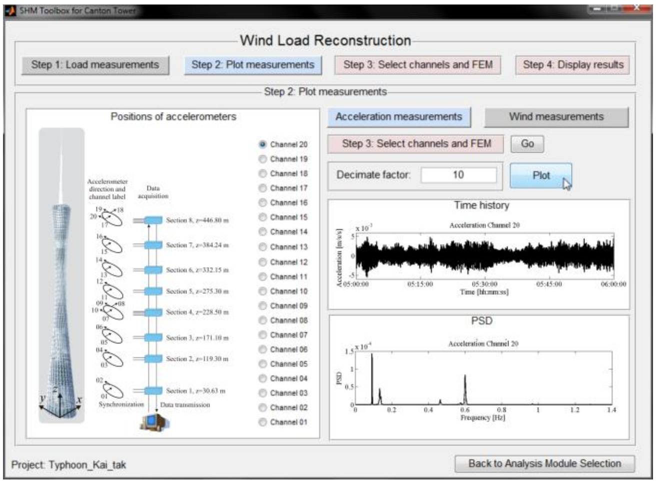

Fig. 2. SHM toolbox for wind load reconstruction – Plot measurements [15]

In the stage 2, given the field measurements from a new wind event, e.g. a typhoon, and the updated state-space model from the stage 1, the wind load can be reconstructed by using an input estimation algorithm. In this study, the measurements from 20 accelerometers and 1 anemometer installed on the tower are used. These measurements were previously recorded and stored in the data warehouse of the SHM system for the Canton Tower.

Based on this methodology, an SHM toolbox for wind load reconstruction has been developed. As an example, the measurements recorded during the Typhoon "Kai-tak" in 2012 were taken out of the data warehouse and imported into the toolbox for analysis. Before passing the recorded data to the input estimation algorithm, a check on data quality is first performed by plotting the data from each sensor in the form of time history and power spectral density (PSD). In such a manner, the data sections with a discontinuity or abnormal outliers can be separated from the analysis. Figure 2 shows a screenshot of the toolbox in checking the data quality of accelerometer channel 20. It can be seen that the measured time history is continuous and no abnormal outlier is noticed. Then the sensor channels with good data quality can be selected, the FEM of the Canton Tower can be loaded and the wind load can be reconstructed with the help of the input estimation algorithm. Figure 3 shows the mean and standard deviation of the reconstructed wind load with respect to the nodes of a reduced-order finite element model (FEM) of the Canton Tower.

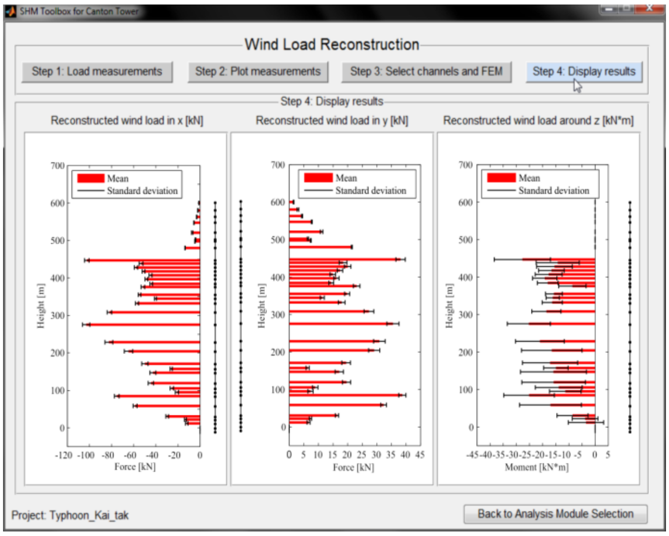

Fig. 3. SHM Toolbox for wind load reconstruction – Display results [15]

Such reconstructed wind load information may assist the health status assessment of the structure, e.g. material fatigue, after the typhoon event, and the decision making process in maintenance scheduling.

B. Conception of the knowledge-based approach

Synergetic use of sensor data for health assessment and reconstruction of wind load information, raises the great potentials for developing the knowledge-based approach for reasoning. As shown in Figure 4, sensor data which are captured from the Canton Tower are used for health assessment. Recorded data of the sensors are stored in the data warehouse. The sensor fault detection component is used to improve the quality of data through analysis of the sensor readings which are unmatched with expected values. The stored data are, therefore, filtered with the help of sensor information from the sensor fault detection component. This ensures that only reliable data are used in the wind load reconstruction process. The force reconstruction toolbox provides information for simulating the behavior of the tower against wind loads. It is used as the main channel of information. The core part of the knowledge-based approach is the rule-based engine. It consists of the mechanism for modeling and updating the rules, inference machine and rule bank. The knowledge

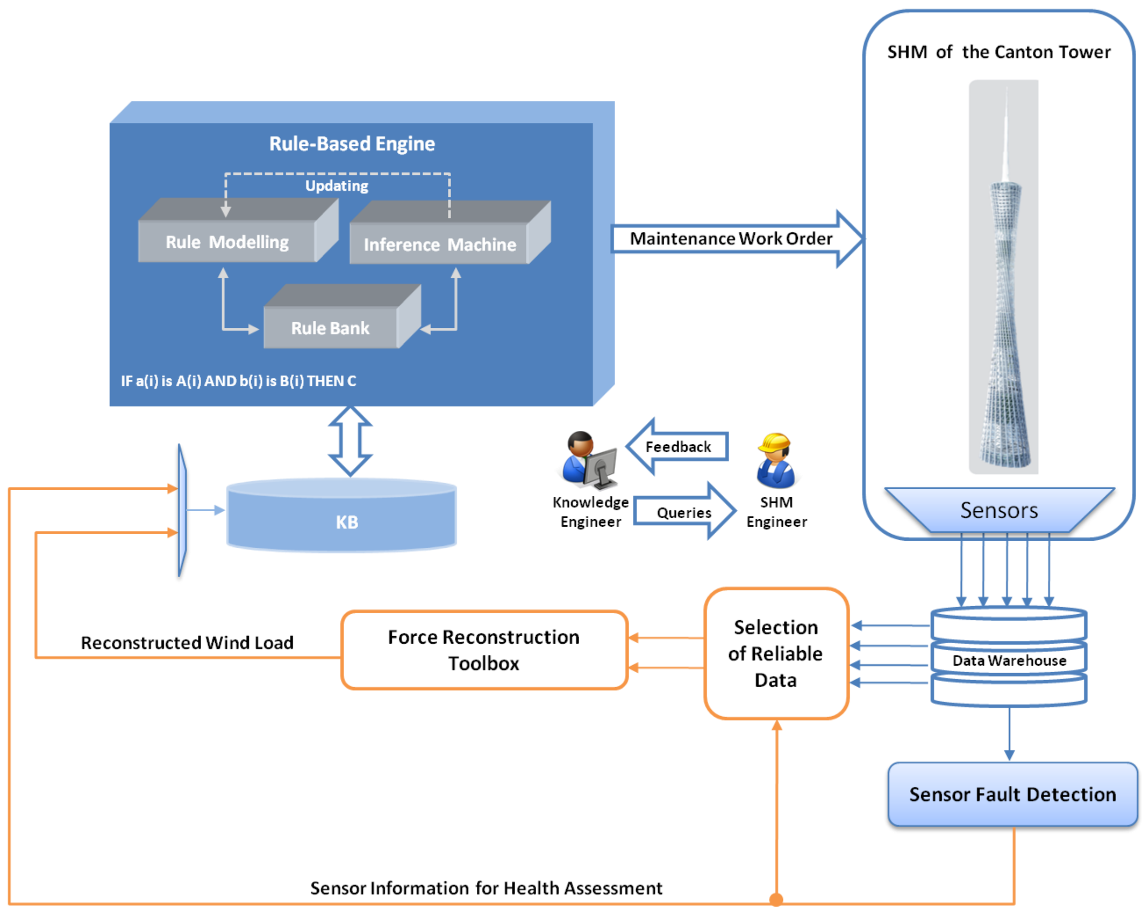

Fig. 4. Conceptual model for integration of knowledge-based approach in SHM

engineer requires a dialogue system (user interface) to access the KB, and to modify (ongoing) rules in the form *IF a(i) is A(i) AND b(i) is B(i) THEN C*. Of course, there should not be always two factors in the condition of the rules. This should be identified in each case (see the sample rules). The rule modeling enhances the use of hybrid approaches through merging and combining linguistic and numerical variables. Thus the knowledge engineer is capable to use flexibly numerical values in the rule conclusion (*THEN C*) which can be, but not necessarily always, a function of input variables. The SHM engineer (i.e. domain expert) may assist based on his/her monitoring and controlling skills and expertise. Once the system is set up, automatic operation is possible. In addition, a learning mechanism can be used for self-adaptive tuning and manipulating of the rule representation *IF-THEN* (i.e. delete redundant rules, and extract relevant or dominant ones).

The inference machine controls the structure (rule interpreter) and provides a methodology for reasoning. It matches the responses given by the users and fires the rules. Thus it needs to trace the rule bank to reach a conclusion on the queries of the user. In this context, the main methods are forward chaining and backward chaining [7], [8].

The currently developed toolboxes in SHM are often limited in the use of advanced rule-based engine for the support of the reasoning process. Therefore the proposed approach may lead to an improved use of knowledge-based analysis in health monitoring and assessment. In the context of SHM, the rules are mainly structured in a form of *IF-THEN*, and the conditions and consequences are defined by the domain experts. Using the case study of force reconstruction, sample rules are developed which only consider the damage resulted from loading. Two sample rules are presented in the following:

Sample rule 1:

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IF (sensor_wind ≥ Threshold_Large)
THEN (Damage_Potential=high)
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Sample rule 2:

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IF (sensor_wind > threshold_wind_risk AND
sensor_earthquake > threshold_eq_risk)
THEN (damage_potential = high)
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The sample rule 1 represents the relation between the readings of the sensor for wind force, and examines whether it exceeds the threshold. The rule 2 includes an additional input from the sensing of vibration (earthquake), and combines both wind force and earthquake sensing. In fact some other mechanical effects (e.g. corrosion, collision) may also be considered. Moreover, the entire reasoning process for health assessment includes cause-effect analysis which leads to develop rules. The conditions and consequences can be adapted, based on the major influential factors in the health assessment of each type of structure and environment. The main advantage of such an approach is the adaptivity of modeling and updating the existing rules, based on conditional changes, and generating of new rules, based on new requirements. However, increasing the number of rules may raise a need to optimize the reasoning process and in turn use learning approaches for automatic adjustment and updating of parameters and preferences.

The reasoning is the pre-step for decision-making. It explains the relation of causes and expected effects and explains the consequent behavior. Therefore the end-result of the reasoning process is to support monitoring and maintenance planning of the structures e.g. Canton Tower. Nevertheless, SHM systems require a decision-making component for optimal prioritization and selection of alternatives (outputs of reasoning process) through incorporating preferences especially economic risk factors.

III. Conclusion and Future work

SHM practitioners deal with considerable amount of data gathered via sensors and inspection. Accumulation of data provides opportunities for elaborating the analyses and outlining a knowledge-base consisting of certain semantics between entities. The semantics relate the entities in a meaningful form to be (re)-usable in reasoning and decision-making. A promising case study of force identification highlighted the potential for integration of knowledge-based approaches in SHM.

This paper commences the collaborative research for the integration of KBS, and related semantic technologies in SHM. The proposed concept foreground potential future research especially dealing with aggregation or hybrid usage of SHM algorithms for discovering and extracting new knowledge in e.g. damage detection and predictive health assessment. Also the feedback component needs to be studied using knowledge visualization and data mining methods to discover improvement potentials for developing new sensors or materials.

The knowledge-based approach also makes the consideration of additional factors and constraints possible. As an exemplary factor for future research economical aspects should be mentioned. The major non-technological risk is associated with economic factors of SHM e.g. cost, present value, and return on investment. Such factors crucially influence the decision-making and maintenance programs as well as the advancement of SHM systems.

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