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IFC-BASED MONITORING INFORMATION MODELING FOR DATA MANAGEMENT IN STRUCTURAL HEALTH MONITORING

Kay Smarsly* and Eike Tauscher

Bauhaus University Weimar, Germany
Email: kay.smarsly@uni-weimar.de

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Abstract. *This conceptual paper discusses opportunities and challenges towards the digital representation of structural health monitoring systems using the Industry Foundation Classes (IFC) standard. State-of-the-art sensor nodes, collecting structural and environmental data from civil infrastructure systems, are capable of processing and analyzing the data sets directly on-board the nodes. Structural health monitoring (SHM) based on sensor nodes that possess so called "on-chip intelligence" is, in this study, referred to as "intelligent SHM", and the infrastructure system being equipped with an intelligent SHM system is referred to as "intelligent infrastructure". Although intelligent SHM will continue to grow, it is not possible, on a well-defined formalism, to digitally represent information about sensors, about the overall SHM system, and about the monitoring strategies being implemented ("monitoring-related information"). Based on a review of available SHM regulations and guidelines as well as existing sensor models and sensor modeling languages, this conceptual paper investigates how to digitally represent monitoring-related information in a semantic model. With the Industry Foundation Classes, there exists an open standard for the digital representation of building information; however, it is not possible to represent monitoring-related information using the IFC object model. This paper proposes a conceptual approach for extending the current IFC object model in order to include monitoring-related information. Taking civil infrastructure systems as an illustrative example, it becomes possible to adequately represent, process, and exchange monitoring-related information throughout the whole life cycle of civil infrastructure systems, which is referred to as monitoring information modeling (MIM). However, since this paper is conceptual, additional research efforts are required to further investigate, implement, and validate the proposed concepts and methods.*

1 INTRODUCTION

Civil infrastructure systems, such as bridges, roads and tunnels, are gradually deteriorating. In Germany, for example, an estimated amount of €7.2bn is missing every year that is required for maintaining existing civil infrastructure [1]. In order to assess the condition of civil infrastructure, structural health monitoring (SHM) systems are deployed to collect monitoring data, i.e. structural, environmental, and operational data. Different sensors, such as accelerometers, displacement transducers or temperature sensors, installed in the civil infrastructure systems are connected to (tethered or wireless) sensor nodes that forward the collected data sets to computer systems. With recent advances in embedded computing and microcontroller technologies, state-of-the-art sensor nodes are capable of intelligent on-board data processing enabling the sensor nodes autonomously processing, analyzing, and condensing the monitoring data in a fully decentralized manner [2]. SHM systems being composed of sensor nodes that possess so called "on-chip intelligence" are referred to as "intelligent SHM systems", and the infrastructure system being equipped with an intelligent SHM system is referred to as "intelligent infrastructure" [3].

To facilitate efficient sensor data management, existing standards allow semantic modeling of sensor information (or sensor metadata), such as sensor type, sampling rate, location, or manufacturer [4-6]. However, with respect to intelligent SHM systems, sensor information is only a small subset of monitoring-related information [7]. Unlike sensor information, which primarily includes local information about single sensors, monitoring-related information includes, for example, information on the configuration and topology of the (tethered or wireless) sensor network, interaction protocols used, hardware specifications, monitoring strategies, or algorithms embedded into the sensor nodes. Although the trend of incorporating intelligent SHM systems into civil infrastructure systems, forming a coherent "intelligent infrastructure" unit, will continue to grow, semantic modeling and digital representation of monitoring-related information is still in its infancy. Specifically, the logics and coherences inherent to intelligent SHM systems – both tethered and wireless systems – cannot adequately been modeled using existing approaches. While building information modeling (BIM) technologies mature and become mandatory in many areas in building and construction industries [8], monitoring information modeling (MIM) has received little attention.

This conceptual paper discusses opportunities and challenges towards monitoring information modeling for intelligent SHM systems in civil engineering. The conceptual MIM approach proposed in this paper builds upon the widely used BIM standard, i.e. the Industry Foundation Classes (IFC) developed as an open data format for the exchange of building information. When implementing the proposed approach in prospective research efforts, it can be expected that the integration of monitoring-related information into existing IFC-based building information models enables a consistent digital representation not only of building information, but also of all relevant monitoring information about the SHM systems throughout the whole life cycle of the civil infrastructure system being monitored.

2 IFC-BASED BUILDING INFORMATION MODELING

Building information modeling, i.e. the integrated, object-based coordination of building information, has begun to emerge as a fruitful technology in various areas of civil engineering. Supporting interoperability and information exchange, BIM is mandatory in publicly-funded building projects in several European countries, such as the U.K., the Netherlands, Denmark, Finland and Norway, and – as recommended by the European Parliament – it will be mandatory in all EU member states by 2016 [8]. The use of BIM technology requires a continuous digital workflow based on a common data format. In accordance with the ISO 10303 standard [9], which specifies a technology for model-based digital product data exchange, the Industry Foundation Classes (IFC) have been developed starting in 1994. In recent years, increasing attention has been paid to extending the IFC object model. Both in the scientific community and in engineering practice, it has been recognized that the possibilities of digitally representing building information using the existing IFC standard (IFC version 4) are very limited in several areas.

In IFC version 4, several aspects of sensor information can be mapped into the IFC object model. However, IFC version 4 primarily supports sensor types that are related to building automation systems. To map sensor information, the IFC entity IfcSensor, provided by the IFC object model, must be used [10]. An IfcSensor object is classified by assigning a predefined sensor type, which is provided by the enumeration IfcSensorTypeEnum. For sensors not predefined in IfcSensorTypeEnum, the sensor type USERDEFINED must be used; the sensor type must be specified by assigning an IfcSensorType object using objectified relations. In addition to sensor types, further sensor information can be mapped into the IFC object model, such as information about manufacturer and about sensor energy consumption using predefined IFC property sets. Some IFC property sets are applicable to all IfcSensor objects in general, while more specific sensor information is only applicable to predefined sensor types. Many sensor types relevant to SHM systems, such as accelerometers or strain gauges, are not predefined. Since these sensors must be mapped as user-defined types, applicable property set definitions are not available, which makes it difficult to store and to retrieve the sensor information [11].

In summary, IFC-compliant mapping of sensor information is possible in principal, but semantic mapping and digital representation of monitoring-related information is not supported in IFC version 4 (e.g. information on the configuration and topology of the sensor network, interaction protocols used, hardware specifications, monitoring strategies, or algorithms embedded into the sensor nodes). In particular, mapping monitoring-related information with respect to intelligent SHM systems, which include sensor nodes possessing on-chip intelligence, is not possible using the IFC standard. A major challenge when mapping such information are the dynamic logics inherent to intelligent SHM systems. Because the type of a sensor node is largely determined by its implemented logic, it is not possible to apply the standardized IFC object typing to intelligent sensor nodes and to the dynamic relationships between communicating sensor nodes. Consequently, it is necessary to extend IFC version 4 in order to be able to specify this logic (e.g. in terms of algorithms embedded into the sensor node) for modeling an intelligent sensor node as part of an IFC-compliant building information model. In the following section, a conceptual approach towards extending the IFC object model for semantic modeling of monitoring-related information is discussed.

3 A CONCEPTUAL APPROACH TOWARDS SEMANTIC MODELING OF MONITORING-RELATED INFORMATION

A semantic model supporting monitoring information modeling is to be developed, which will be integrated, in further steps, into the IFC object model, resulting in a monitoring-related IFC model labeled "IFC Monitor". Focusing on civil infrastructure systems, the development of the semantic model is a three-step process comprising of (i) a review of available SHM regulations and guidelines, (ii) a review of existing sensor models and modeling languages, and (iii) the definition and classification of specific monitoring-related information relevant to intelligent SHM systems.

3.1 Structural health monitoring regulations and guidelines

In several countries, regulations and guidelines related to monitoring of civil infrastructure systems have been established. However, most regulations and guidelines promote "conventional" monitoring activities (such as visual inspections or non-destructive testing), rather than automated SHM activities. In Germany, for example, the DIN 1076 standard, first published in 1930, is the legal basis for monitoring and inspecting civil infrastructure systems [12]. For automated SHM activities, a number of guidelines has been proposed by several research groups, institutes, and committees. For example, the "Guidelines for Structural Health Monitoring", proposed by the Intelligent Sensing for Innovative Structures (ISIS) Canada Research Center, provide practicing engineers with detailed guidelines for SHM systems [13]; a "Guideline and Recommendations for SHM" are proposed in a book chapter published by Wenzel [13]; the "FIB Bulletin No. 22" of the International Federation for Structural Concrete (FIB) summarizes the important inspection and measuring methods [14]; and the "Guideline for Structural Health Monitoring", published by the Structural Assessment Monitoring and Control (SAMCO) network in association with the German Federal Institute of Materials Research and Testing (BAM), introduces SHM procedures and technologies and gives recommendations for their application [15].

3.2 Sensor models and modeling languages

A broad wealth of standards exists that enable semantic modeling of sensor information (or sensor metadata), such as sensor type, sampling rate, location, or manufacturer. For example, the Sensor Web Enablement (SWE) initiative of the Open Geospatial Consortium (OGC), an international consortium of industry, academic and government organizations, provides standardized web services and communication protocols for the web-based integration of sensors and sensor networks in order to make all types of sensors as well as sensor data repositories accessible via the Web. As a part of the SWE initiative, the Sensor Model Language (SensorML) provides a sensor information model and XML encodings for describing sensors and processes associated with sensor measurements [4]. To overcome the general problem of too much data and not enough knowledge, the semantic sensor Web (SSW) couples sensor technologies and semantic Web technologies [5]. Extending the SWE standards of the OGC with semantic Web technologies, the World Wide Web Consortium (W3C) has initiated the Semantic Sensor Networks Incubator Group (now transitioned into the Semantic Sensor Networks Community Group), which has defined an ontology for modeling sensors and sensor networks [6]: The Semantic Sensor Network (SSN) ontology can describe sensors in terms of capabilities, measurement processes, observations, and deployments. The SSN ontology covers large parts of the OGC standards (e.g. SensorML), i.e. it can interpret sensor metadata advertised in SensorML documents, but it is not constrained by the OGC standards.

Fig. 1 illuminates the SSN ontology in more detail. As can be seen from Fig. 1, the ontology enables the description of sensors, including their measuring capabilities and measuring properties (accuracy, resolution, response time, etc.), features of interest as well as the corresponding sensing processes. In addition, concepts for operating and survival ranges, often part of a given sensor specification, are included.

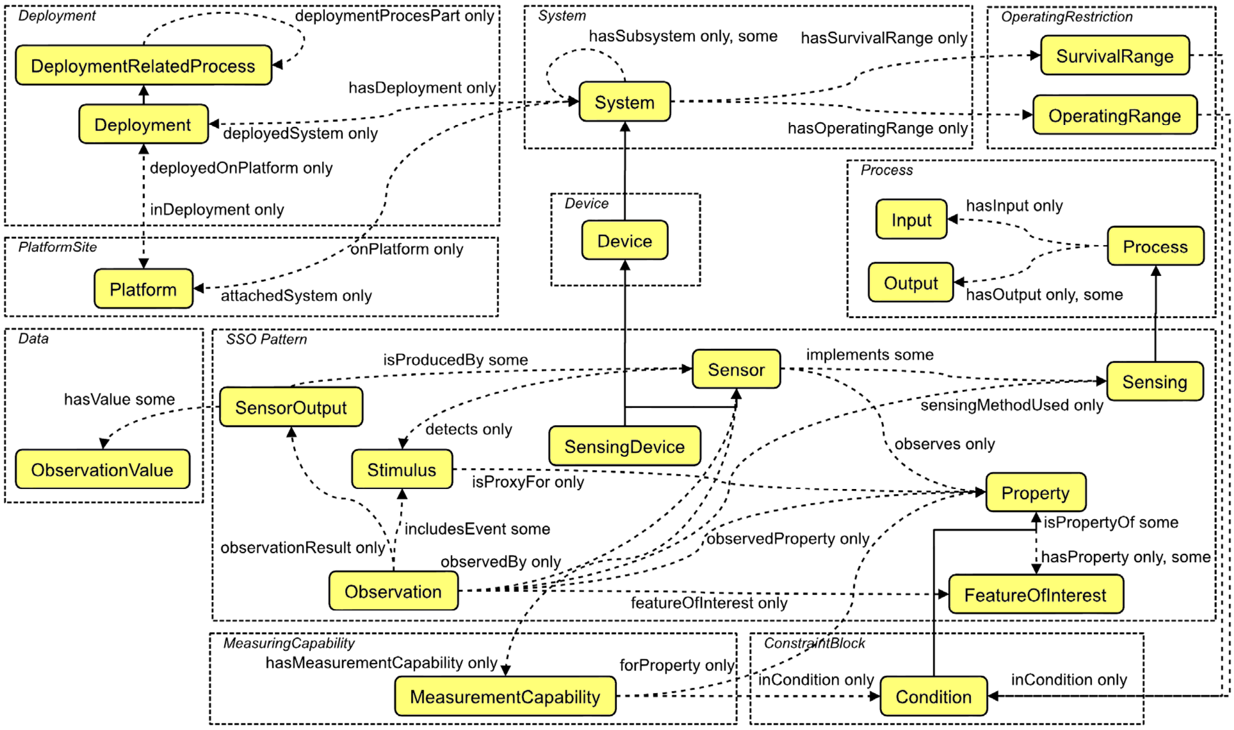

Figure 1: Classes and properties of the SSN ontology, subdivided by conceptual modules (source: [9], modified)

3.3 Monitoring-related information for intelligent SHM systems

Covering a plenitude of semantic modeling features, existing sensor models (or modeling languages) are truly useful for semantic modeling of sensors and sensor networks. While some monitoring-related information, such as hardware specifications, can be mapped by existing standards, it is not possible to map all aspects necessary to describe intelligent SHM systems. First, it is not possible to map the inherent, dynamic logics of intelligent sensor nodes that are implicitly specified by the algorithms embedded. Furthermore, it is not possible to map SHM-specific information on the configuration and topology of the (tethered or wireless) sensor network, interaction protocols used, or monitoring strategies implemented. In conclusion, these aspects must be defined and classified when developing a semantic model for mapping monitoring-related information. In order to define and clarify monitoring-related information, it is useful to distinguish between global and local monitoring-related information.

3.4 A conceptual approach towards IFC-based mapping of monitoring-related information

A conceptual approach towards defining a semantic model is proposed for mapping monitoring-related information based on the Industry Foundation Classes. The IFC Industry Foundation Classes are used to close the gap between sensor models and building information modeling, because the IFC are the most important standard for building information modeling in the construction industry. When defining a semantic model, particular emphasis is put on intelligent SHM systems deployed to civil infrastructure systems. As elucidated in the previous subsections, available SHM regulations/guidelines (subsection 3.1), existing sensor models/modeling languages (subsection 3.2), and specific monitoring-related information relevant to intelligent SHM systems (subsection 3.3) may serve as a conceptual basis. As shown in Fig. 2, a reference model, mapping the information stemming from existing SHM regulations/guidelines and sensor models/modeling languages, is to be generated. In addition, a monitoring-related model, representing the specific monitoring-related information, is to be defined. In a further step, both models, the reference model and the monitoring-related model, are to be coupled in order to achieve a semantic model used to extend the existing IFC 4 object model. The extended IFC 4 object model, as shown in Fig. 2, is termed "IFC Monitor", representing a monitoring-related extension of the existing IFC standard.

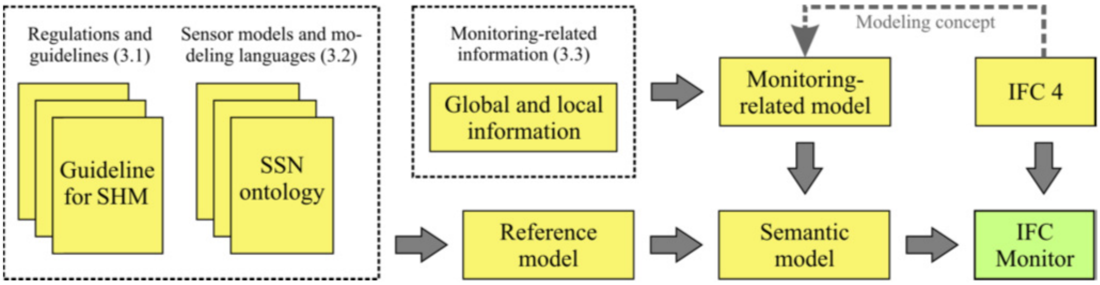

Figure 2: Conceptual approach towards IFC-based mapping of monitoring-related information

SUMMARY AND DISCUSSION

This conceptual paper has discussed opportunities and challenges towards monitoring information modeling (MIM) for intelligent structural health monitoring systems in civil engineering, focusing on civil infrastructure systems. The conceptual MIM approach proposed in this paper builds upon the widely used BIM standard, i.e. the Industry Foundation Classes (IFC) developed as an open data format for the exchange of building information. As has been showcased in this paper, several SHM regulations and guidelines as well as sensor models and modeling languages are available for semantic modeling and digital representation of sensor information. However, sensor information is only a small subset of monitoring-related information, which cannot adequately be modeled using existing standards. As illustrated in this paper, specific monitoring-related information relevant to intelligent SHM systems is defined and classified. The set of available SHM regulations/guidelines, existing sensor models/modeling languages and specific monitoring-related information serves as a basis to define a semantic model for digital representation of monitoring-related information. The semantic model, used to extend the existing IFC 4 standard, results in an extended IFC model, labeled "IFC Monitor".

Since this paper is conceptual, additional research efforts are required to further investigate, implement, and validate the conceptual MIM approach proposed herein. It can be expected that implementing this conceptual approach into existing, IFC-based building information models would enable a consistent digital representation of all relevant monitoring information about the SHM systems throughout the whole life cycle of civil infrastructure systems, thus substantially enhancing the monitoring quality and the assessment of civil infrastructure.

REFERENCES

[1] German Bundestag, 2014. Verkehrsinfrastruktur chronisch unterfinanziert. Press release. Berlin, Germany: German Bundestag, Committee on Transport and Digital Infrastructure. Available at: https://www.bundestag.de/dokumente/textarchiv/2014/49449197_kw07_pa_verkehr/215644 [Accessed: 28/05/2015].

[2] K. Dragos and K. Smarsly, 2015. Decentralized infrastructure health monitoring using embedded computing in wireless sensor networks. In: Sextos, A. and Manolis, G. D.

(eds.). Dynamic Response of Infrastructure to Environmentally Induced Loads. Cham, Switzerland: Springer International Publishing AG.

[3] K. Dragos and K. Smarsly, K., 2015. A Comparative Review of Wireless Sensor Nodes for Structural Health Monitoring. In: Proceedings of the 7th International Conference on Structural Health Monitoring of Intelligent Infrastructure. Turin, Italy, 07/01/2015.

[4] OGC, 2014. OGC SensorML: Model and XML Encoding Standard. Open Geospatial Consortium (OGC), Wayland, MA, USA.

[5] A. P. Sheth and S. S. Sahoo, 2008. Semantic Sensor Web. IEEE Internet Computing, 12(4), pp. 78-83.

[6] L. Lefort, et al., 2011. Semantic Sensor Network XG Final Report. W3C Incubator Group, World Wide Web Consortium (W3C), Cambridge, MA, USA.

[7] K. Law, K. Smarsly and Y. Wang, 2014. Sensor Data Management Technologies for Infrastructure Asset Management. In: M. L. Wang, J. P. Lynch and H. Sohn (eds.). Sensor Technologies for Civil Infrastructures. Pp. 3-32. Woodhead Publishing, Ltd., Sawston, UK.

[8] European Parliament, 2015. Directive 2014/24/EU of the European Parliament and of the Council. Brussels, Belgium.

[9] ISO, 2014. ISO 10303:2014 – Industrial automation systems and integration - Product data representation and exchange. International Organization for Standardization (ISO), Geneva, Switzerland.

[10] BuildingSMART, 2013a. Industry Foundation Classes Release 4 (IFC4). Documentation for 7.2.3.9 IfcSensor. March 12, 2013. Available at: http://www.buildingsmart-tech.org/ifc/IFC4/final/html/link/ifcsensor.htm [Accessed: May 20, 2015]

[11] BuildingSMART, 2013b. Industry Foundation Classes Release 4 (IFC4). Documentation for 4.2.1 Property Sets for Objects. March 12, 2013. Available at: http://www.buildingsmart-tech.org/ifc/IFC4/final/html/link/property-sets-for-objects.htm

[12] DIN, 1999. DIN 1076:1999-11 – Ingenieurbauwerke im Zuge von Straßen und Wegen - Überwachung und Prüfung. Normenausschuss Bauwesen (NABau) within the Deutsches Institut für Normung e.V. (DIN), Beuth Verlag GmbH, Berlin, Germany.

[13] A. A. Mufti, 2001. ISIS Design Manual 2: Guidelines for Structural Health Monitoring. Intelligent Sensing for Innovative Structures (ISIS), Winnipeg, MB, Canada.

[14] H. Wenzel, H., 2009. Guideline and Recommendations for SHM. In: Health Monitoring of Bridges, John Wiley & Sons, Ltd, Chichester, UK.

[15] FIB, 2003. FIB Bulletin No. 22 – Monitoring and safety evaluation of existing concrete structures. International Federation for Structural Concrete (FIB), Lausanne, Switzerland.

[16] W. Rücker, F. Hille and R. Rohrmann, 2006. Guideline for Structural Health Monitoring. Report “F08b”. German Federal Institute of Materials Research and Testing (BAM), Berlin, Germany.