Monitoring information modeling for semantic mapping of structural health monitoring systems

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Abstract

Intelligent structural health monitoring systems are composed of sensor nodes capable of on-board processing and analysis of the sensor data. The information necessary to mathematically represent such structural health monitoring (SHM) systems is defined as "monitoring related-information". Monitoring-related information includes, for example, information about the inherent, dynamic logics of intelligent sensor nodes, about the overall SHM system, and about the monitoring strategies being implemented. While numerous sensor modeling languages, ontologies, schemas and models have been proposed to describe conventional sensor information (such as type and location of sensors), semantic models for representing monitoring-related information specifically for intelligent SHM systems are not available. This conceptual paper describes a semantic model for a consistent, digital representation of monitoring-related information. This paper also illustrates how to implement and to validate the semantic model based on the Industry Foundation Classes (IFC). The IFC are a widely-used, open standard for digital modeling of building information ("building information modeling", BIM), but it is not possible to represent monitoring-related information with the IFC schema. Therefore, a conceptual approach is showcased for extending the current IFC schema in order to include monitoring-related information, in a process defined as "monitoring information modeling" (MIM). As a result, it can be expected that, through the novel methodology proposed herein, monitoring-related information can coherently be integrated into standardized building information models being widely used in civil engineering, facilitating the integrated design and maintenance of intelligent SHM systems.

Keywords: Building information modeling (BIM), monitoring information modeling (MIM), intelligent structural health monitoring (SHM) systems, semantic modeling, sensor networks.

1. INTRODUCTION

There exists a clear need to monitor existing infrastructure systems over their operational life. More than €7.2bn are required every year for maintaining existing civil infrastructure in Germany (German Bundestag, 2014). The situation in other countries is similar. In the U.S., for example, the overall infrastructure condition is rated D+, which is equivalent to $3.6tn needed to invest (ASCE, 2013). To reliably assess the structural condition of civil infrastructure and to cost-efficiently schedule maintenance and repair work, structural health monitoring (SHM) systems are deployed. Different types of sensors, such as accelerometers, displacement transducers and temperature sensors, are installed in the structures to collect monitoring data, i.e. structural, environmental, and operational data. The sensors are connected to (tethered or wireless) sensor nodes that forward the collected data sets to computer systems.

Eradicating the need for long wires associated with tethered SHM systems, wireless sensor nodes are increasingly employed for structural health monitoring (Chang & Kopsaftopoulos, 2015). This trend, which will continue to grow in the next years, is attributed to the merits of wireless sensor nodes in terms of reduced installation time, lower cost and increased flexibility, as compared with tethered systems. Wireless sensor nodes combine sensing technologies with local computational power and wireless transmission functionalities. A typical wireless sensor node platform consists of three basic components: a sensing unit, a processing unit, and a wireless transceiver – and, possibly, actuation modules used for structural control. The basic function of a wireless sensor node includes data collection through the sensing unit using an analog-to-digital converter, storage and local processing of the collected data in the processing unit, and wireless communication of the processed data via the transceiver.

To overcome the constraints posed by the inherently limited resources of wireless sensor nodes, much research has been attempted to integrate embedded algorithms into wireless sensor nodes for local data processing in order to efficiently utilize the computational power collocated with the decentralized, autonomous condition assessment of the civil infrastructure systems (Dragos & Smarsly, 2015a). Since the issue of data management is of fundamental importance, the key advantage of local data processing is that (potentially) meaningful

information from processed data is considerably smaller than the raw data, and the reduced size of the processed data, as compared to raw data, decreases the power consumption caused by wireless data transmission (Law et al., 2014). 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 analyzing, communicating, and condensing the monitoring data in a fully decentralized manner (Dragos & Smarsly, 2015b). 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".

Several approaches have been proposed to facilitate efficient sensor data management. In particular, standards have been published considering the semantic modeling of sensor information (or sensor metadata), such as sensor type, sampling rate, location, or manufacturer. However, with respect to intelligent SHM systems, sensor information is only a small subset of monitoring-related information (Smarsly & Tauscher, 2015). While sensor information essentially includes local information about single sensors (e.g. sensor type or sampling rate), monitoring-related information includes, e.g., 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 towards "intelligent infrastructure" or "smart structural systems", incorporating intelligent SHM systems into civil infrastructure systems, will continue to grow, semantic modeling and digital representation of monitoring-related information has received little attention. Specifically, the logics and coherences inherent to intelligent SHM systems cannot adequately be modeled using existing approaches. While building information modeling (BIM) technologies mature and become mandatory in many areas in building and construction industries, monitoring information modeling (MIM) is still in its infancy.

This paper proposes a conceptual approach towards monitoring information modeling for intelligent SHM systems in civil engineering. The MIM approach builds upon a widely used BIM standard, the Industry Foundation Classes (IFC), developed as an open data format for the exchange of building information. When implementing the proposed approach in future 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. Moreover, it would be possible, through continuous updating of the monitoring-related information, to achieve an enhanced monitoring quality, thus facilitating the assessment of the civil infrastructure systems being monitored. This paper first provides a brief overview of IFC-based building information modeling. Upon analyzing background information, e.g. on available SHM regulations/guidelines and existing sensor models and modeling languages, the conceptual MIM approach is presented. The paper concludes with a summary and a brief discussion of research efforts required to further investigate methods and concepts for mapping monitoring-related information.

2. BUILDING INFORMATION MODELING BASED ON THE INDUSTRY FOUNDATION CLASSES

Over the past decades, building information modeling (BIM) has matured into a significant technology in the building and construction industry for analysis and design of civil infrastructure (Eastman et al., 2011). The objective of BIM is to provide an integrated digital methodology that supports planning, maintenance and operation of structures throughout their whole lifecycle. Supporting interoperability and information exchange, BIM is recommended in publicly-funded building projects in several European countries, such as the U.K., the Netherlands, Denmark, Finland and Norway, and – according to the European Parliament (European Parliament, 2014) – it will be recommended in all EU member states by 2016. The use of BIM technology requires a continuous digital workflow based on a common data format. In compliance with the ISO 10303 standard (ISO, 2014), which specifies a technology for model-based digital product data exchange, the Industry Foundation Classes (IFC) have been developed starting in 1994. Representing an open data format for the exchange of BIM data, the IFC are standardized in ISO 16739, being continuously evolved under the guidance of BuildingSMART International (ISO, 2013). Technically, the IFC object model maps building elements as entities with attributes and relationships, using the standardized data modeling language EXPRESS (ISO, 2004). For the exchange of IFC models, the Standard for the Exchange of Product Model Data (STEP) or – based on the Extended Markup Language (XML) – the STEP-XML standard can be used, both specified in ISO 10303 (ISO, 2014).

Considerable efforts have been devoted in the past years to the extension of the IFC object model. It has been recognized both in the scientific community and in engineering practice that the possibilities of digitally representing building information using the existing IFC standard (IFC version 4) are very limited in several areas. To give an example, these technical limitations are obvious in the area of civil infrastructure systems; here, it is not yet possible to sufficiently model specific objects, such as bridge bearings and street courses. Therefore,

a number of research projects focuses on extending the IFC object model, such as, e.g., the projects IFC-Bridge (Ji et al., 2013), IFC-Tunnel (Borrmann et al., 2015), or BuildingSmart's IFC-Alignment project, which extends the IFC model for routes and roadways (BuildingSMART, 2015). These projects essentially extend the IFC object model with additional entities necessary for semantic mapping of infrastructure-related information.

Using the current IFC object model, i.e. IFC version 4, several aspects of sensor information can be mapped. However, IFC version 4 primarily supports sensor types related to building automation systems rather than sensor types used in structural health monitoring. To map sensor information, the IFC entity IfcSensor, provided by the IFC object model, must be used (BuildingSMART, 2013a). An IfcSensor object is classified by assigning a predefined sensor type, which is provided by the enumeration IfcSensorTypeEnum (Fig. 1). In total, 23 different sensor types are included in the IfcSensorTypeEnum enumeration. 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 the objectified relation IfcRelDefinesByType, as shown in Fig. 1. To specify the sensor type, the attribute ObjectType of the IfcSensorType object is to be used, which is ensured by formal propositions of the IFC object model. This IFC concept is referred to as "Object Typing" (BuildingSMART, 2013b).

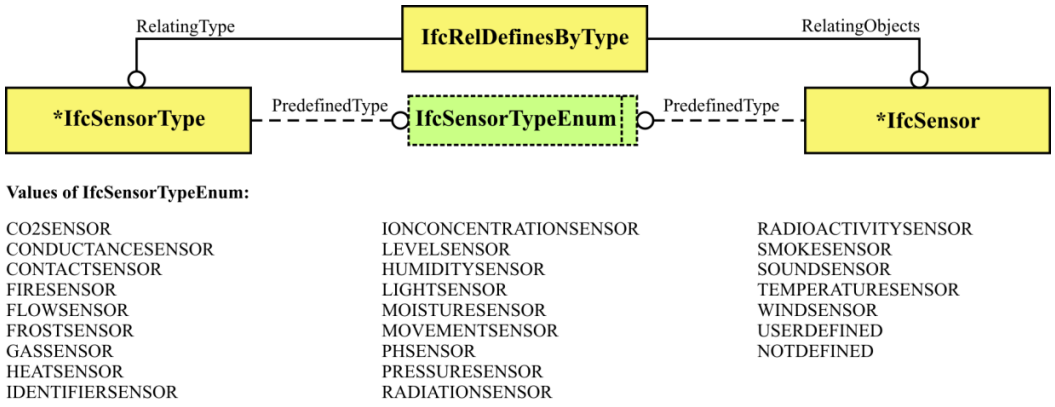


Figure 1. Representation of sensor information in IFC version 4

In addition to sensor types, further sensor information can be mapped into the IFC object model, such as information about manufacturer or about sensor energy consumption. Such information is mapped using the IFC concept of "Property Sets for Objects", which describes how an object can be related to a single or to multiple property sets (BuildingSMART, 2013c). Some IFC property sets are applicable to all IfcSensor objects in general, while more specific sensor information is only applicable to specific sensor types, e.g. temperature values sensed to indicate the presence of fire are only applicable to the predefined sensor type FIRESENSOR. Many sensor types relevant to SHM systems, such as accelerometers or strain gauges, are not predefined. As a consequence, these sensors must be mapped as user-defined types, and applicable property set definitions are not available, thus complicating the storage and retrieval of the sensor information (Rio et al., 2013). Fig. 2 shows the mapping of sensor information in IFC version 4 using property sets.

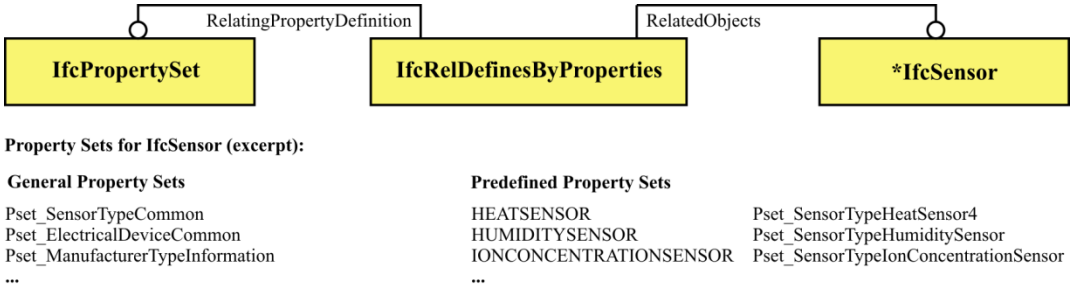


Figure 2: Mapping of sensor information in IFC version 4 using property sets

It can be concluded that IFC-compliant mapping of sensor information is possible in general, but semantic mapping and digital representation of monitoring-related information is not supported in the current IFC standard (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). Moreover,

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 (e.g. in terms of algorithms embedded into the sensor node). 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 the current IFC standard in order to be able to specify this logic for modeling intelligent sensor nodes as part of an IFC-compliant building information model. The following section presents a conceptual approach towards extending the IFC object model for semantic modeling of monitoring-related information.

3. SEMANTIC MODELING OF MONITORING-RELATED INFORMATION – A CONCEPTUAL APPROACH

A semantic model is to be developed, facilitating monitoring information modeling on a mathematical basis. In further steps, the semantic model is to be integrated into the IFC object model to achieve monitoring-related IFC model, named "IFC Monitor". In this conceptual paper, the process of developing the semantic model is defined as a three-step process comprising

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.

First, the review of available SHM regulations and guidelines serves as a basis for defining minimum requirements for the semantic model, including mandatory requirements for SHM systems. Second, the review of existing sensor models and modeling languages aims at analyzing existing ontologies and schemas for sensor information. Since available SHM regulations/guidelines and existing sensor models/modeling languages do not reflect monitoring-related information relevant to intelligent SHM systems, the third step intends to define and to classify specific monitoring-related information relevant to intelligent SHM systems representing the conceptual basis for the semantic model.

3.1 Structural health monitoring regulations and guidelines

There exists a number of regulations and guidelines related to monitoring of civil infrastructure systems. When analyzing these regulations and guidelines, it must be emphasized that most of which promote "conventional" monitoring activities (such as visual inspections or non-destructive testing), rather than automated SHM activities. For example, the German DIN 1076 standard, first published in 1930, is the legal basis for monitoring and inspecting civil infrastructure systems (DIN, 1999). For automated SHM activities, several guidelines have been proposed by different research groups, institutes, and committees. To give some examples, 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 (Mufti, 2001); a "Guideline and Recommendations for SHM" are proposed in a book chapter published by Wenzel (Wenzel, 2009); the "FIB Bulletin No. 22" of the International Federation for Structural Concrete (FIB) summarizes the important inspection and measuring methods (FIB, 2003); 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 (Rücker, 2006). Taking the latter guideline as an example, Fig. 3 shows a formal representation of monitoring-related information with emphasis on sensor information. As can be seen from Fig. 3, sensor information can be used as selection criteria for sensor installation, which includes, among others, minimal change of the measurands (resolution, linearity, and accuracy), measuring ranges, and types of measurements (static, dynamic, etc.).

3.2 Sensor models and modeling languages

Nowadays, it is common practice to instrument civil infrastructure systems with sensors already in the construction phase. As a consequence, there is an increasing number of standards that facilitates semantic modeling of sensor information (or sensor metadata), such as sensor type, sampling rate, location, or manufacturer. Clearly, there have been several standards proposed for well-defined, specific engineering areas. To give an example, the Open Building Information Xchange (OBIX) describes a web services interface specifically designed for building automation, facilitating the exchange of information between intelligent buildings (OBIX, 2015). However, standards restricted to certain engineering areas are not suitable for solving the SHM problem reflected in this paper and are thus not considered hereafter.

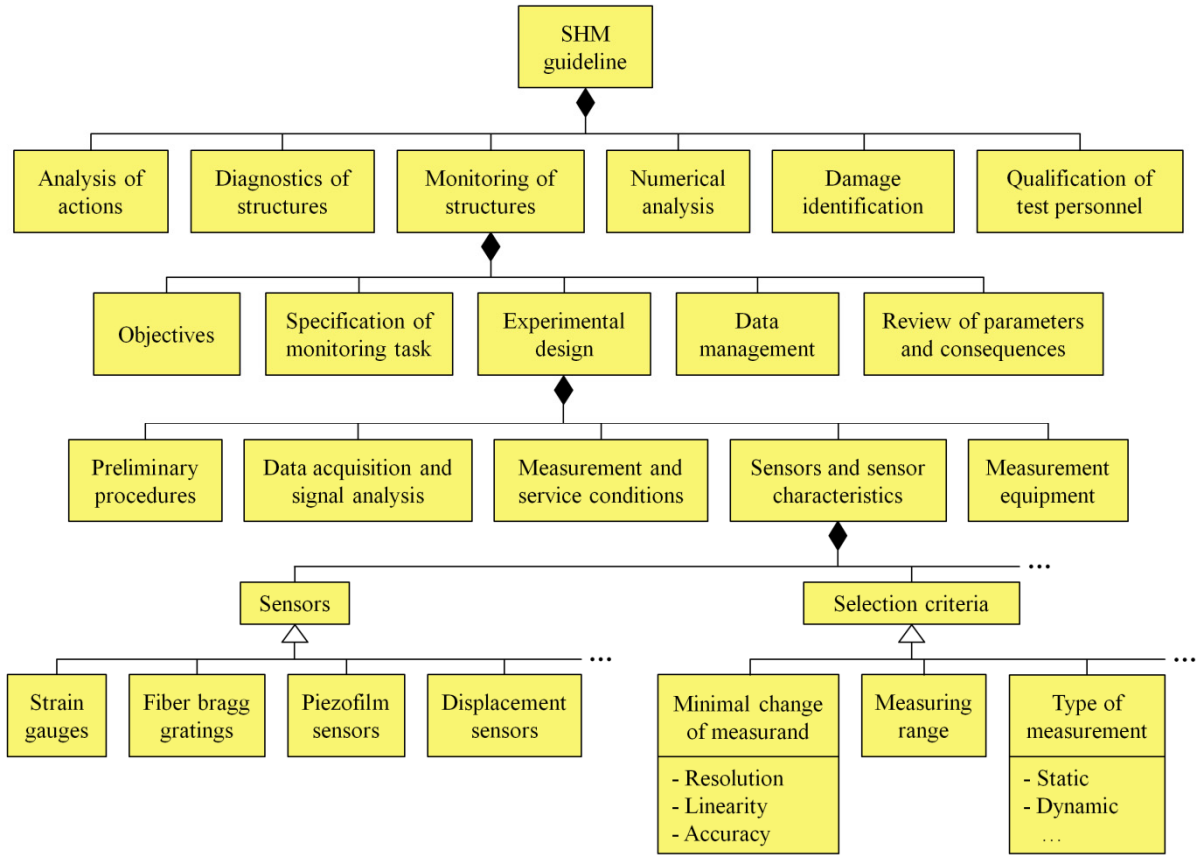


Figure 3. Formal representation of monitoring-related information inherent to a SHM guideline (Rücker, 2003)

To make sensors as well as sensor data repositories accessible via the Web, 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. 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 (OGC, 2014). SensorML does not encode sensor measurements directly, which is possible, for example, using the set of standards of the IEEE 1451 family developed by the Institute of Electrical and Electronics Engineers (IEEE) (Lee, 2000). The IEEE 1451 standards describe network-independent communication interfaces for connecting sensors (and other transducers) to microprocessors, instrumentation systems, and control/field networks. 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 (Sheth and Sahoo, 2008). 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: 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. The SSN ontology was originally developed for the Semantic Sensor Web and is based on W3C's Web Ontology Language (Lefort et al., 2011).

The basic concept of the SSN ontology is visually elucidated in Fig. 4. As shown in Fig. 4, the ontology supports 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 are included, which are often part of a given sensor specification.

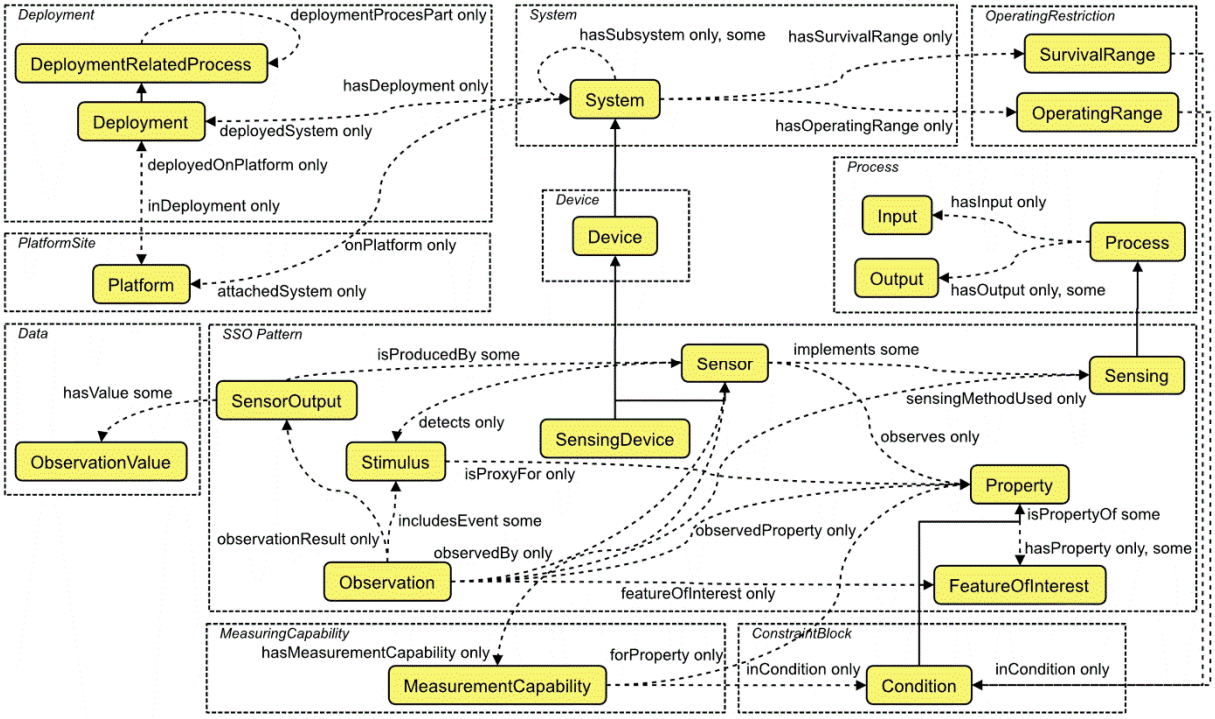


Figure 4. Classes and properties of the SSN ontology, subdivided by conceptual modules (source: Compton et al., 2012, modified)

3.3 Monitoring-related information for intelligent SHM systems

When considering intelligent SHM systems, it becomes clear that existing sensor models (or modeling languages) are not suitable for a consistent semantic modeling of monitoring-related information. As has been illuminated in the previous subsection, existing sensor models cover a broad wealth of semantic modeling features, but 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 the nature of monitoring-related information, it is useful to distinguish between global and local monitoring-related information, as listed in Table 1.

Table 1. Overview of most relevant global and local monitoring-related information

Global monitoring-related information	Local monitoring-related information
• Hardware specifications of sensor nodes (types, configurations, etc.) • Configuration and topology of the sensor network • Interaction protocols • Base stations and gateways • Global methods for automated diagnosis and prognosis (i.e. analysis) of the structural conditions of the structure being monitored (including, e.g. multi-sensor data fusion, model generation, feature extraction) • Persistent data storage • Report generation • Monitoring strategies implemented	• Types and placement of sensors as well as sensor measurements recorded for adequately sensing both impacts and reactions of the structure • Data acquisition (sampling rates, etc.) • Local preprocessing of sensor data (signal processing, normalization, plausibility checks, data reduction, data conversion) • Algorithms embedded into the sensor nodes: Local (embedded), energy-efficient methods for data analysis, particularly data-based approaches • Inherent redundancies and correlations between sensors (and sensor measurements, respectively) for detection of hardware and software faults (“analytical redundancy”)

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

For mapping monitoring-related information based on the Industry Foundation Classes, a conceptual approach towards defining a semantic model is proposed. The IFC 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 shown 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. 5, 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. To achieve a semantic model used to extend the existing IFC 4 object model, both models, the reference model and the monitoring-related model, are to be merged into an extended IFC object model. The extended IFC 4 object model, representing a monitoring- related extension of the existing IFC standard, is termed "IFC Monitor" (Fig. 5).

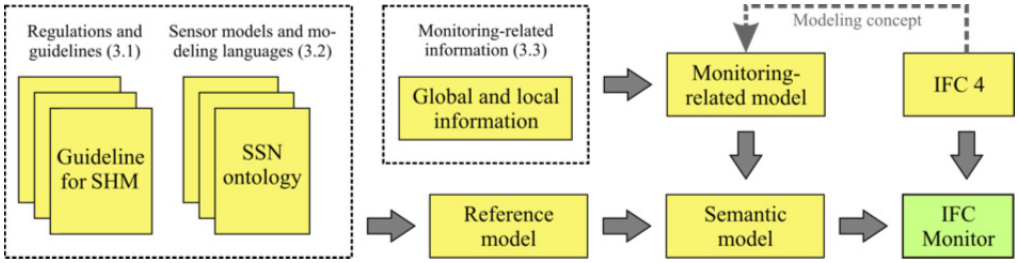


Figure 5. Conceptual approach towards IFC-based mapping of monitoring-related information

3. SUMMARY

Opportunities and challenges towards monitoring information modeling (MIM) for intelligent structural health monitoring systems have been discussed. 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 demonstrated 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. In this paper, specific monitoring-related information relevant to intelligent SHM systems has been defined and classified. The set of available SHM regulations/guidelines, existing sensor models/modeling languages and specific monitoring-related information have been used as the 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 information relevant to intelligent SHM systems throughout the whole life cycle of civil infrastructure systems, thus substantially enhancing the monitoring quality.

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