Wireless structural health monitoring (SHM) systems are installed at a growing number of civil engineering structures to detect potential damage or unexpected structural response. In the past years, building information modeling (BIM) has substantially been changing the workflow of planning and operating engineering structures. Typically, building information is stored and exchanged via model files that are based, for example, on the Industry Foundation Classes (IFC) standard. Even though the IFC provide tools to model certain sensor types, modeling a complete SHM system including information about sensors and monitoring strategies, which in the case of wireless SHM systems encompasses, for example, information on sensor nodes and embedded algorithms (“monitoring-related information”), is not possible with current IFC standard. This paper reviews and assesses different semantic approaches towards modeling monitoring-related information for a BIM-based representation of wireless SHM systems. Using a laboratory test structure, a case study is presented to demonstrate the modeling approach on a wireless SHM system. Autoregressive analysis algorithms are illustratively embedded into the wireless sensor nodes for damage detection. The case study is used for assessing potential limitations of current standards. Finally, the outcome of the case study is discussed and approaches towards BIM-based modeling of wireless SHM systems using the IFC standard are proposed.

Keywords: Structural health monitoring (SHM), building information modeling (BIM), wireless sensor networks, monitoring information modeling.

Introduction

Structural health monitoring is a key technology for assessing and maintaining the structural safety of civil infrastructure. In recent years, maintaining existing civil infrastructure has received increasing attention. The need for infrastructure maintenance has been emphasized in reports from national institutions, such as the American Society of Civil Engineers (ASCE, 2013) or the German Committee on Transport and Digital Infrastructure (Deutscher Bundestag, 2014). In Germany, financial projections for maintaining existing civil infrastructure reach the amount of € 7.2 billion (Deutscher Bundestag, 2014). Implementing structural health monitoring systems facilitates infrastructure maintenance, thus reducing the probability of damage as well as the need for extensive repair works.
Wireless structural health monitoring systems are composed of wireless sensor nodes with embedded computing capabilities that allow processing and analyzing sensor measurements on board. Wireless SHM systems, as compared to cable-based SHM systems, are easier to install and relatively low-cost. With the growing use of wireless SHM systems, there is an increasing need for modeling wireless SHM systems to facilitate the documentation and the communication of monitoring-related information. Monitoring-related information in wireless SHM systems includes, for example, the description of the algorithms embedded into wireless sensor nodes, information about the monitoring strategies, or the interactions among wireless sensor nodes. Some approaches towards a semantic description of wireless SHM systems have been proposed in the fields of electrical and software engineering as, for example, reported in Compton et al. (2012). However, describing monitoring-related information of wireless SHM systems in civil engineering has not been adequately addressed.

Building information modeling (BIM) is a widely employed technology in the building and construction industry. BIM is gaining increasing importance in civil engineering for planning and design of civil infrastructure. The objective of BIM is to provide an integrated digital methodology that supports planning, maintenance and operation of structures throughout their whole life cycle. Supporting interoperability and information exchange, BIM is recommended in publicly-funded building projects in all European countries (European Parliament, 2014). In Germany, planning and building with BIM becomes mandatory for infrastructure projects in 2020 (BMVI, 2015). In the UK, authorities release the “Digital Built Britain” strategy, in which “BIM Level 3” proposes the integration of data, such as sensor information, into the BIM process (HM Government, 2015).

As a technological basis, the Industry Foundation Classes (IFC) are a widely-used, open standard for digital modeling of building information. Using the current IFC standard, information relevant to SHM, such as sensor measurements, can be mapped. However, with the current IFC standard, it is not possible to map all monitoring-related information required to adequately represent wireless SHM systems. Integrating monitoring-related information into the IFC standard would facilitate documenting wireless SHM systems, while enabling a consistent digital representation of all information relevant to wireless SHM systems throughout the whole life cycle of civil infrastructure, thus substantially enhancing the monitoring quality.

This paper focuses on the review and assessment of existing guidelines related to modeling wireless structural health monitoring systems. Furthermore, existing ontologies to be used for modeling sensor systems are reviewed and compared with the IFC standard to evaluate the possibilities of integrating monitoring-related information into IFC. A prototype wireless SHM system is modeled using two different modeling approaches, the Semantic Sensor Network (SSN) ontology and the IFC standard. The prototype system is implemented and validated in laboratory tests on a frame structure. Specifically, embedded autoregressive time series analysis algorithms are implemented into the wireless sensor nodes for structural assessment. The design and implementation, of the wireless SHM system, based on SSN and IFC, is discussed. Finally, conclusions with respect to extending the current IFC standard are drawn.

**Modeling of structural health monitoring systems**

To develop a semantic model for wireless SHM systems, existing regulations and standards are considered that provide the minimum requirements for the information the model must include. Apart from SHM regulations, an increasing number of standards for semantic modeling of sensor information have been developed and published in the past years (Daum,
In this section, existing regulations and standards are reviewed, while approaches towards semantic modeling of monitoring-related information, based on existing regulations and standards, are proposed.

**Existing regulations and standards**

Most regulations related to monitoring focus on traditional monitoring activities, such as visual inspections, rather than on automated SHM procedures. In Germany, the inspection and test of engineering structures in connection roads must be conducted in accordance with the DIN 1076 standard (DIN, 1999). On the other hand, several research groups have reported approaches to describe the implementation and documentation of monitoring techniques (Rücker, 2006). For example, the German Federal Institute of Material Research and Testing (BAM) together with the Structural Assessment Monitoring and Control network (SAMCO), have published the “Guideline for Structural Health Monitoring”, which describes different monitoring technologies along with instructions about their application. The “Guideline for Structural Health Monitoring” includes, for example, selection criteria for sensors, such as sensor resolution, measurement accuracy, and measurement frequency.

In addition to the regulations and guidelines, the semantic modeling of sensor information has been approached in multiple modeling languages and standards. Most standards related to semantic sensor information modeling are assigned to specific fields of engineering, such as the Open Building Information Xchange (OBIX) for building automation, or the Sensor Model Language (SensorML). SensorML is part of the Sensor Web Enablement (SWE) initiative, which provides standardized communication protocols and web services in order to describe sensors and the measurement process. Using SensorML as a basis, the World Wide Web Consortium (W3C) has started the SSN Incubator Group in 2009, which has defined the SSN ontology to describe sensors and related information (Compton et al., 2012). Therefore, the SSN ontology models a sensor, concentrating on what is sensed and how. The main focus is on the sensor measurements, the system as well as the deployment of sensors and the properties that describe the sensor and the observations.

**Integrating monitoring-related information into building information models**

Building information modeling integrates multi-level data covering all phases of the life cycle of structures, including design, construction, maintenance, and, possibly, reuse or demolition, thus improving cost efficiency and enabling a better planning (Eastman et al, 2008). With respect to modeling SHM systems, a few research endeavors combining structural health monitoring and building information models can be found in the literature (e.g. integrating real-time sensor measurements into BIM). For example, Chen et al. (2014) and Rio et al. (2013) demonstrated how integrated sensor measurements can be visualized, evaluated and further used in BIM-based applications. However, the integration of monitoring-related information, as defined previously, into BIM has not received adequate attention. A main idea behind BIM is to have one centralized working model for the whole life cycle of a building, with the building information being accessible and editable any time. In this context, models created in the design phase are unable to “react” to changes during the life cycle of the building.

As mentioned earlier, the IFC are an open standard for building information modeling (ISO, 2013). Developed and maintained by BuildingSMART International, the IFC standard provides a common data format supporting interoperability between different software packages and stakeholders. It is defined in the ISO 16739 standard (ISO, 2014). An IFC object model is composed of entities with specific attributes and relationships among the
entities. The modeling language EXPRESS is used to formalize the data, whereas the “Standard for the Exchange of Product Model Data and the Extended Markup Language” (STEP-XML) provides a basis for exchanging the IFC models. The IFC standard mainly focuses on buildings; in the past years, several research projects have made efforts to extend the IFC (version 4) format in order to integrate infrastructure elements such as roadways (BuildingSMART, 2015), tunnels (Borrmann et al., 2015), and bridges (Ji et al., 2013). To evaluate, what entities and relationships are required for an adequate representation of a wireless SHM system, the relevant modeling possibilities and options in the current IFC version 4 need to be investigated (Smarsly & Tauscher, 2015). Therefore, a case study investigating the mapping a wireless SHM system with embedded auto-regressive models with exogenous inputs using the IFC standard is shown and evaluated in the following section.

**Modeling a wireless SHM system using the SSN ontology and the IFC object model**

The goal of this case study is to assess the modeling possibility of a wireless SHM system with embedded algorithms and distributed processing. A wireless SHM system, equipped with embedded autoregressive analysis algorithms for damage detection, is modeled, implemented, and validated. The SNN ontology and the IFC object model are chosen due to the modeling opportunities and functionality of these semantic modeling languages. While the SSN ontology, which builds on SensorML, includes multiple entities to describe the measurement process, the IFC object model provides a structure to add sensor information into building information models. As opposed to the modeling process, for the sake of clarity the wireless SHM system is first presented, followed by the illustration of the underlying models, i.e. in the following subsections, the laboratory test structure is described and the embedded algorithm is introduced. Then, the monitoring-related information is identified and modeled using the SSN ontology and the IFC object model. Finally, the capabilities of the SSN and the IFC standard with respect to modeling monitoring-related information are discussed.

**Laboratory test setup and implementation**

The sensor nodes used in this case study are of type “Sun SPOT” (Oracle, 2009). The sensor nodes have a 32 bit 400 Hz ARM main processor with 1 MB random access memory and 8 MB flash memory. For wireless communication, an IEEE 802.15.4-compliant TI CC2420 radio transceiver is included in the sensor nodes. The sensor board comprises an internal 3D digital-output accelerometer, type MMA7455L, which is used for collecting measurement data (accelerations) in this study.

As shown in Figure 1, the sensor nodes are deployed on a four-story frame structure. The floors, made of 0.8 mm thick steel plates, have dimensions of 25 cm (width) by 50 cm (length). The height of each story is 23 cm, while the columns are fixed on a solid block at the base of the structure. The response of the structure in terms of accelerations is measured with the wireless sensor nodes placed at the middle of each story, as shown in Figure 1.
Autoregressive models (AR) and autoregressive models with exogenous inputs (ARX) are embedded into the wireless sensor nodes for assessing the condition of the laboratory test structure. Autoregressive analysis algorithms for damage detection have proven to be effective in structural health monitoring (Sohn et al., 2001). Autoregressive models for structural assessment, in general, involve comparison of two or more states, an “initial” (or “undamaged”) state and a “current” state of the structure. At the initial state, a prediction model for the structural response is developed to be used as a reference for comparison with the current state in order to detect structural changes. Deviations between the response obtained by the prediction model and the response obtained at the current state indicate an abnormal condition and potential damage. The prediction model employed in this study is shown in Eq. 1.

\[ x(t) = \sum_{i=1}^{p} \phi_{xi}(t-i) + e_x(t) \]  

where \( x(t) \) is the measured response time series and \( e_x(t) \) the residual error (a white noise signal). The autoregressive analysis algorithm is specified by the order \( p \) and are the AR coefficients \( \phi_{xi} \) determined using the Yule-Walker equations (Lynch et al., 2003).

The procedure of the structural condition assessment is described by the steps shown in Figure 2. First, one time series of accelerations obtained in the initial state is sent to a server, where a reference database is created, i.e. a family of AR coefficients, by splitting the time series in segments of the same size and progressively shifting each segment until the complete time series is covered. The error term \( e_x(t) \) of Eq. 1 is affected by the excitation force, and, as a result, reconstructing \( x(t) \) under all excitation conditions is not possible. Hence, the relationship between \( x(t) \) and \( e_x(t) \) is modeled, essentially considering \( e_x(t) \) as exogenous input (ARX model), as shown in Eq. 2.
Then, a time series of newly collected accelerations $y(t)$ is processed directly on the sensor node and the corresponding AR coefficients are obtained on board. Subsequently, the AR coefficients of time series $y(t)$ are sent to the server to browse the database and retrieve the closest matching AR coefficients from the segments of the initial time series $x(t)$. Upon obtaining the closest match of AR coefficients, the corresponding ARX coefficients are sent back to the sensor nodes. A damage sensitive index $h$ is calculated as the ratio of the standard deviations of the two error terms $\sigma(\varepsilon_x)$ and $\sigma(\varepsilon_y)$. Deviations of $h$ from unity are indicative of structural changes and potential damage.

Figure 2: Structural assessment with embedded AR-ARX algorithm.

Modeling the wireless SHM system using the SSN ontology and the IFC standard

To categorize the monitoring-related information that is needed to model the wireless SHM system, the information is divided into two main categories, global and local monitoring-related information (Smarsly & Tauscher, 2016). Global information includes, for example, the configuration and topology of the wireless sensor network, the interaction protocols used, and the overall monitoring strategy with global diagnosis methods. Also, information required for data storage and for the generation of reports is part of the global monitoring-related information. Local monitoring-related information describes, for example, the specifications regarding single sensor nodes, such as hardware and software parameters as well as the embedded algorithms.

The wireless SHM system model based on the SSN ontology is shown in Figure 3. When using the SSN ontology to model the wireless SHM system, it turns out that the specifications of the sensors themselves can be modeled very well. To be more specific, by using the entity...
ssn:Sensor, local parameters can be defined as subclasses of ssn:MeasurementProperty (e.g. ssn:Accuracy or ssn:Resolution). These properties are collected in the entity ssn:MeasurementCapability (Figure 3). The wireless sensor node, in this case a node of type Oracle SunSPOT, is described by the entity ssn:SensingDevice. Individual sensor measurements are be stored in the entity ssn:ObservationValue.

While the means provided by the SSN ontology are sufficient for modeling single sensors being part of the local monitoring-related information, modeling the global monitoring-related information is hardly possible. The entity ssn:Deployment is capable to describe the monitored structure as well as locations and types of sensors, but relations within the wireless sensor network or between sensors and sensor nodes cannot sufficiently be modeled using the given entities. Moreover, the embedded algorithms are not representable in the SSN ontology, representing one of the major drawbacks of the SSN ontology as a semantic model for wireless SHM systems.

The SSN ontology is capable of mapping the sensing procedure as well as sensor properties and measurement values. To integrate such semantic mapping into BIM, it would be helpful to identify such entities in the Industry Foundation Classes. The IFC object model provides means to model sensors; according to BuildingSMART, the entity IfcSensor must be used to map the information regarding sensors and sensor measurements. An IfcSensor object can be specified by another entity, the IfcSensorType, and its attribute ObjectType. A number of sensor types are predefined in IFC, such as FIRESENSOR or WINDSENSOR. However many sensor types, such as accelerometer that is used in this case study to create a time series for the autoregressive analysis, are not available in IFC and have to be USERDEFINED. Other information can be mapped in the IFC object model by the use of IfcPropertySet. A lot of additional information, such as the accuracy or energy consumption of a sensor can be mapped by using the IfcPropertySet, but only predefined sensor types have applicable property sets to describe its characteristics. For the undefined accelerometer type, for
example, the option using a user-defined property set is not straightforward. Furthermore, the relationships between the wireless sensor nodes and the server as well as the algorithms implemented are hardly describable using property sets.

Discussion of the results

Illustrating the feasibility of modeling monitoring-related information, Table 1 summarizes the comparison between the entities available in the SSN ontology and in the IFC object model. In general, both semantic languages provide possibilities to map single sensors and the measurement values. For undefined sensor types, the IFC object model hardly has available properties. Furthermore, both modeling languages are not designed to map or describe monitoring strategies and embedded algorithms, such as the autoregressive analysis. Therefore, new entities to map monitoring-related information of wireless SHM systems are needed.

Table 1a: Comparison of entities for modeling monitoring-related information (excerpt).

<table>
<thead>
<tr>
<th>Monitoring-related information</th>
<th>SSN ontology</th>
<th>IFC object model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware specifications:</td>
<td><em>Nodes and Server</em></td>
<td>ssn:System [not available]</td>
</tr>
<tr>
<td>Topology of the sensor network:</td>
<td><em>Positions (x,y,z) and story</em></td>
<td>ssn:Deployment (ssn:Platform) IfcRelConnectsElement [element to which sensor is attached]</td>
</tr>
<tr>
<td>Data storage:</td>
<td><em>Type of database</em></td>
<td>[not available] IfcPropertyListValue</td>
</tr>
<tr>
<td>Monitoring strategies:</td>
<td><em>Sequence of monitoring (send-receive)</em></td>
<td>[not available] [not available]</td>
</tr>
</tbody>
</table>
Table 1b: Comparison of entities for modeling monitoring-related information (excerpt).

<table>
<thead>
<tr>
<th>Monitoring-related information</th>
<th>SSN ontology</th>
<th>IFC object model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Local monitoring-related information (about the sensor/wireless sensor node)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of sensor:</td>
<td>MMA7455L Accelerometer</td>
<td>IfcSensorTypeEnum [no defined entity]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(IfcRelDefinesByType)</td>
</tr>
<tr>
<td>Sensitivity:</td>
<td>±2g, ±4g, ±8g for 8-bit Mode</td>
<td>ssn:Sensitivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ssn:MeasurementProperty)</td>
</tr>
<tr>
<td>Sampling rate:</td>
<td>125Hz / 250 Hz</td>
<td>ssn:Frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ssn:MeasurementProperty)</td>
</tr>
<tr>
<td>Power range:</td>
<td>2.4 V – 3.6 V</td>
<td>ssn:OperatingPowerRange</td>
</tr>
<tr>
<td>Measured values:</td>
<td>Acceleration [g]</td>
<td>ssn:ObservationValue</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ssn:SensorOutput)</td>
</tr>
<tr>
<td>Processed parameters:</td>
<td>List of numbers [double]</td>
<td>[not available]</td>
</tr>
<tr>
<td>Algorithm:</td>
<td>AR-ARX procedure</td>
<td>[not available]</td>
</tr>
</tbody>
</table>

**Summary and conclusions**

In this paper, existing semantic modeling languages and standards to represent monitoring-related information of wireless SHM systems have been discussed by the example of the SSN ontology and the IFC object model. It has been demonstrated that integrating monitoring-related information into building information models helps categorizing, documenting and updating monitoring-related information throughout the whole life cycle of the monitored structure. However, this paper has shown that the current IFC standard (IFC 4) does not provide sufficient entities to holistically model (and digitally represent) an overall wireless SHM system. Specifically, information related to the wirelessly communicating sensor nodes with embedded algorithms cannot be adequately modeled. Semantic modeling languages, such as the SSN ontology, may provide a sound basis, because they provide entities whose nature is closer to monitoring. However, semantic modeling languages usually focus on sensor and measurement specifications rather than on overall wireless SHM systems. Therefore, BIM standards need to be extended by a semantic model capable of representing monitoring-related information.
References


