A semantic model for wireless sensor networks in cognitive buildings

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ABSTRACT

Cognitive buildings, being aware of their own performance, actively learn and adapt to the environment, enhancing comfort and safety of occupants. While the integration of Internet of Things (IoT) technology, machine learning, reasoning, and augmented reality into cognitive building concepts has made substantial progress, the integration of structural health monitoring (SHM) and control systems into cognitive buildings has received little attention. In this paper, a semantic model for describing SHM and control systems associated with cognitive buildings is proposed. The semantic model, formally describing SHM and control systems components as well as interrelations between the components, serves as a basis to document, to manage, and to optimize cognitive buildings. Through the semantic model, a laboratory test structure, mimicking a cognitive building, and a prototype SHM and control system, which is installed on the laboratory test structure, are described using building information modeling (BIM). Both the cognitive building and the SHM and control system are physically implemented in the laboratory for validation tests. The results clearly demonstrate the ability of the semantic model to formally describe SHM and control systems associated with cognitive buildings.

INTRODUCTION

Nowadays, buildings are instrumented with sensors that collect various type of data. For example, room temperature data is used to optimize heating, data from lights and elevators is used to optimize energy consumption, and data from heating and air conditioning is used to optimize the operation of the devices. When data is automatically processed, and buildings respond accordingly, buildings are referred to as “cognitive buildings” (Ploennigs et al. 2017). Reading, reasoning, learning, and making inferences from data are key features of cognitive computing, used by cognitive buildings to ensure comfortability and safety of occupants (Chen et
Comfortability denotes that occupants feel easy and relaxed inside buildings, while safety suggests that buildings behave with structural integrity as planned by engineers.

Structural integrity of cognitive buildings is typically assessed by means of structural health monitoring (SHM) (Smarsly and Hartmann 2010). SHM systems are composed of sensor nodes, which are deployed forming cable-based or wireless sensor networks, the latter being widely advantageous in cost and deployment efforts (Smarsly et al. 2011). Wireless sensor networks for SHM systems usually include embedded data processing, advancing decentralized damage detection, sensor fault diagnosis, and structural parameter identification (Cawley 2018; Dragos and Smarsly 2016). Cognitive computing concepts are implemented in SHM and control systems for intelligent data processing, i.e. data processing and active response of buildings, e.g. through active damping devices (“structural control”). In SHM and control systems, some key features of cognitive computing have been studied by Serov (2017), implementing cognitive functions for detecting changes in buildings. Moreover, Yu et al. (2013) have applied radar techniques in numerical models for damage detection; and Ploennigs et al. (2017) have studied the scalability of cognitive computing in cognitive buildings and implemented a platform to detect temperature anomalies for mapping data to semantic models automatically.

As shown by Ploennigs et al. (2017), semantic models, describing capabilities, interoperability, and data integration from multiple sources, serve as a link between sensor data and self-learning capabilities in cognitive computing. More general, semantic models can be applied to first formally describe (engineering) systems and then, based on the semantic models, to optimize the systems throughout the lifetime and to document changes in the systems. Semantic models of SHM systems have been studied by Theiler et al. (2018) for describing algorithms in SHM systems and, further, for implementing semantic models into building information models. For example, Theiler and Smarsly (2018) describe and implement monitoring-related information, i.e. information required for specifying SHM systems, using the Industry Foundation Classes (IFC), an open building information modeling (BIM) standard. More precisely, the schema describing the IFC standard (“IFC schema”) is complemented by an extension referred to as “IFC Monitor”, which specifically describes SHM systems on a meta level, including SHM system components and interrelations between SHM system components. Smarsly et al. (2017) have proposed another IFC schema extension for describing cyber-physical systems, i.e. systems composed of physical and computational subsystems, such as SHM and control systems. Hüthwohl et al. (2018) describe structural defects detected by SHM using a BIM-based formalism in compliance with the IFC standard. In summary, while much progress in semantically describing SHM systems has been achieved, describing SHM and control systems associated with cognitive buildings has not been fully addressed yet. The first step towards describing SHM and control systems associated with cognitive buildings is to define semantic models that describe components of SHM and control systems and interrelations between the components.

In this study, a semantic model of SHM and control systems, as vital parts of cognitive buildings, is presented. The semantic model is based on monitoring-related information extracted
from guidelines, standards, and research related to SHM systems. As will be shown in this paper, the semantic model, in compliance with the IFC standard, is implemented into a building information model, and validation tests are conducted in the laboratory. The paper concludes with a summary and conclusions drawn from this study.

**MONITORING-RELATED INFORMATION EXTRACTED FROM SHM GUIDELINES, STANDARDS, AND RESEARCH**

In this section, knowledge sources related to SHM systems, used to extract monitoring-related information to develop the semantic model, are exemplarily presented, categorized into SHM guidelines, standards, and research.

One of the first guidelines on SHM systems is the “Guideline for structural health monitoring”, presented by the Structural Innovation and Monitoring Technologies Resource Center (Mufti 2001). Therein, SHM systems components, i.e. components ensuring data acquisition, communication, processing, storage, diagnosis, and data retrieval, are introduced. Moreover, depending on the testing type applied, i.e. how data is physically collected, SHM systems are categorized into static, dynamic, periodic, and continuous monitoring systems. Furthermore, information on sensor data and algorithms are discussed in the guideline. Another technical report related to SHM systems, entitled “Development of a model health monitoring guide for major bridges”, has been published by the United States Department of Transportation (Aktan et al. 2013). In the technical report, performance, health monitoring, and structural identification are defined. Moreover, SHM systems technologies are categorized as experimental, analytical, and information-related technologies, i.e. measuring and testing technologies, linear and nonlinear analysis technologies, and data acquisition, processing, and interpretation technologies. Furthermore, sensor selection criteria and sensor classifications are presented along with data acquisition systems, network communication, calibration, and data management and interpretation.

The technical report “UNI-TR 11634:2016 Guidelines for structural monitoring” has been published by the Italian Organization for Standardization (UNI 2016) and is intended to become a standard in the future. In the UNI report, conception, design, management, and equipment of SHM systems are covered. The focus of the UNI report is put on bridge and building monitoring, extendible to other structural types, such as offshore and underground structures. In the UNI report, defining SHM system objectives depending on the structure to be monitored is one step in designing SHM systems as well as defining measuring strategies, SHM network topologies, data acquisition systems, data processing, and data management. A compulsory standard is the “Technical code for monitoring of building and bridge structures – GB 50982-2014” published by the Chinese Ministry of Transportation in 2014 (Moreu et al. 2018). The technical code focuses on sensor requirements (e.g. durability and maintenance), data requirements (collection, transmission, processing, and management), and safety evaluation requirements. Additionally, the technical code gives instructions for applying SHM systems in different infrastructure types.
For semantically describing SHM systems, Theiler and Smarsly (2018) have proposed an IFC extension. The extension, based on a semantic model developed by the authors, considers the structure being monitored and the corresponding SHM system, which includes computers and sensor networks, as one unit to be described as a whole. Sensor networks are composed of sensor nodes, optionally equipped with sensors and actuators. In related research, Matthus (2017) has described SHM-related algorithms on a semantic basis, while Fitz (2018) has formally described communication in SHM systems. Hüthwohl et al. (2018) have described bridge defects using IFC, considering bridge inspection information and defect details, such as location and extension.

In the following section, the knowledge taken from SHM guidelines, standards, and research is materialized in terms of monitoring-related information in the semantic model for describing cognitive buildings.

A SEMANTIC MODEL FOR SHM AND CONTROL SYSTEMS IN COGNITIVE BUILDINGS

In the semantic model, the knowledge identified from the sources in the previous section is formalized. The semantic model developed by Theiler and Smarsly (2018) is deployed as a conceptual basis, extended in this study by elements relevant to cognitive buildings (Figure 1).

As shown in Figure 1, a cognitive building is composed of a building that is monitored by a SHM system. In addition, control mechanisms for actuation are devised, entailing a SHM and control (SHMC) system. The semantic model extensions proposed in this work primarily focus on the description of node specifications. The node specifications are divided into performance, constraints, economy, and history. Performance is related to sensitivity, resolution, measurement...
range, linearity, hysteresis, accuracy, repeatability, stability, response time, and frequency response. Constraints are related to environmental conditions, under which nodes perform properly, and include node characteristics for coping with environmental conditions, i.e. temperature range, humidity range, size, and isolation. Economy is related to component costs, availability, durability, and installation efforts. Finally, history accounts for changes to which nodes are subjected, as specified by information related to date and components changed.

BIM-BASED IMPLEMENTATION AND VALIDATION OF THE SEMANTIC MODEL

The semantic model is implemented into an IFC schema extension serving as a metamodel to describe cognitive buildings on a BIM basis. In compliance with the current IFC version “IFC 4 – Addendum 2”, standardized in ISO 16739:2013 (ISO 2013), information related to SHM and control can be described, starting from components of sensor nodes and advancing to descriptions of compositions of sensor networks and of SHM and control systems. The IFC schema extension is validated using test software of the official IFC certification program and, to demonstrate the descriptive capacities of the IFC schema extension, a prototype cognitive building is exemplarily described in this section.

![Figure 2. Extract of the IFC schema with the extension illustrated by grey-colored elements.](image)

As can be seen from Figure 2, using the relationship `IfcRelAggregates`, sensor nodes represented by `IfcSensorNode` entities are described as compositions of entities, such as sensors (`IfcSensor`), actuators (`IfcActuator`), controllers (`IfcController`), communication units (`IfcCommunicationAppliance`), and power units (`IfcElectricFlowStorageDevice`) of specific enumeration types. For example, the sensor type enumeration `IfcSensorTypeEnum` defines different types of sensors including strain sensors and acceleration sensors added to `IfcSensorTypeEnum`. Providing a common purpose or function of the sensor nodes, such as SHM and control of buildings, `IfcSensorNode` entities can be connected to sensor networks (`IfcSensorNetwork`),
applying the IfcRelAssignsToGroup relationship. A selection of standardized property sets that apply to IfcSensorNode are shown in Figure 2. Property sets, such as Pset_ServiceLife and Pset_ManufacturerTypeInformation, contain subsets of sensor specifications for precisely describing SHM and control systems in cognitive buildings (IfcBuilding) according to the semantic model. For example, service life durations can be described using lower and upper bounds as well as setpoints for indicating typical service life durations. Basic information about manufacturers, sensor models, and production dates are summarized in the property set Pset_ManufacturerTypeInformation. Furthermore, property sets are available for describing, e.g., sensor conditions, energy consumption, and electrical parameters, such as current and voltage. Semantic references of IfcSensorNode entities to property sets are realized by IfcRelDefinesByProperties relationships. As SHM and control systems are composed of sensor nodes forming sensor networks and a computer system, IfcSHMCSystem entities, IfcSensorNetwork entities, and IfcCommunicationAppliance entities of enumeration type “COMPUTER” are connected using IfcRelAssignsToGroup relationships. To provide logical connections between all SHM and control system components of type IfcSensorNode and of type IfcCommunicationAppliance representing a computer system, IfcRelConnectsElements is applied with respect to the enumeration IfcNetworkTopologyEnum for determining network topologies.

To validate the IFC-based modeling approach for cognitive buildings (shown in Figure 2), and thus the semantic model (shown in Figure 1), a cognitive building and a SHM and control system are modeled and then physically implemented in the laboratory (Figure 3).

Figure 3. IFC-based BIM model (left) and physical implementation (right) of the prototype cognitive building and the SHM and control system.

The geometries of the cognitive building and the SHM and control system (Figure 3, left) are modeled using a conventional IFC-compliant BIM software tool. The BIM model is composed of a four-story shear frame structure, a semi-active tuned liquid column damper (TLCD, IfcDamper) on the topmost story, and the SHM and control system monitoring acceleration and controlling the TLCD. The shear frame structure with a story height of 300 mm each is made of
five 300 mm x 200 mm x 15 mm aluminum slabs fixed to four aluminum columns of 20 mm x 2 mm rectangular cross section. The semi-active TLCD is equipped with an electrical valve connected to a sensor node serving as a controller. Specific information about the SHM and control system is added to the IFC file exported from the BIM software tool to receive a full IFC-compliant BIM model of the cognitive building (*IfcBuilding*) and the SHM and control system (*IfcSHMCSys*). The SHM and control system is composed of two WiFi-enabled sensor nodes (*IfcSensorNode*), based on the Raspberry Pi 3B platform with embedded SHM and control algorithms, that are connected to a computer in star topology. While one sensor node serves as a controller for the TLCD (*IfcActuator*), the second sensor nodes is, via a cable-based connection, equipped with two acceleration sensors to monitor the structure (*IfcSensor*). Figure 3 (right) shows the prototype cognitive building and the SHM and control system implemented in the laboratory. Finally, in a test procedure manual excitation of the structure is conducted, corroborating proper operation of the SHM and control system.

**SUMMARY AND CONCLUSIONS**

In this paper, a semantic model has been proposed to describe SHM and control systems in cognitive buildings. The semantic model serves as metamodel, which is technology-independent and can be used within various modeling languages. For validation, the IFC schema has been extended and implemented into an IFC-compliant BIM model describing a prototype cognitive building and a SHM and control system, both of which physically implemented in the laboratory. The results show the ability of the semantic model to describe information related to SHM and control systems in cognitive buildings. In future work, the semantic model may be extended for covering further system components of cognitive buildings.

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