A metamodel for cyber-physical systems

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Abstract. With the advent of the Internet of Things and Industry 4.0 concepts, cyber-physical systems in civil engineering experience an increasing impact on structural health monitoring (SHM) and control applications. Designing, optimizing, and documenting cyber-physical system on a formal basis require platform-independent and technology-independent metamodels. This study, with emphasis on communication in cyber-physical systems, presents a metamodel for describing cyber-physical systems. First, metamodeling concepts commonly used in computing in civil engineering are reviewed and possibilities and limitations of describing communication-related information are discussed. Next, communication-related properties and behavior of distributed cyber-physical systems applied for SHM and control are explained, and system components relevant to communication are specified. Then, the metamodel to formally describe cyber-physical systems is proposed and mapped into the Industry Foundation Classes (IFC), an open international standard for building information modeling (BIM). Finally, the IFC-based approach is verified using software of the official IFC certification program, and it is validated by BIM-based example modeling of a prototype cyber-physical system, which is physically implemented in the laboratory. As a result, cyber-physical systems applied for SHM and control are described and the information is stored, documented, and exchanged on the formal basis of IFC, facilitating design, optimization, and documentation of cyber-physical systems.

Keywords: Cyber-physical systems, structural health monitoring (SHM), wireless sensor networks, metamodeling, semantic modeling, building information modeling (BIM), Industry Foundation Classes (IFC)

1. Introduction

A cyber-physical system (CPS) is commonly referred to as a coupled system integrating computing, networking, and physical processes [1]. As such, cyber-physical systems are hybrid hardware/software systems coupling heterogeneous subsystems able to sense, to act, and to communicate through networks [2]. Recent advancements in Industry 4.0-related research have paved the way for CPS applications in civil engineering [3]. Specifically, modern structural health monitoring (SHM) and control systems exhibit all features listed in the above CPS definition [4]. SHM and control systems enable real-time monitoring and assessment of structural conditions by automated data acquisition, data analysis, and appropriate actions performed by intelligent sensor networks and networked control devices spatially distributed over the structures being monitored. In civil engineering, cyber-physical systems consisting of SHM and control systems are used to improve structural control of civil structures, such as bridges [55] or high-rise buildings in earthquake areas [56].

In recent years, cable-based SHM systems traditionally applied in structural health monitoring have been progressively replaced by wireless SHM systems using “smart” sensor nodes with embedded intelligence or on-board computing and sensing capabilities, respectively [5]. The terms “smart” or “intelligent”, unlike common definitions of intelligence in computer science, denote the embedment of algorithms and models for on-board data analysis into sensor nodes [6]. SHM systems, according to [7], provide, on demand, reliable data about conditions of structures being monitored. Therefore, wireless SHM systems need to integrate sensing devices into sensor networks distributed over a structure that perform on-board data acquisition, data processing, and data communication [8]. By embedding engineering models, such as models of the structure or structural components, into SHM systems, automated damage detection is supported [9].

Taking into account the rapid advancements in sensing technologies, formal semantic information modeling concepts are needed to describe information about cyber-physical systems applied for SHM and control. Information about SHM and control, referred to as “monitoring-related information”, and not to be confused with sensor data, must be described independently of technical platforms and programming languages [5, 10]. Technology-independent semantic descriptions of SHM and control systems hold essential potentials for documenting and exchanging information about system compositions and system states, including documentations of changes in setup and functioning of cyber-physical systems [11]. Using ontologies and description languages designed for describing distinct subdomains of monitoring-related information, e.g. sensor characteristics or network characteristics, the description of SHM and control systems is partially possible. However, limitations are obvious, if communication-related information is to be described in the context of structural systems of a CPS. Typically, referencing capabilities from communication-related information to elements of the structural system of a CPS is not possible. In addition, distinct characteristics of SHM and control systems are not covered by the ontologies and description languages, e.g. embedded algorithms, overall SHM strategies, diagnosis levels, and history of sensor configurations. To overcome the absence of referencing capabilities and distinct characteristics, this paper uses building information modeling (BIM) concepts to describe both the structural system and communication-related information in a holistic approach. In the architecture, engineering and construction industry, technology-independent semantic descriptions of buildings using BIM based on the Industry Foundation Classes (IFC) standard are already well-established and using IFC-based BIM approaches is mandatory in many countries [12, 13, 14]. In Germany, following a phase plan published in 2015, BIM is to be applied to all new projects in the area of the Federal Ministry of Transport and Digital Infrastructure from 2020 onwards [15]. The German Federal Ministry of Transport and Digital Infrastructure states that IFC-based data exchange in structural engineering is well-established. Additionally, the descriptiveness of civil infrastructure may be improved by extending the IFC standard.

Although describing building information and infrastructure information using IFC is an active field, recent research has shown that the current version of the IFC schema is not yet sufficient to describe all aspects that enable the use of BIM models over the life cycle of buildings or infrastructure. For example, for BIM models describing cyber-physical systems, monitoring-related information and communication-related information need to be incorporated into the IFC schema [5, 16]. Communication-related information is a subset of monitoring-related information describing communication technologies, such as communication protocols, routing of communication including origin and destination of each communication process, transmission media, and technical devices employed to realize sensor communication. Besides technological aspects, information about the data exchanged between communicating sensor nodes is of interest for detailed descriptions of cyber-physical systems.

To describe communication-related information on a well-defined basis, in this study, first an overview of metamodeling approaches relevant to cyber-physical system modeling is provided (Section 2). Then, theory and technical details on network communication are summarized in a literature review (Section 3). Next, a BIM-based metamodel for cyber-physical systems applied for SHM and control systems is presented using a technology-independent metamodel, with emphasis on semantic descriptions of communication-related information (Section 4). Subsequently, preparing a validation of the BIM-based description approach applied in this study, the metamodel is mapped into the IFC schema that is extended for BIM-based descriptions of cyber-physical systems in form of an IFC schema extension (Section 5). Upon verification of the extended IFC schema, the validation is shown on a prototype CPS applied for SHM and control in the laboratory (Section 6). Finally, the results are summarized and conclusions are drawn in Section 7.

2. Metamodeling approaches relevant to modeling cyber-physical systems in civil engineering

For modeling cyber-physical systems, a variety of metamodeling approaches can be applied. In this section, basic concepts of metamodeling are illuminated and three common metamodeling approaches are analyzed for describing information related to cyber-physical systems, (i) the Unified Modeling language (UML) and additional modeling languages published by the Object Management Group (OMG), (ii) the seven standards forming the Sensor Web Enablement (SWE) framework, and (iii) the data modeling language EXPRESS, all following the object-oriented paradigm, are metamodeling approaches frequently used in computing in civil engineering.

In software engineering and systems engineering, models are used to capture real-world aspects of problem domains with different levels of abstraction [10]. While models are abstractions of phenomena in the real world, metamodels are further abstractions that specify the structure, the semantics, and the constraints for a family of models that are situated in a certain domain. The term "modeling" describes design techniques and development processes that require technical frameworks for information integration and for tool interoperability. Software and systems engineering approaches based on models are described in technical frameworks, referred to as model-driven development (MDD). In 2000, the OMG, an international, open-membership, non-profit technology standards consortium, has published the Model-Driven Architecture (MDA) standard, which is today a widely used realization of MDD [17]. The MDA framework has been developed to separate specifications of system functionalities from platform-specific system implementations [17, 18]. Therefore, the MDA design process starts with a platform-independent model (PIM) describing functionalities and behavior of a system. In subsequent steps, a PIM is converted into a platform-specific model (PSM) and into a working implementation. The purpose of a PIM, e.g. for describing cyber-physical systems, is to remain stable as technology evolves and to enable mapping between different modeling languages, such as between UML and other OMG standards, the SWE framework, and the EXPRESS data model analyzed in the following subsections.

2.1 UML and other OMG standards

To develop models that remain stable as technology evolves, modeling languages, which are, e.g., based on OMG's Meta Object Facility (MOF) are used to describe models in a platform-independent manner [19]. As can be seen from the schema of a MOF-based metamodeling approach in Figure 1, the MOF is a so called "meta-metamodel", situated on layer M3 providing a platform-independent metadata management foundation for MDA and serves as a model of different modeling languages, referred to as "metamodels" on layer M2 shown in the schema. The main goal of the MOF is to provide a basis for defining and extending metamodels and models (layer M1) by generalizing the core concepts of different modeling languages. The key modeling concept of MOF follows object-oriented paradigms of classifiers and instances, or classes and objects, respectively. Thus, it is possible to navigate from an instance (layer M0) to its class (layer M1), i.e. the metaobject, across any metalevel or degree of abstraction, respectively [20].

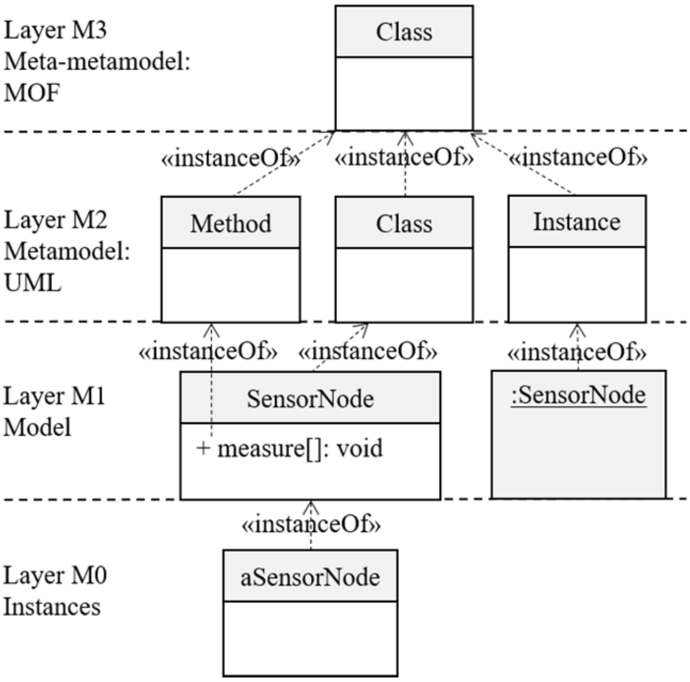


Figure 1 MOF-based metamodeling approach.

The sequence of deriving metamodels from a meta-metamodel and models from metamodels forms the basis of a well-defined modeling process. As a result, different models and metamodels can be interchanged, because syntax and semantics of modeling languages are clearly defined, thus being mappable to each other.

With the MOF, MDA of OMG aims to create, to store, and to transform machine-readable models based on a rigorous underlying modeling infrastructure. Applying MOF-based modeling standards, such as Unified Modeling Language (UML) and other OMG specifications, the meaning of diagram elements and relationships between elements of systems can be captured in a machine-readable form, enabling automated consistency control and generation of application code [25]. MOF reuses a subset of structural modeling symbols of UML 2, which contains key modeling concept of classifier and instance (or classes and objects) for software development [20].

Within the UML specification, the semantics of UML, defining the meaning of statements made in UML models, are subdivided into two semantic categories, structural semantics and behavioral semantics [26]. Structural semantics, forming the basis of behavioral semantics in UML, define the meaning of UML model elements, such as classes, components, relationships, and data types. Behavioral semantics describe the communication between structural elements influenced by methods of associated model elements. Behavioral modeling can be used to express interaction sequences necessary to describe communication processes. Regarding cyber-physical systems and, in particular, communication-related information, UML offers a wide variety of notations and modeling constructs to describe architecture and behavior of computational systems. An advantage of UML is the technical capability of UML to derive MOF-compliant metamodels from the general UML specification by creating profiles for different modeling purposes and domains, which may be used to develop metamodels of cyber-physical systems.

2.2 The SWE framework

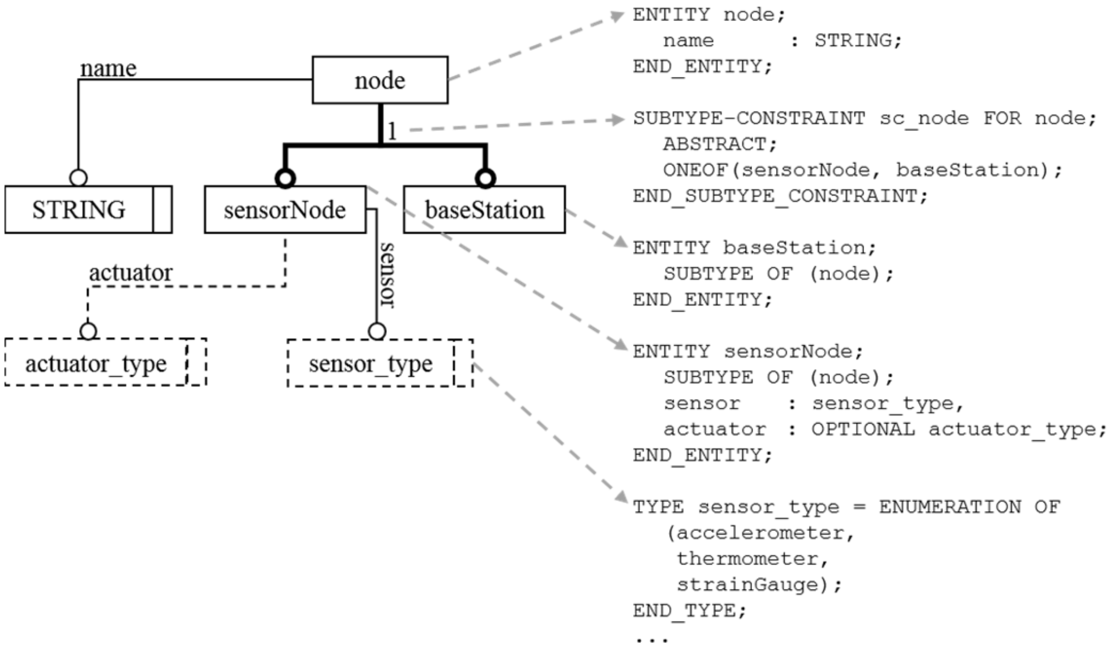
The Open Geospatial Consortium (OGC), an international non-profit organization, has published a family of standards forming the SWE framework and providing metamodeling capabilities for geospatial systems, such as sensor systems, with the key idea to make data of sensor systems online accessible through interfaces and protocols following well-defined standards. The SWE framework is composed of seven standards employing UML notations and XML notations to represent conceptual schemas for describing sensor networks, sensors, sensor observations, and measurements [28]. Within the standards family of the SWE framework, the Sensor Model Language (SensorML) is used to encode sensor descriptions. Sensor observations are described using the Observation & Management (O&M) standard. To provide standardized access to sensor data and to sensor descriptions, the Sensor Observation Service (SOS) has been introduced [27]. In compliance with its concept of metamodeling, the SWE framework aims to link several sensor-related technologies, while avoiding restrictions upon specific products and approaches. Systems created using design principles of the SWE framework are thus technology-independent and allow further extensions [28, 29].

The SWE framework also focuses on processes and processing components of sensor systems using syntax and semantics of the SensorML metamodel. The core concept of SensorML is to describe components of sensor systems (e.g. sensors or actuators) as processes. In general, processes may receive inputs, generate outputs, and have parameters. Hence, SensorML is a process description language supporting data of different formats exchanged between logical processes [30, 31]. SensorML is independent from communication protocols used to exchange data between system components [32]. In addition, SensorML can be used to describe interface characteristics, such as communication protocols, baud rates (speed of communication over a data channel), and port settings (e.g. port number, port type) [32]. However, no graphical notation or exhaustive XML encoding has been standardized for interface characteristics.

2.3 The EXPRESS metamodel

Another metamodel relevant to modeling cyber-physical systems in civil engineering is EXPRESS, standardized in ISO 10303-11 [33]. EXPRESS is a data modeling language and a metamodel that provides computer-interpretable representations of product information, designed to enable product data exchange [33]. EXPRESS is used in civil engineering to formally define the IFC specifications as a basis for open-source BIM [34]. Recent research on integrating sensor data into building information models has demonstrated the effectiveness of EXPRESS-based data modeling, therefore modeling capacities of EXPRESS with respect to describing monitoring-related and communication-related information are further discussed here [5]. The key concept of ISO 10303 is to create models of product data that may be used in software applications during the life cycle of products. The life cycle of products includes, e.g., design, construction, production, marketing, application, and recycling.

To realize consistent exchange, storage, archiving, and transformation of product data defined in EXPRESS-based data models, the "Standard for the Exchange of Product Model Data" (STEP, ISO 10303-21 [35]) is used. The metamodel EXPRESS includes a textual as well as a graphical representation, EXPRESS-G, that comprises a subset of constructs of the textual modeling language. Figure 2 shows main elements of EXPRESS-G describing the composition a node that can be either a base station or a sensor node having a sensor or an optional actuator attached. Accordingly, the entities describing nodes are shown in textual EXPRESS notation.



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ENTITY node;
   name      : STRING;
END_ENTITY;

SUBTYPE-CONSTRAINT sc_node FOR node;
   ABSTRACT;
   ONEOF(sensorNode, baseStation);
END_SUBTYPE_CONSTRAINT;

ENTITY baseStation;
   SUBTYPE OF (node);
END_ENTITY;

ENTITY sensorNode;
   SUBTYPE OF (node);
   sensor    : sensor_type,
   actuator  : OPTIONAL actuator_type;
END_ENTITY;

TYPE sensor_type = ENUMERATION OF
   (accelerometer,
    thermometer,
    strainGauge);
END_TYPE;
...
```

Figure 2 Example of EXPRESS-G and EXPRESS.

2.4 Summary

Although the metamodels presented in this section vary in (textual or visual) notation, models, i.e. instances of metamodels representing real-world systems can be derived following metamodel-specific syntaxes and semantics. UML and related OMG specifications, in comparison to EXPRESS, possess a more comprehensive range of modeling capacities, because more visual notations are standardized and can be represented. UML is characterized by a high flexibility and adaptability to various modeling purposes. Using UML profiles, additional metamodels can be derived from UML that are as well in compliance to MOF and the MOF-based metamodeling approach. The SWE framework also applies UML notations, thus being comparable to special-purpose UML profiles restricting the variety of UML notations for a special-purpose metamodel. The standards forming the SWE framework provide UML models and XML schemas facilitating technology-independent descriptions of sensor networks including physical system elements and constructs, such as observations and measurements

In summary, UML is the most general and most flexible metamodel reviewed herein. The wide scope and notational variety reason the complexity of UML and make the metamodel applicable to many modeling purposes, such as to describing cyber-physical systems. Thus, UML constructs for structural modeling and behavioral modeling are exceptionally valuable for describing communication-related information in cyber-physical systems. While components of cyber-physical systems, such as communication units of sensor nodes, can be described using class diagrams, algorithms may be modeled using state machine diagrams, and processes implemented in communication protocols can be visualized in sequence diagrams. On the other hand, it should be emphasized that, due to the growing importance of open BIM in civil engineering, the modeling approaches of EXPRESS along with the IFC standard to describe structural systems is gaining attention in research and practice.

3. Communication in cyber-physical systems

To describe cyber-physical systems using metamodeling approaches, system components, including attributes and methods, need to be defined. As a basis to characterize attributes and methods, in this section, network topologies applied for communication in cyber-physical systems are studied. Also, a survey of network communication is provided, and communication protocols suitable for cyber-physical systems are reviewed. Developing a metamodel capturing communication-related information, such as system components related to communication, network topologies, network communication characteristics, and communication protocols, enables distinct advantages, such as effective planning of SHM and control systems, improved data control and management in the operation and maintenance phase of CPS, or linking of SHM and control system components with communication-related information.

As nodes of wireless sensor networks are spatially distributed, autonomous devices, power consumption and resource management are important criteria in designing communication protocols and network topologies [36]. Topologies typically applied in wireless sensor networks are shown in Figure 3 [9, 37]. Star topologies and mesh topologies are suitable for communication in cyber-physical systems, therefore frequently applied in SHM and control applications. In star topologies, sensor nodes are connected to a central node, e.g. to a base station. Communication is exclusively realized between sensor nodes and the central node. As a consequence, failures of a central node result in failure of the total sensor network. However, star topologies are tolerant to failure of single sensor nodes, rendering star topologies suitable for SHM and control applications. Mesh topologies enable communication across all nodes in a network. Partially connected and fully connected mesh networks can be distinguished. In fully connected mesh networks, nodes directly communicate with other nodes, whereas in partially connected mesh networks several nodes are connected indirectly. Mesh topologies allow calculating optimal routing paths, which contributes to an efficient exploitation of energy resources distributed over a wireless sensor network.

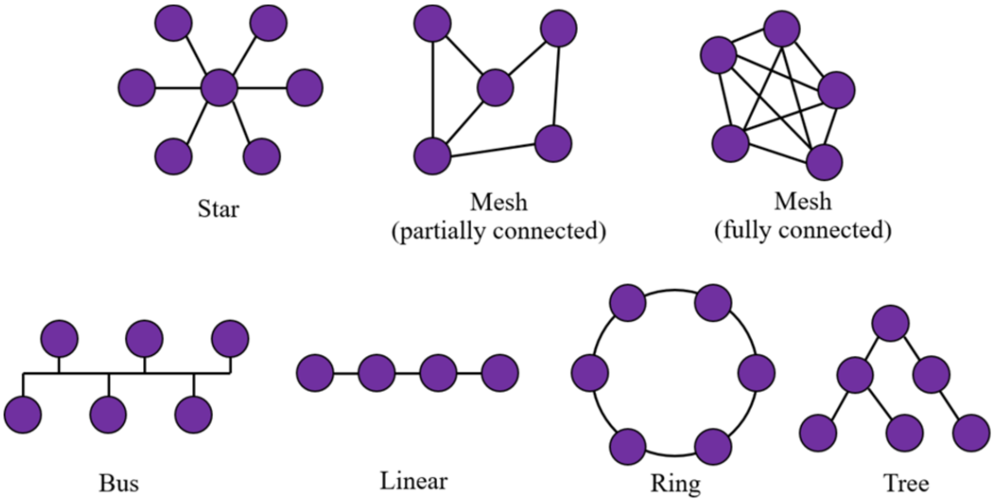


Figure 3 Visual representation of network topologies.

As data exchanged in sensor networks encompasses several layers of abstraction, a layered model of networking has been developed by the International Organization for Standardization (ISO), published in ISO/IEC 7498-1:1994 [38]. The "Open Systems Interconnection (OSI) reference model" defines seven layers of abstraction in network communication, shown in Figure 4, and the function of each layer. Following the OSI reference model, nodes of networks communicate at equivalent layers of abstraction by layer-specific protocols. Every layer of abstraction n-1 provides services to higher abstraction layers n through service access points specified for each layer [39].

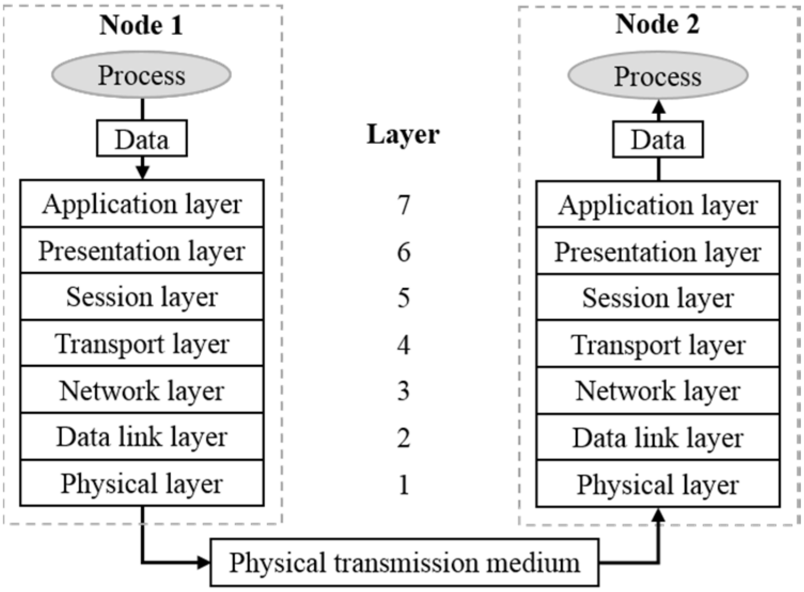


Figure 4 Node-to-node communication using the OSI reference model.

In the OSI reference model, layers 1 to 4 form the transport system of a network, while layers 5 to 7 represent application-oriented layers. On the **physical layer** (layer 1), bit transmission over a physical medium, such as air or water, is specified. Protocols on the physical layer encode parameter modulation schema, transmit power, and hop distance of data packets, which contribute to energy consumption of wireless sensor networks. The modulation schema specifies the transformation of the bit values 0 and 1 into electrical quantities. The term "transmit power" denotes the amount of energy required to transmit data packets. Transmit power is in inverse proportion to errors in data transmission and related to the distances between the transmitter and the receiver of communicating nodes, which is called "hop distance" [37, 39]. The **data link layer** (layer 2) organizes bits of data units into frames, referred to as multiplexing and demultiplexing, respectively. The data link layer is responsible for error detection through check sums added to a data packet, and it provides flow control to manage data transmission rates. Furthermore, medium access control (MAC) is performed on the data link layer. The **network layer** (layer 3) manages routing, i.e. identifying optimal paths to forward data from sensor nodes to base stations by passing intermediate nodes [37, 39]. The fourth layer, or **transport layer**, establishes communication between nodes defined by the routing process of the network layer. Transport layer protocols transform data units (multiplexing or demultiplexing) to make data accessible to end-system processes. Moreover, transport layer protocols provide services, such as error detection in data units, flow control and service reliability by the authorization of retransmission of a data unit [40]. The **session layer** (layer 5) enables and controls communication processes for complete data exchange between nodes by managing multiple transport layer connections. Following the session layer, the **presentation layer** (layer 6) performs data transformations to make data processable by the **application layer** (layer 7) [37]. The data format is defined by a uniform syntax, referred to as transform syntax, enabling correct representations of data with respect to encoding mechanisms, such as ASCII code or Unicode. Finally, the application layer provides protocols to be used by software applications [39].

On each layer of the OSI reference model, several protocols exist that can be combined to a specific protocol stack. In a protocol stack, data is transmitted from a node to another node by passing every layer of abstraction (Figure 4). Starting from the application layer of a sending node, control information is successively added to a data unit and removed in inverse direction at a receiving node. Regarding the energy constraints of wireless sensor networks, which are typically composed of battery-powered components, the deployment of cross-layer protocols improves communication efficiency within a network. Cross-layer protocols integrate several functionalities of different OSI communication layers into one protocol to enable highly reliable communication with minimal energy consumption, adaptive communication decisions, and local flow control [41].

Due to the plenitude of communication protocols, suitable communication protocols for cyber-physical systems are defined when designing a CPS for structural health monitoring and control, following a requirements analysis applying specific criteria, such as the size of data packets to be transmitted, the data transfer frequency, and the transfer range between nodes. Furthermore, limits on the number of communicating nodes and security issues must be considered in selecting communication protocols. Security is of growing importance in in cyber-physical systems specially in those applied in Industrial Internet of Things (IIoT) applications [42]. Security objectives in communication between nodes of a network are (i) confidentiality and integrity of data, (ii) authenticity of system elements, and (iii) data access authorization [43]. Data confidentiality denotes restrictions of readability of data to authorized network components, while data integrity describes the verification of sources sending data as well as the detection of data modified and sent by unauthorized sources. Therefore, system elements require unique identifiers (authenticity) and access authorizations to read, to write, and to manipulate data. As security issues are of growing importance in CPS, IoT, and IIoT (however not within the main scope of this study), information describing security-related network properties is formalized along with communication-related information and monitoring-related information.

Table 1 provides an example selection of communication protocols frequently applied for wireless communication in cyber-physical systems, including Bluetooth, ZigBee, Wi-Fi, and the Message Queue Telemetry Transport protocol (MQTT). ZigBee and MQTT are characterized by low power consumption and provide embedded security strategies with a high degree of scalability with respect to the number of nodes. High-level protocols, such as ZigBee and MQTT, are based on implementations of the physical layer and the data link layer of the OSI model (Figure 4) [41,44]. A number of low-level networking protocols, encompassing functionalities of the physical layer and the data link layer, are standardized in the IEEE 802 standards [45], such as Wi-Fi (IEEE 802.11.a/b/g) and Bluetooth (IEEE 802.15.1). A low-power and low-cost solution for wireless communication is given by the low-rate wireless personal area network (LR-WPAN) standard IEEE 802.15.4 that allows setting up networks with star and mesh topologies. An overview of frequency ranges and data rates in compliance with local regulations is given in Table 2 [46]. Two physical layers, i.e. the 2.4 GHz band layer and the 868/915 MHz band layer, are defined in the IEEE 802.15.4 standard. The worldwide unlicensed 2.4 GHz band layer is characterized by higher data rates compared to the 868/915 MHz band layer, which is due to higher frequencies and the digital modulation schema applied. While for binary phase-shift keying (BPSK) two phases separated by 180° are used for digital modulation, offset quadrature phase-shift keying (O-QPSK) uses four phases to modulate data for high data rates. The offset in the modulation schema is applied for limiting large amplitude fluctuations undesired in communication systems.

Table 1 Comparison of wireless standards [41, 44]

	Bluetooth	**ZigBee**	**Wi-Fi**	**MQTT**
Specification	IEEE 802.15.1	Based on IEEE 802.15.4	IEEE 802.11a/b/g	ISO/IEC 20922:2016
Application	Wireless connectivity between, e.g., phones, PDA, laptops, headsets	Industrial control and monitoring, sensor networks, building automation, home control and automation	Wireless LAN connectivity, broadband Internet access	Communication in machine to machine (M2M) and Internet of Things (IoT) contexts, devices at remote locations, low power enabled devices
Network topologies	Point-to-point, star, mesh (partially and fully connected)	Star, tree, mesh (partially and fully connected)	Line, ring, star, tree, mesh (partially and fully connected)	Star, partially connected mesh (through bridging of brokers)
Transmission distance	10 m	10 m to 20 m (100 m in networks)	100 m	Depending on the choice of low level protocols (physical and data link layer)
Max number of nodes	8 active devices, 255 in park mode	> 65,000	Unlimited	Unlimited

Table 2 IEEE 802.15.4:2003 frequency bands and data rates

Physical layer (MHz)	**Frequency band (MHz)**	**Geographical region**	**Modulation**	**Number of channels**	**Bit rate (kbps)**
868	868-868.6	Europe	BPSK	1	20
915	902-928	United States	BPSK	10	40
2450	2400-2483.5	Worldwide	O-QPSK	16 (11 to 26)	250

4. A metamodel for describing communication-related information

In this section, the metamodel for describing cyber-physical systems is presented based on the results of analyzing metamodeling approaches frequently used in computing in civil engineering (Section 2) and the topologies and communication protocols used in in cyber-physical systems (Section 3). Developing the metamodel is based on a formal analysis of communication processes. A model of communication processes that dates back to the work of Shannon [47] is shown in the schematic diagram in Figure 5. The schematic diagram shows the main elements of a communication system and relationships between the elements. In general, communication systems include (i) transmitters, (ii) transmission media, (iii) receivers, and (iv) messages, which are transformed into (v) electrical signals. Messages are initiated by (vi) information sources (i.e. sensor nodes) making observations (i.e. temperature, acceleration) and are processed at (vii) destinations of communication systems (i.e. other sensor nodes, base stations, or computer systems). In addition, the model of Shannon describes effects of noise that perturbates signals transmitted between a sending and a receiving device. Due to noise in communication systems, signals sent by transmitters may differ from signals received by receivers.

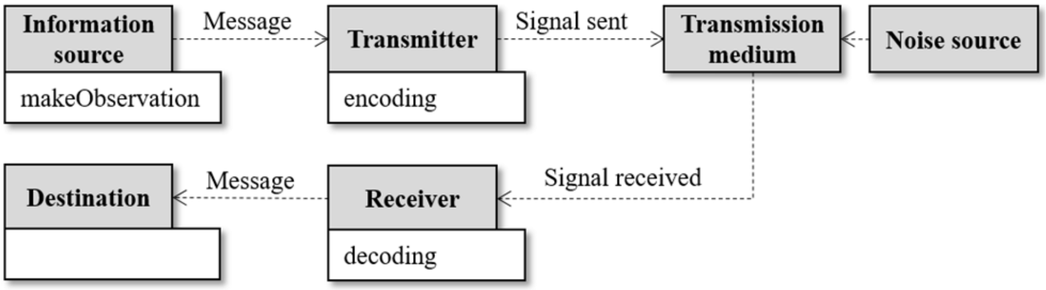


Figure 5 Schematic diagram of a communication system [47].

Two processes involved in communication are *encoding* and *decoding*. Encoding on the transmitter end of communication systems specifies the translation of messages into languages (or code), in compliance with defined syntaxes and semantics. As a result, messages are transformed into transmittable signals that can be received and understood by receivers provided with suitable methods to decode incoming signals. The decoding process on receiver side of communication systems denotes the re-translation of signals into messages that can be processed by destinations, such as data management systems or software applications controlling actuators [48]. In cyber-physical systems, semantically and syntactically correct encoding and decoding of messages is ensured by communication protocols, as introduced earlier.

The main elements and processes involved in communication within cyber-physical systems are assembled as communication-related information in the metamodel, illustrated in terms of a UML class model based on previous research the authors [5, 16] (Figure 6). The UML classes shaded in gray represent elements relevant to communication-related information in cyber-physical systems proposed in this study, while the total UML class model represents a metamodel for describing cyber-physical systems overall.

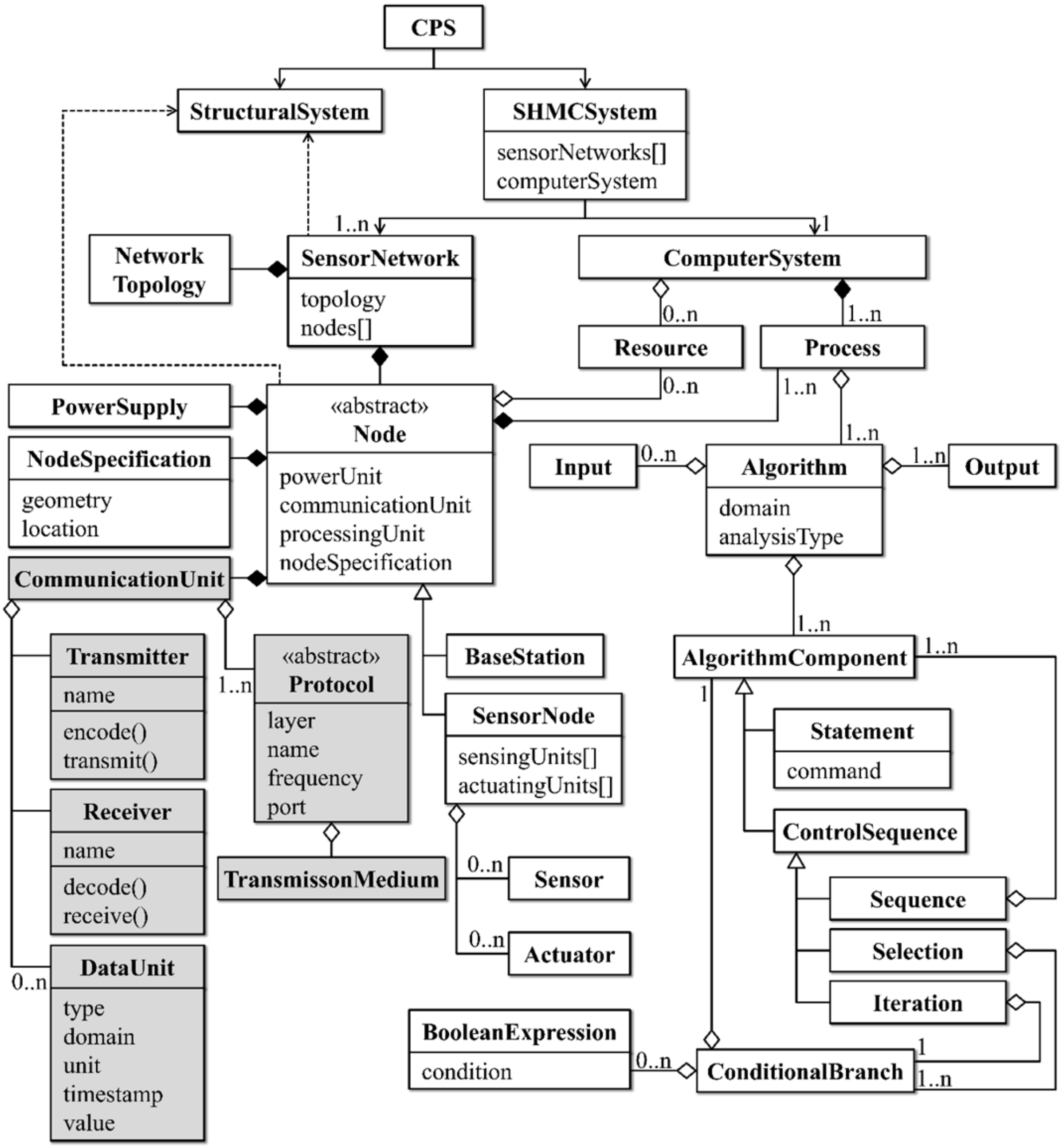


Figure 6 Metamodel of cyber-physical systems applied for structural health monitoring and control including communication-related information (shaded in gray).

The metamodel shown in Figure 6 distinguishes two main components of cyber-physical systems, *ComputerSystem* and *SensorNetwork*. Computer systems provide resources and processes for data management and data analysis. Sensor networks are composed of nodes realizing distinct tasks (*Node*). Therefore, two types of nodes are distinguished, *SensorNode* and *BaseStation*. Sensor nodes are responsible for data collection and data processing (*Sensor*). In addition, sensor nodes can control actuators in response to events measured by cyber-physical systems (*Actuator*). Base stations realize communication between sensor nodes and on-site computer systems. Both node types, sensor nodes and base stations, are composed of *PowerSupply*, *Resource*, *Process*, and *CommunicationUnit* and share common attributes, e.g. for specifying node location and node geometry (*NodeSpecification*). According to communication capabilities of nodes, different network topologies are defined by characteristic communication paths. A network topology is adapted with respect to the structural system being monitored. To relate nodes to a physical component of a structural system, on-board computation capacities of the sensor nodes may be used, for example, to integrate models describing the structural response of a structure being monitored.

In the metamodel, communication units are described as aggregations, termed *CommunicationUnit*, which are composed of several aggregates. The class *DataUnit* describes raw or preprocessed data to be transmitted or received by a communication unit. The cardinalities in Figure 6 denote that a single communication unit can send or receive a range of different data units. Data units are characterized by attributes, such as *type*, to define, e.g., acceleration data or temperature data. The attribute *domain* further specifies data either of time domain or frequency domain.

The classes *Transmitter* and *Receiver* are aggregates of the class *CommunicationUnit* and implement methods to encode outgoing data units and to decode incoming signals into data units that can be processed. Encoding and decoding is performed following the regulations from the communication protocols applied. For prescribing regulations for encoding of messages and for decoding of signals, the class *Protocol* is defined as an aggregate of the class *CommunicationUnit*. Following the OSI reference model presented in Figure 4, a protocol stack may contain different communication protocols. Due to the diversity of communication protocols, the class *Protocol* is defined as an abstract class that inherits attributes and methods defined by specific protocols used in a cyber-physical system.

The transmission medium, through which the communication is realized, puts further restrictions on the implementation of communication in cyber-physical systems and is thus be part of the metamodel. The class *TransmissionMedium* inherits attributes and methods from specific media, such as cable, radio, or Internet, i.e. hardware and communication protocols are chosen in dependence of the transmission medium.

With the semantic model presented, it is capable to describe monitoring-related information, containing the subset of communication-related information, in the context of structural models of cyber-physical systems. For preparing the validation of the BIM-based description approach towards describing SHM and control systems, the semantic model is mapped into the IFC schema in the following section.

5. BIM-based description of communication-related information using the metamodel

In this section, for describing cyber-physical systems on the basis of open BIM, an extension of the IFC schema, standardized in ISO 16739:2013 [34] is proposed enabling documentation and optimization of cyber-physical systems applied for SHM and control. The focus is put on describing communication-related information in cyber-physical systems. The IFC schema extension, building upon the "IFC Monitor extension" proposed by the authors in [5], comprises two property sets, presented in Table 3 and 4, for describing communication-related properties of the IFC entities *IfcDistributionSystem* and *IfcDistributionPort* that are already standardized in IFC. In the remainder of this section, upon introducing the extended IFC schema the proposed property set *Pset_DistributionSystemTypeCommunication* to describe *IfcDistributionSystem* entities used for communication systems is explained, followed by an illumination of the property set *Pset_DistributionPortTypeRadio*. The radio enumerator described by *Pset_DistributionPortTypeRadio* is added to the EXPRESS schema and specifies *IfcDistributionPort* entities. In Figure 7, existing IFC entities (colored in white) and the proposed IFC extension used for describing communication-related information (colored in gray) are shown. The semantics of the IFC schema extension originate from the most abstract fundamental entity *IfcRoot*. *IfcRoot* is the common supertype of all IFC entities and is described by the obligatory attribute *GlobalId* assigning a globally unique identifier to entities and optional attributes, such as names and textual specifications. As can be seen from Figure 7, the entities *IfcObjectDefinition* and the *IfcRelationship* inherit attributes of the entity *IfcRoot* and supplement attributes in the IFC inheritance tree.

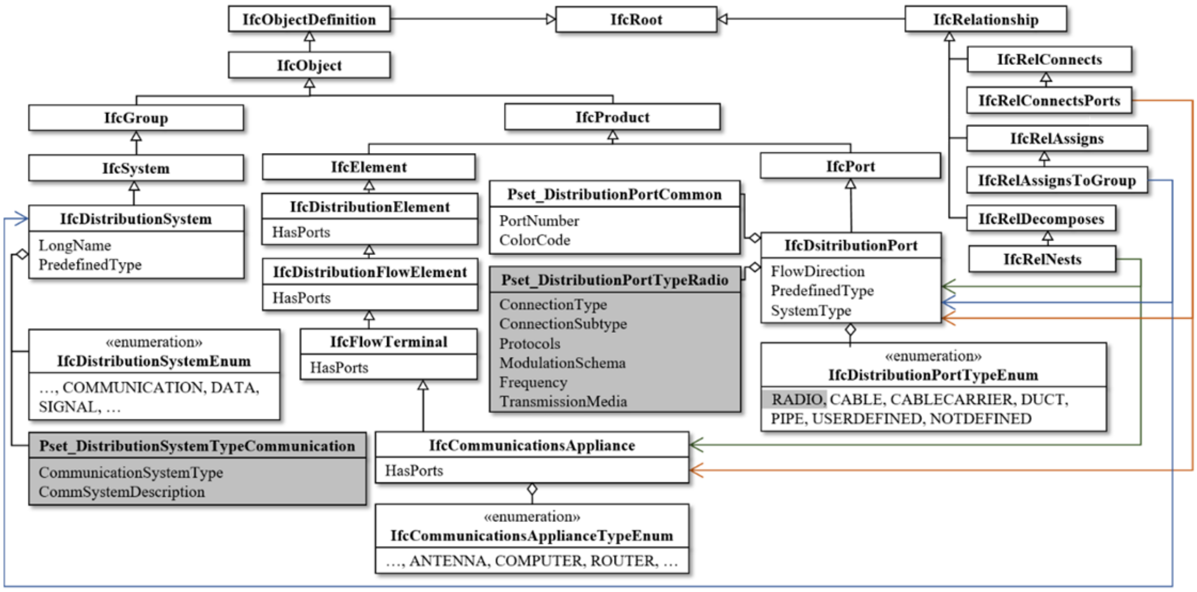


Figure 7 Extract of the extended IFC schema showing entities relevant to describing communication-rated information.

The IFC entities *IfcCommunicationsAppliance* and *IfcDistributionPort* shown in Figure 7 are of major importance for describing communication-related information and are related to each other by two objectified relationships, *IfcRelConnectsPorts* and *IfcRelNests*. Entities of type *IfcCommunicationsAppliance* describe communication appliances for transmission and reception of digital information, such as sensor data. Therefore, *IfcCommunicationsAppliance* entities are used to describe communication units that are components of sensor nodes, base stations, and computer systems. Inherited from *IfcDistributionElement* entities, *IfcCommunicationsAppliance* entities feature an attribute termed *HasPorts* indicating the connection between IFC elements and ports being components of a communication appliance. A port, in general, provides means for connecting an element to other elements [46]. To semantically describe *IfcPort* entities as parts of *IfcElement* entities, such as *IfcCommunicationsAppliance* entities, the objectified relationship *IfcNests* is used. The connection of exactly one port of an element to exactly one port of another element, e.g. for describing communication between two sensor nodes or between two *IfcCommunicationsAppliance* entities, is realized through the objectified relationship *IfcRelConnectsPorts*. In the IFC schema, one subtype of *IfcPort* exists, which is termed "*IfcDistributionPort*". The *IfcDistributionPort*, as shown in detail in Figure 8, has inherited the attributes (i) *ContainedIn*, (ii) *ConnectedFrom*, and (iii) *ConnectedTo* from *IfcPort* and is additionally specified by the attributes (i) *SystemType*, (ii) *FlowDirection*, and (iii) *PredefinedType*. The attribute *ContainedIn* describes a port as a component of a communication appliance, while the attributes *ConnectedFrom* and *ConnectedTo* define the connection between ports of Ifc entities connected by the media exchanged between two ports in a distribution system. To describe distribution systems interconnecting different *IfcDistributionPort* entities of the same type in detail, the property set *Pset_DistributionSystemTypeCommunication* is proposed.

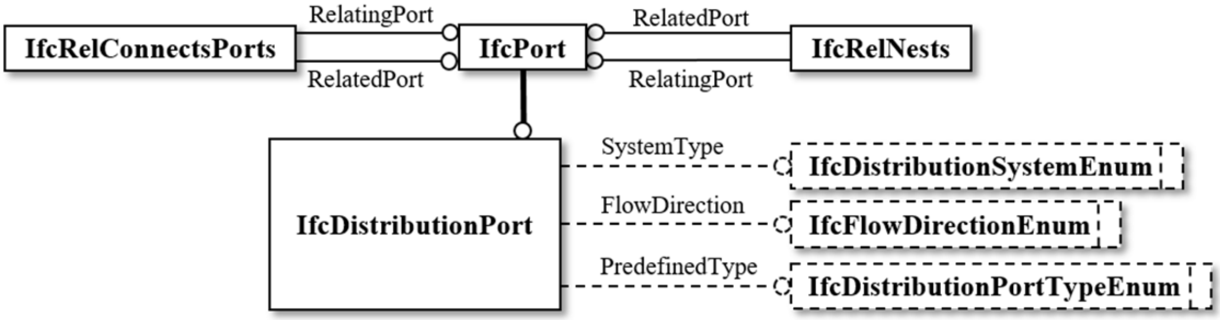


Figure 8 EXPRESS-G diagram of IFC entities and attributes for describing communication-related information.

Property set *Pset_DistributionSystemTypeCommunication*

In IFC, distribution systems are assigned to a specific function by assigning a value to the attribute *SystemType*. The connectivity of ports within systems is restricted to ports of the same system type. The enumeration of system types available in IFC (*IfcDistributionSystemEnum*) provides the enumerators relevant to cyber-physical systems, such as *DATA*, *SIGNAL*, and *COMMUNICATION*. Following the specifications of the current IFC schema [49], the *DATA* enumerator is applied for networks of general-purpose usage and the enumerator *SIGNAL* describes systems for distributing analog signals, such as modulated sensor data. The *COMMUNICATION* enumerator is listed without any definition or specification. For specifying distributions systems, such as cyber-physical systems, with a *COMMUNICATION* enumerator assigned, in Table 3 the property set *Pset_DistributionSystemTypeCommunication* is shown. As can be seen from Table 3, using the attributes *CommunicationSystemType* and *CommSystemDescription* of the property set proposed, communication systems in cyber-physical systems are specified by types and can be described qualitatively.

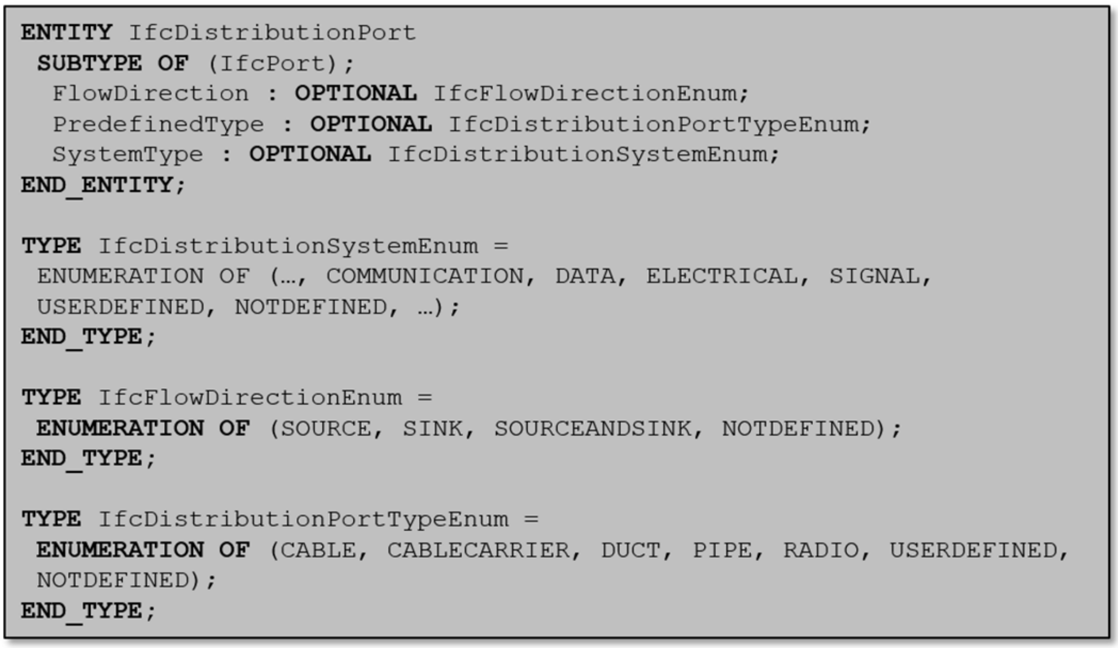
Table 3 Property set *Pset_DistributionSystemTypeCommunication* for describing *IfcDistributionSystem* entities of type COMMUNICATION

Name	**Type**	**Description**
CommunicationSystemType	P_ENUMERATEDVALUE / IfcLabel / PEnum_Distribution SystemCommunicationType	Property enumerators are, e.g., Wi-Fi, ZigBee, MQTT and other WPAN networks
CommSystemDescription	P_SINGLEVALUE / IfcLabel	Qualitative description of the network technology

Property set *Pset_DistributionPortTypeRadio*

For describing communication in cyber-physical systems using *IfcDistributionSystem* entities, *IfcDistributionPort* entities of different system components are semantically connected. To define transmitting ports and receiving ports of signals, the attribute *FlowDirection*, representing flow directions at distribution ports, is used. Enumerators of the *IfcFlowDirectionEnum* enumeration are *SOURCE*, *SINK*, *SOURCEANDSINK*, and *NOTDEFINED*. Ports, where communication signals are modulated, have *SOURCE* enumerators assigned that correspond to transmitters shown in the metamodel of communication-related information (Figure 6). Hence, receiving ports, denoted as *SINK*, correspond to receivers in the metamodel and are responsible for demodulation of signals. The enumerator *SOURCEANDSINK* can be applied to devices serving as transmitter and receiver, while *NOTDEFINED* is used, when specific options are not applicable.

The *IfcDistributionPortTypeEnum* enumeration is applied for specifying port types, which limit the compatibility of ports to distribution systems. In the current version of the IFC schema, distribution port types are limited to the enumerators *CABLE*, *CABLECARRIER*, *DUCT*, *PIPE*, *USERDEFINED*, and *NOTDEFINED*. To enhance the descriptive capacities of the enumeration with respect to cyber-physical systems, the port type enumerator *RADIO* is added to the list of enumerators available. The RADIO enumerator describes wireless connections between ports of different IFC elements for distribution of modulated signals, or data, respectively. Figure 9 shows an extract of the extended IFC schema, including the RADIO enumerator, written in EXPRESS.



```
ENTITY IfcDistributionPort
 SUBTYPE OF (IfcPort);
  FlowDirection : OPTIONAL IfcFlowDirectionEnum;
  PredefinedType : OPTIONAL IfcDistributionPortTypeEnum;
  SystemType : OPTIONAL IfcDistributionSystemEnum;
END_ENTITY;

TYPE IfcDistributionSystemEnum =
 ENUMERATION OF (…, COMMUNICATION, DATA, ELECTRICAL, SIGNAL,
 USERDEFINED, NOTDEFINED, …);
END_TYPE;

TYPE IfcFlowDirectionEnum =
 ENUMERATION OF (SOURCE, SINK, SOURCEANDSINK, NOTDEFINED);
END_TYPE;

TYPE IfcDistributionPortTypeEnum =
 ENUMERATION OF (CABLE, CABLECARRIER, DUCT, PIPE, RADIO, USERDEFINED,
 NOTDEFINED);
END_TYPE;
```

Figure 9 Extract of the IFC schema extension showcasing entities relevant to describe communication in cyber-physical systems.

To describe all types of distribution ports, the property set *Pset_DistributionPortCommon* containing the properties *PortNumber* and *ColorCode* is used. Depending on the port type and on the type of the distribution system, multiple property sets can be added to the IFC model of distribution systems describing communication-related information in cyber-physical systems. In the current version of the IFC schema, property sets for describing distribution ports of type cable, duct, and pipe exist, while wireless ports, such as the *RADIO* port proposed in Figure 9, cannot be adequately described.

To enable IFC-based descriptions of wireless communication according to the metamodel introduced in this study, the property set *Pset_DistributionPortTypeRadio* is shown in Table 4. The property set is used for describing the wireless port type RADIO, taking into account communication protocols and properties describing the protocols applied in cyber-physical systems.

Table 4 Property set *Pset_DistributionPortTypeRadio* for describing *IfcDistributionPort* entities of type RADIO

Name	**Type**	**Description**
ConnectionType	P_ENUMERATEDVALUE / IfcLabel / PEnum_DistributionPortRadioType	The physical port connection can be, among others, Wi-Fi, Bluetooth, ZigBee antennas defined in the property enumeration
ConnectionSubtype	P_SINGLEVALUE / IfcLabel	Further specifications can be added to connection types. For example: • Wi-Fi: IEEE 802.11a/b/g/n • Bluetooth: basic, enhanced data rate, high speed, low energy configuration
Protocols	P_LISTVALUE / IfcIdentifier	Listing of every communication protocol in the protocol stack
ModulationSchema	P_SINGLEVALUE / IfcLabel	Signal modulation schema (e.g. BPSK, O-QPSK)
Frequency	P_BOUNDEDVALUE / IfcFrequencyMeasure	Actual signal frequency and operable frequency band (MHz) of the physical layer (OSI reference model)
TransmissionMedium	P_SINGLEVALUE / IfcLabel	Medium (such as air) where communication takes place

The extended IFC schema (Figure 9) is verified in a three-step verification procedure. Within the verification procedure, which is illustrated in detail in [5], syntactic checks, semantic checks, and unit tests are devised. The verification procedure is conducted using the test software of the official IFC certification program [50, 51]. As a result of the verification procedure, the IFC schema extension is positively verified, confirming the compliance with the current IFC schema. In the following section, the IFC schema extension is validated by example modeling of a prototype cyber-physical system.

6. Validation of the metamodel

In the previous section, the metamodel has been mapped into the IFC schema, as materialized in terms of a verified IFC schema extension. In this section, to validate the metamodeling approach, the IFC schema extension is applied to describe communication-related information of a prototype cyber-physical system installed on a laboratory test structure. The cyber-physical system is composed of (i) two sensor nodes for structural health monitoring and control, (ii) an Internet-enabled computer system, and (iii) a semi-active tuned liquid column damper (TLCD) to reduce the structural response of the laboratory test structure. For test purposes, acceleration response is automatically recorded and processed by the cyber-physical system to control the TLCD.

The laboratory test structure, a four-story shear frame, is modeled using a conventional BIM software tool. As shown in Figure 10, the test structure is composed of five aluminum slabs of dimensions 300 mm × 200 mm × 15 mm (length × width × thickness) resting on four 20 mm × 2 mm aluminum columns. The story height is 300 mm and the plate-to-column connections are fully fixed. The base plate and columns are clamped on a solid block at the base of the structure. In the center of the top story, the semi-active TLCD is installed, which is controlled by an actuator connected to a wireless senor node. As shown in Figure 10, the second wireless sensor node has two acceleration sensors attached via cable-based connections and is fixed in the middle of the third aluminum plate. The acceleration sensors are fixed to the second and fourth story of the test structure. In laboratory tests, the structure is subjected to free vibration induced by manual deflections of the top story of the test structure.

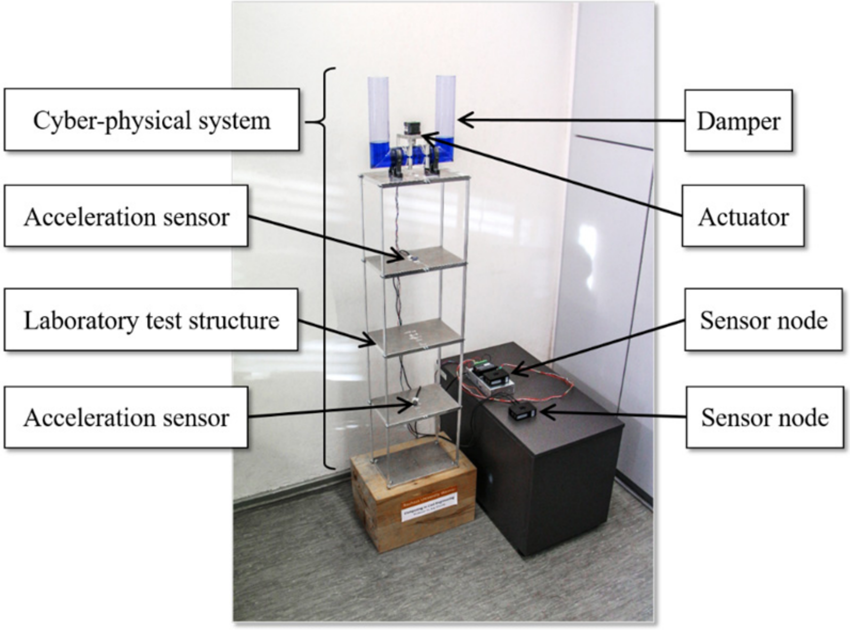


Figure 10 Laboratory test structure and the cyber-physical system.

The wireless prototype cyber-physical system is composed of wireless sensor nodes of type Raspberry Pi 3 Model B+ and connected to a computer system via Wi-Fi. The Raspberry Pi sensor nodes possess a system on chip (SoC) of type Broadcom BCM2837B0 including a quad-core Cortex-A53 (ARMv8) 64-bit processor running at 1.4 GHz [52]. The two Raspberry Pi nodes are connected to a computer system in star topology. The node responsible for monitoring acceleration is connected to two 3-axis ADXL345 acceleration sensors via two GPIO signal pins [53]. The second Raspberry Pi node serves as an actuator connected to the semi-active TLCD controlling an electrical valve. In terms of wireless communication, two specifications are implemented into the Raspberry Pi 3 Model B+, (i) 2.4 GHz and 5GHz IEEE 802.11.b/g/n/ac wireless LAN and (ii) Bluetooth Low Energy 4.2. In the prototype cyber-physical system, sensor data is communicated between the sensor nodes and the computer system using a Wi-Fi connection. The computer system provides remote access to the cyber-physical system through an Internet connection.

Communication-related information of the prototype cyber-physical system is summarized in an UML object diagram shown in Figure 11 serving as a digital representation of the real-world prototype cyber-physical system. The UML object diagram is derived from the metamodel proposed in this study and, more precisely, from the communication-related information described by the metamodel (Figure 6).

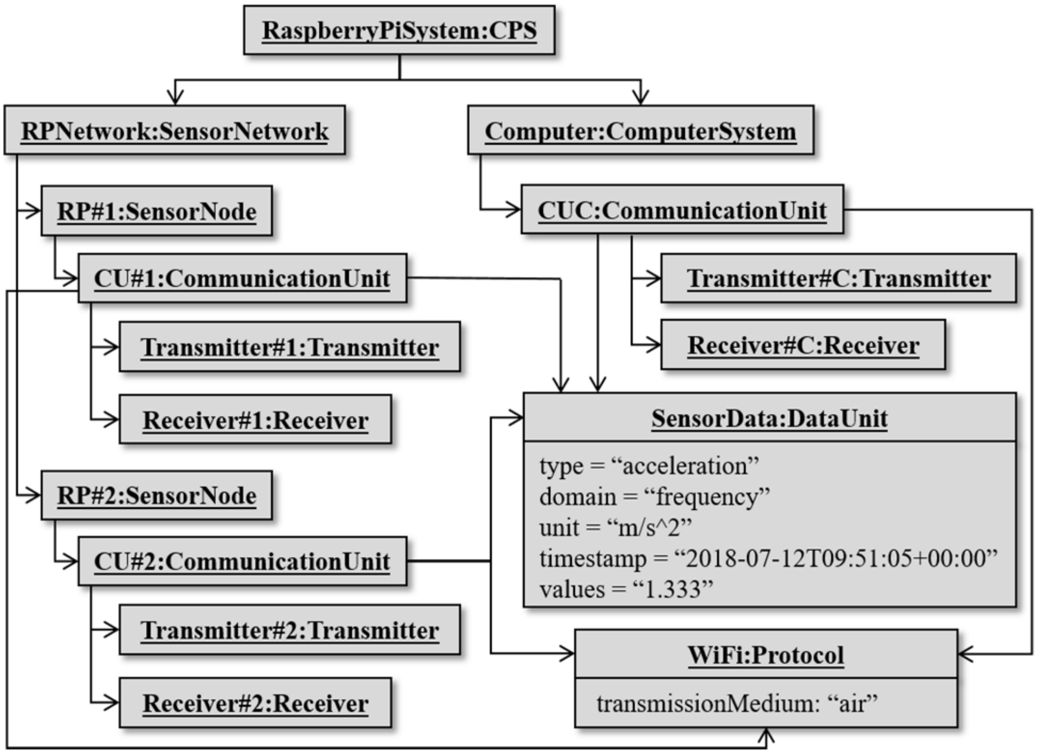


Figure 11 Object diagram of the prototype cyber-physical system.

The cyber-physical system is shown in the top of Figure 11 (*CPS*), composed of a Raspberry Pi-based sensor network (*RPNetwork)* and a computer system (*Computer)*. The computer system provides resources for data storage and data management. Both the computer system and the sensor network have communication units equivalent to type *CommunicationUnit* described in the metamodel. The sensor network is composed of two nodes *RP#1* and *RP#2*, featuring communication units including transmitters and receivers that take advantage of Wi-Fi communication protocols. The computer is an instance of the class *ComputerSystem* featuring a communication unit with transmitters and receivers. Sensor data exchanged between communicating system components is described by the instance "*SensorData*" of class "*DataUnit*" and is part of every communication unit of the cyber-physical system.

While the structure of the prototype cyber-physical system is described in Figure 11, the behavior of the system with regard to communication is visualized in the sequence diagram shown in Figure 12, which exemplarily shows the communication between sensor node *RP#1* and the computer system. Sensor node *RP#1* is applied for measuring acceleration response and *RP#2*, the topmost node of the cyber-physical system, is connected to the semi-active TLCD. Communication unit *CU#1*, connected to *RP#1*, encodes sensor data following the syntax of Wi-Fi communication protocols and transmits data units to the communication unit *CUC* of the computer system. The computer decodes the data units and generates control sequences to be forwarded to *RP#2* for controlling the TLCD. Encoding of structural control sequences is performed by communication unit *CUC* of the computer system according to the Wi-Fi protocol. Structural control sequences are sent to communication unit *CU#2* of *RP#2* that has the actuator attached.

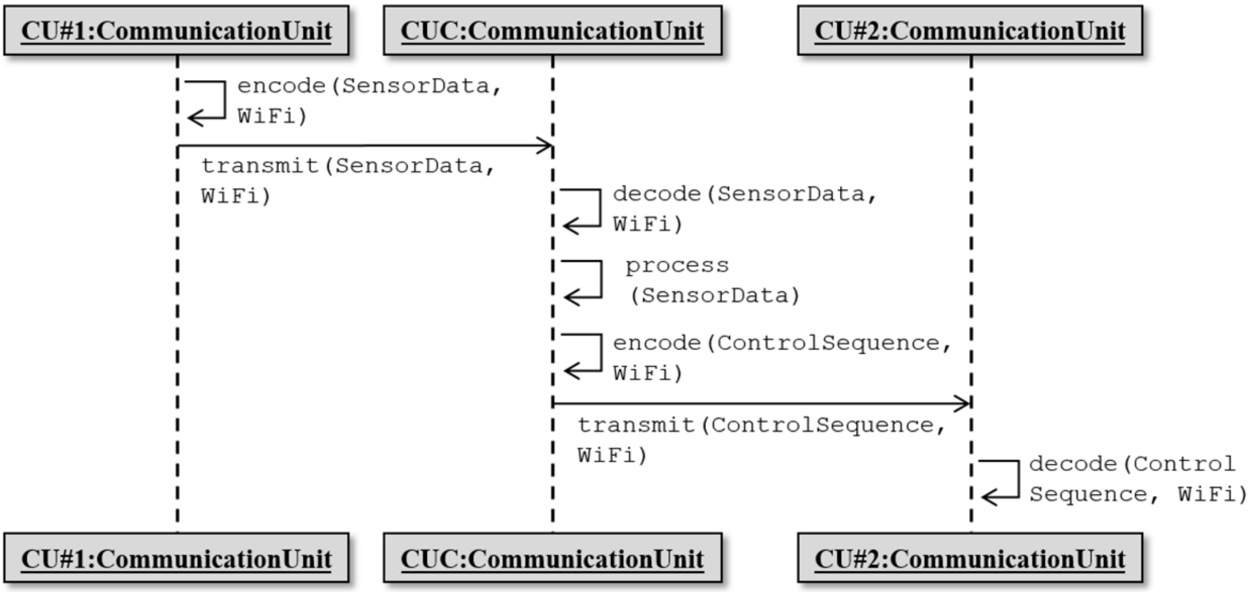
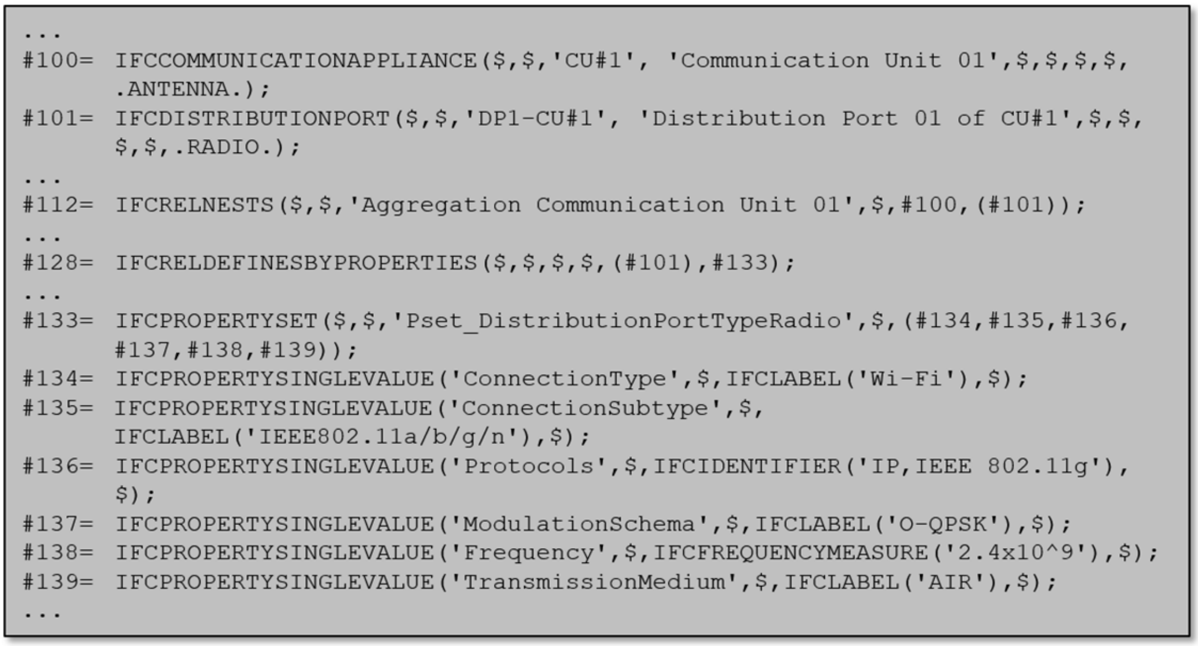


Figure 12 Sequence diagram of communication processes between the Raspberry Pi nodes and the computer system.

The IFC-compliant representation of communication-related information in cyber-physical systems, corresponding to the object-oriented description illustrated above, is shown in Figure 13 in form of a BIM model. In Figure 13, an extract of the BIM model is listed using the Standard for the Exchange of Product Model Data (STEP) [54]. The listing exemplarily illustrates distinct components and properties of the communication unit of sensor node *RP#1* to demonstrate the descriptive capacities of the IFC property sets representing critical elements to map the metamodel into the IFC schema extension. In the listing, the communication unit of *RP#1* is described by an *IfcCommunicationsAppliance* entity featuring an *IfcDistributionPort* entity. The entities are related by the objectified relationship *IfcRelNests* and specified by the property set *Pset_DistributionPortTypeRadio* including the properties shown in lines #134 to #139.



```
...
#100= IFCCOMMUNICATIONAPPLIANCE($,$,'CU#1', 'Communication Unit 01',$,$,$,$,
      .ANTENNA.);
#101= IFCDISTRIBUTIONPORT($,$,'DP1-CU#1', 'Distribution Port 01 of CU#1',$,$,
      $,$,.RADIO.);
...
#112= IFCRELNESTS($,$,'Aggregation Communication Unit 01',$,#100,(#101));
...
#128= IFCRELDEFINESBYPROPERTIES($,$,$,$,(#101),#133);
...
#133= IFCPROPERTYSET($,$,'Pset_DistributionPortTypeRadio',$,(#134,#135,#136,
      #137,#138,#139));
#134= IFCPROPERTYSINGLEVALUE('ConnectionType',$,IFCLABEL('Wi-Fi'),$);
#135= IFCPROPERTYSINGLEVALUE('ConnectionSubtype',$,
      IFCLABEL('IEEE802.11a/b/g/n'),$);
#136= IFCPROPERTYSINGLEVALUE('Protocols',$,IFCIDENTIFIER('IP,IEEE 802.11g'),
      $);
#137= IFCPROPERTYSINGLEVALUE('ModulationSchema',$,IFCLABEL('O-QPSK'),$);
#138= IFCPROPERTYSINGLEVALUE('Frequency',$,IFCFREQUENCYMEASURE('2.4x10^9'),$);
#139= IFCPROPERTYSINGLEVALUE('TransmissionMedium',$,IFCLABEL('AIR'),$);
...
```

Figure 13 Extract of the BIM model in STEP format describing communication-related information of sensor node RP#1

While the structural components of the prototype cyber-physical system are modeled using a conventional BIM tool (Figure 14), monitoring-related information and, in particular, communication-related information is added to the BIM model by manual postprocessing. The manual postprocessing is implemented using the APSTEX IFC framework for manipulating IFC-based BIM models programmatically [50].

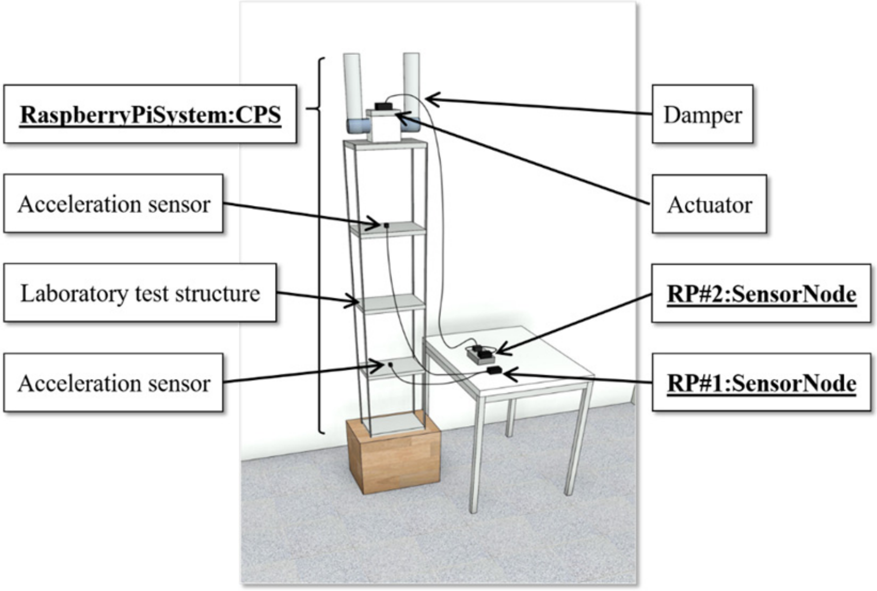


Figure 14 BIM model of the laboratory test structure and the cyber-physical system.

As elucidated by describing and implementing the laboratory test structure and the cyber-physical system, the metamodel developed to describe cyber-physical systems is suitable for real-world SHM and control applications, such as BIM-based documentation and maintenance of information about cyber-physical systems. Using the metamodel, structural semantics as well as behavioral semantics of communication-related information in cyber-physical systems can be described. With the metamodel, planning of SHM and control systems can be optimized, data control and management can be improved, and SHM and control system components can be linked to communication-related information. As a result, the metamodeling concept applied to communication-related information in the prototype cyber-physical system demonstrated in this study can be used to formally describe a variety of systems and communication processes based on building information modeling in compliance with the IFC standard.

7. Summary and conclusions

In this study, metamodeling approaches have been analyzed with respect to capabilities of describing cyber-physical systems applied for SHM and control of structures. The focus has been emphasized on the formal description of communication processes in cyber-physical systems, referred to as “communication-related information”. A cyber-physical systems metamodel, capable of describing communication-related information, has been proposed, based on the analysis of three metamodeling approaches that are applied in a broad range of applications, (i) UML and other OMG standards, (ii) the SWE framework, and (iii) the EXPRESS metamodel.

UML and other OMG specifications are adaptable to a wide scope of applications. Models derived from MOF-compliant modeling languages are compliant to the principles of metamodeling, which are particularly advanced by OMG’s MDA. OGC specifications forming the SWE framework, proposed to make sensor data better accessible and usable via the Internet, are related to UML by reusing UML notations. EXPRESS and EXPRESS-G are of importance in architecture, engineering and construction for open-source building information modeling and, thus, have been under consideration in this study, representing the third metamodeling approach. Limitations of the modeling capacities of EXPRESS, of EXPRESS-G, and of the SWE framework have been found with respect to describing communication-related information. In particular, models developed using EXPRESS-G are restricted to descriptions of structural semantics. As for the SWE framework, the UML notations used to describe sensor networks exclude communication-related information. Rather, the description of communication-related information is restricted to a non-exhaustive XML encoding without graphical representation. In consequence, UML has been found the most general metamodel, which is adaptable to other modeling languages. Hence, UML has been taken as a basis to develop the metamodel for cyber-physical systems on a well-defined, formal basis.

Based on background information on network topologies and on theory on network communication, communication-related information in cyber-physical systems has been semantically described in the technology-independent metamodel. As cyber-physical systems are gaining importance in SHM and control of civil structures and advancements in describing building information using the BIM-compliant IFC standard are still ongoing, the metamodel is mapped into the IFC schema. An IFC schema extension has been proposed, because the current descriptive capacities of the IFC schema are not sufficient to fully describe cyber-physical systems. For verification of the IFC schema extension, test software used in the official IFC certification program has been emploid confirming the compliance of the IFC schema extension with the current IFC schema. Subsequently, the metamodel proposed in this study has been validated by implementing a prototype cyber-physical system based on the metamodel and using the extended IFC schema to describe communication-related information in the cyber-physical system for SHM and control.

The results have demonstrated that the metamodel proposed in this study is suitable for describing cyber-physical systems and specifically communication-related information of cyber-physical systems, thus providing a formal basis for documenting and optimizing cyber-physical systems. In future work, both the metamodel and the IFC schema extension may be enhanced by formal semantic representations of sensor data and control sequences, which cannot yet be adequately modeled using the IFC standard. In addition, the documentation capacities of the metamodel may be extended from cyber-physical systems for SHM and control towards other engineering domains, such as environmental monitoring applications and other applications in the field of the Industrial Internet of Things.

8. Acknowledgments

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