Metamodeling wireless communication in cyber-physical systems

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Abstract. With recent developments in embedded sensing technologies, cyber-physical systems, materializing Industry 4.0 concepts, are increasingly implemented in civil engineering to advance structural health monitoring (SHM) and control applications. Recent studies have shown the potential of metamodels enabling information integration and interoperability between different platforms and technologies, while metamodeling of cyber-physical systems has been scarce. In this study, a metamodel for describing cyber-physical systems, putting emphasis on communication issues, is proposed and implemented into a SHM and control system. The metamodel is mapped into the Industry Foundation Classes (IFC) data schema that is standardized for describing structures compliant to the principles of building information modeling (BIM). Finally, the metamodel proposed in this study is validated by IFC-compliant, BIM-based example modeling and implementation of a cyber-physical system designed to monitor and control a laboratory test structure.

1. Introduction

Through the Internet of Things concept and the progress made in Industry 4.0 technologies, cyber-physical systems applied in the field of structural health monitoring (SHM) and control evolve by achieving higher degrees of interconnection (Rajkumar et al. 2010), by cognitive automation (Ibanez et al. 2019), and by shifting the process of data collection and processing into cloud-based applications (OGC 2019). Cyber-physical systems integrate mechanical and electrical components in intelligent networks realizing computational and physical processes (Lee 2008). The term "intelligent" denotes the embedment of algorithms and data processing capabilities into nodes forming networks, such as sensor networks for SHM and control, in which sensor data, e.g. temperature data or acceleration data for building automation or structural control, is automatically recorded, processed, exchanged, and stored. To distinguish computational and physical processes, the architecture of cyber-physical systems is structured into a physical domain and a cyber domain. The physical domain comprises physical processes as well as mechanical and electrical components controlling physical processes. The cyber domain encompasses networking and computational processes to evaluate sensor data originating from physical processes and to control actuators that manipulate the physical domain (Legatiuk & Smarsly 2018).

Networking processes, including wireless communication in cyber-physical systems, must provide reliable information exchange between the physical domain and the cyber domain to establish a sound basis for system automation (Wollschläger et al. 2017). State-of-the-art approaches towards synchronized, reliable, and efficient communication between individual system components are, e.g., Ethernet time-sensitive networking and telecommunication based on fifth-generation (5G) telecom networks. To integrate all individual system components, multiple sensing, processing, and communication technologies must be coupled. Coupling of various technologies accounts for the complexity of cyber-physical systems and renders unified and semantic information modeling a prerequisite for implementing cyber-physical systems.

Semantic modeling, or metamodeling respectively, encompasses methods for platform-independent and technology-independent information modeling following the syntax and semantics defined by modeling languages (Hitzler et al. 2009). Metamodels contain information about the structure and the functionalities of a family of systems and are origins to derive models describing individual systems of specific purposes, such as SHM and control (Legatiuk et al. 2017). To enable system documentation and information exchange with respect to the rapid advancements in sensing technologies and the complexity of cyber-physical systems, metamodels are needed (Lee 2015, Fitz et al. 2019). In civil engineering, technology-independent semantic descriptions of structures and of structural components using open building information modeling (BIM) are well-established. The standard ISO 16739:2013 "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries" specifies a metamodel for describing building information including building components, construction schedules, and facility management services on a formal basis (ISO 16739:2013).

Cyber-physical systems for SHM and control are integral parts of modern, automated structures that are, in current engineering practice, typically modeled using BIM. For incorporating information describing cyber-physical systems into BIM models, recent research of Theiler et al. (2018) has shown that describing information related to SHM and control is not yet fully possible using the current IFC standard. To fully describe information related to monitoring and control, the IFC standard needs to be extended. In this paper, a metamodel to describe cyber-physical systems for SHM and control is presented. The focus is set on describing communication-related information as a subset of monitoring-related information including communication technologies, such as communication protocols and technical devices for coupling different communicating system components. To describe and document cyber-physical systems for SHM and control conjointly modeled with structures being monitored, the metamodel is mapped into the IFC schema extended by Theiler & Smarsly (2018).

To develop and to validate the metamodel and the extended IFC schema, this paper is structured as follows. In Section 2, the principles of metamodeling as well as different metamodeling approaches are introduced, followed by a description of the metamodel. Subsequently, the metamodel is mapped into the IFC schema extended by components related to monitoring and control, presented in Section 3. Modeling capabilities added to the current version of the IFC standard to describe communication in cyber-physical systems are highlighted. In Section 4, to investigate the descriptive capacities of the metamodel and of the extended IFC schema, a prototype cyber-physical system for monitoring and control of a test structure is setup and described by an IFC-compliant BIM model. The results of the study are summarized and an outlook on future work is given in Section 5.

2. Metamodeling communication-related information

Metamodeling comprises methodologies for describing the meaning (i.e. the semantics) of information to cast human knowledge into machine-processable formats (Hitzler et al. 2009). For describing cyber-physical systems, a variety of object-oriented modeling languages standardized, e.g., by the Object Management Group (OMG), by the Open Geospatial Consortium (OGC), or by the International Standardization Organization (ISO) may be used. In this section, the principles of metamodeling are illuminated and three metamodeling approaches frequently used in computing in civil engineering are introduced: (i) approaches based on Unified Modeling Language (UML), developed and maintained by OMG, (ii) the Sensor Web Enablement (SWE) framework of OGC, and (iii) the data modeling language EXPRESS standardized in ISO 10303-11. Subsequently, information for describing cyber-physical systems for SHM and control are formalized and compiled in the metamodel. The focus is put on metamodeling information that describes communication technologies and components referred to as communication-related information.

2.1 Metamodeling approaches relevant to metamodeling cyber-physical systems in civil engineering

UML-related approaches

Established by OMG, the Model-Driven Architecture (MDA) standard is a widely used realization of model-driven development subsuming software and systems engineering approaches based on technology-independent metamodels (Favre 2010, OMG 2014). To develop metamodels that remain stable as technology evolves, the MDA metamodeling approach starts with a platform-independent model (PIM) describing functionalities and behavior of systems. In subsequent metamodeling steps, the PIM is converted into a platform-specific model (PSM) and into a working implementation.

For technology-independent and platform-independent metamodeling, OMG has established a variety of special-purpose and multi-purpose modeling languages, such as UML, the Common Warehouse Metamodel (CWM), the System Modeling Language (SysML), and the Software & System Process Engineering Metamodel (SPEM). To comply with the MDA principle of creating reusable and extendable models, the OMG modeling languages are translatable into each other because of a common meta-metamodel, termed Meta Object Facility (MOF), defining syntax and semantics (OMG 2016). Meta-metamodels serve as models for different modeling languages as the basis for automated mapping of metamodels and models defined in different modeling languages. The OMG format for automated mapping of models is an XML-based interchange format, XML Metadata Interchange (XMI), for standardizing XML document formats and schemas (OMG 2015).

The UML modeling (and metamodeling) approach is widely applied in the field of computing in civil engineering because UML offers a broad wealth of notations and modeling constructs to describe architecture and behavior of computational systems. In UML, two semantical categories are distinguished, (i) structural semantics and (ii) behavioral semantics (OMG 2017). Structural semantics, materialized in classes, relationships, and data types are used to describe system architectures. Based on structural semantics, behavioral semantics, e.g. implemented through activity diagrams, state machine diagrams, and sequence diagrams, can be used to express interaction sequences for describing communication processes in cyber-physical systems for SHM and control.

Extension mechanisms included in the ULM standard enable UML to be adapted for further domains by creating UML "dialects", so-called "profiles", that remain in semantic compliance to MOF (Fuentes et al. 2004). To create UML profiles describing a specific domain, the number of available UML modeling constructs may be restricted and constraints can be added to restrict the way in which a metamodel can be used.

The SWE framework of OGC

The key idea of the SWE framework is to make data of sensor systems online accessible through interfaces and protocols following well-defined standards (OGC 2019). To provide metamodeling capabilities for geospatial systems, a selection of UML modeling constructs is reused according to the principles of UML profiles. As a result, the seven OGC standards forming the SWE framework provide UML notations (and XML notations) for describing sensor networks, sensors, sensor observations, and measurements that are as well relevant to metamodeling cyber-physical systems for SHM and control. However, for communication-related information, graphical notations or exhaustive XML encodings have not been standardized within the SWE framework.

The data modeling language EXPRESS

Another data modeling language, and a metamodel that provides computer-interpretable descriptions of semantic information, is EXPRESS and the graphical notation EXPRESS-G. Though the graphical notational capacities of EXPRESS-G are limited compared to UML, EXPRESS is of gaining importance for information modeling in civil engineering. The IFC specifications forming the basis for open BIM are formally described using EXPRESS and EXPRESS-G. In conjunction with the “Standard for the Exchange of Product Model Data” (STEP) in ISO 10303-21, EXPRESS models are used to realize consistent exchange, storage, archiving, and transformation of building information (ISO 10303-21:2016, ISO16739:2013, ISO10303-11:2004).

Summary

In summary, UML possesses the most comprehensive range of metamodeling capabilities of the modeling languages introduced herein. The wide scope and notational variety for structural and behavioral modeling render a UML-based metamodeling approach applicable to many modeling purposes. On the other hand, it should be emphasized that information modeling using EXPRESS along with the IFC standard to describe buildings and infrastructure is gaining attention in research and practice. For the above reasons, the UML modeling capabilities are used as a formal basis to develop the metamodel for describing communication-related information in cyber-physical systems.

2.2 A metamodel for describing communication-related information in cyber-physical systems

To formally describe communication-related information in cyber-physical systems, components of cyber-physical systems for SHM and control are characterized and communication-related information is defined. Subsequently, the information related to monitoring and communication is compiled in a metamodel using UML class diagrams.

Communication-related information is a subset of monitoring-related information describing communication technologies applied in cyber-physical systems. Communication technologies metamodeled in this study encompass, e.g., communication protocols, routing of communication (including origins and destinations of communication processes), transmission media, and technical devices employed to realize sensor communication. The metamodel presented in Figure 1 essentially shows UML classes to describe cyber-physical systems, with elements describing communication-related information, shaded in gray, primarily stemming from the mathematical theory of communication proposed by Shannon (1948) and from reviews of wireless communication standards, such as ZigBee, Wi-Fi and MQTT frequently applied in wireless sensor networks (Fahmy 2016).

As reflected in the gray-shaded elements of Figure 1, communication systems include (i) transmitters, (ii) transmission media, (iii) receivers, and (iv) data units, which are transformed into (v) electrical signals. Data units 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). Two processes involved in communication are encoding on the transmitter side of communication systems and decoding on receiving system components. Encoding and decoding are performed in compliance with syntax and semantics defined by communication protocols. As nodes of wireless sensor networks for cyber-physical systems are spatially distributed, autonomous devices, power consumption, and resource management are important criteria in choosing suitable communication protocols and network topologies.

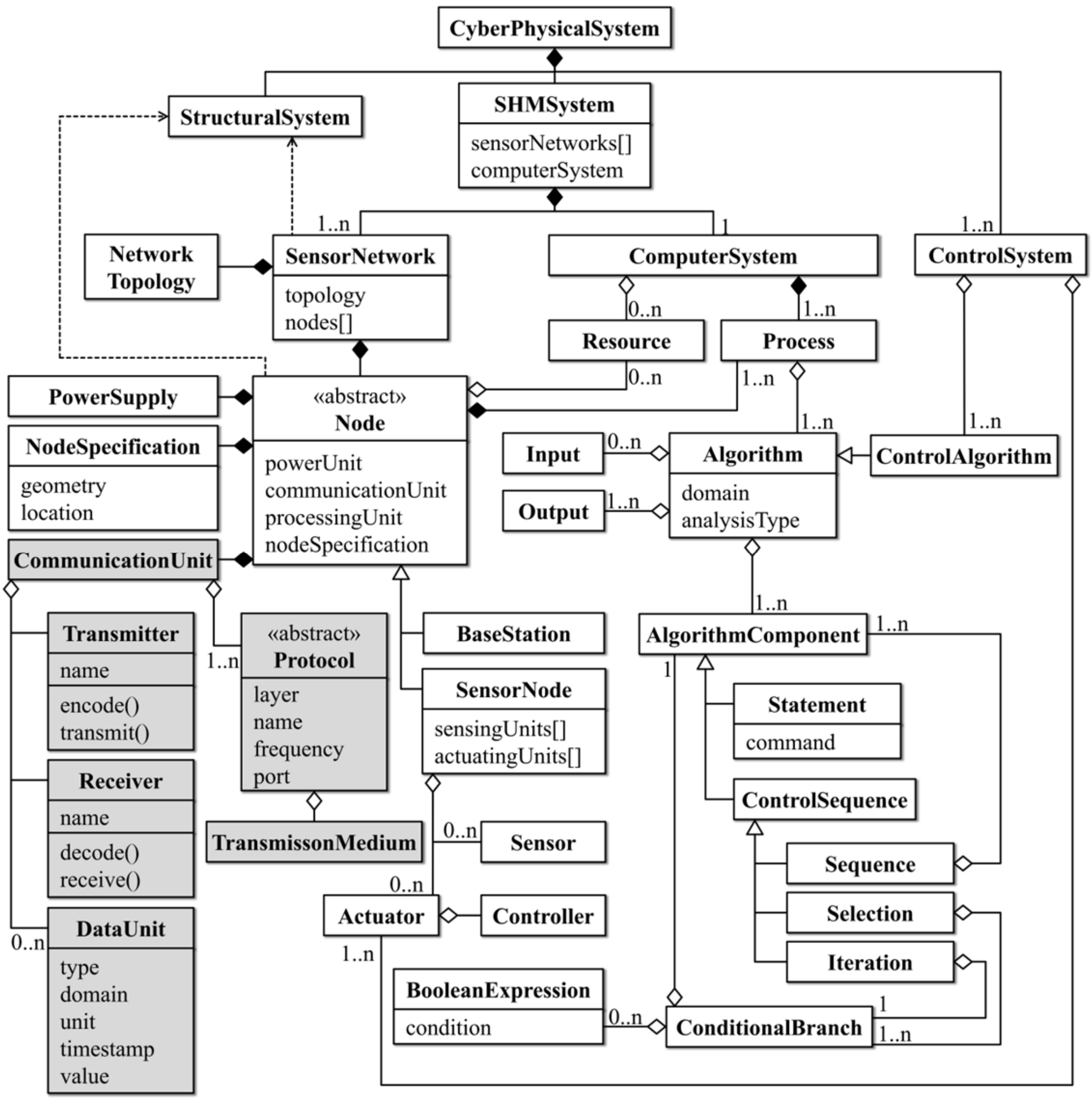

Figure 1: Metamodel of cyber-physical systems for SHM and control including control-related elements (red) and communication-related information (gray)

From the metamodel shown in Figure 1, it can be seen that cyber-physical systems are composed of a computer system and of one or more sensor networks. In sensor networks, two types of nodes are distinguished. Both, sensor nodes and base stations, possess power units, processing units, and communication units similar to computer systems. To formally describe communication-related information, communication units are modeled in terms of aggregations of transmitters, receivers, data units describing raw or preprocessed data, and communication protocols that are, dependent on the transmission media and characterized by multiple attributes and methods. To account for the variety of communication protocols applicable to cyber-physical systems for SHM and control, the protocol class is defined as an abstract class.

3. BIM-based description of cyber-physical systems

In this section, for describing cyber-physical systems for SHM and control on the basis of open BIM, the metamodel is mapped into the IFC schema. For mapping, entities and objectified relationships of the IFC schema standardized in ISO 16739:2013 and of the IFC schema extension "IFC Monitor" proposed by Theiler and Smarsly (2018) are taken as a basis. Entities to describe cyber-physical systems, sensor networks, and sensor nodes are provided according to the UML classes shown earlier in the metamodel. By the objectified relationship *IfcRelAggregates*, sensor nodes are semantically connected to a communication unit termed *IfcCommunicationsAppliance*. As can be seen from Figure 2, *IfcCommunicationsAppliance* entities together with *IfcDistributionPort* and *IfcDistributionSystem* entities form the basis for describing communication-related information. *IfcCommunicationsAppliance* entities have ports, e.g. used as transmitters and receivers for communication, as being part of *IfcDistributionSystem* entities that can be determined to signal or data transmission or to communication in general.

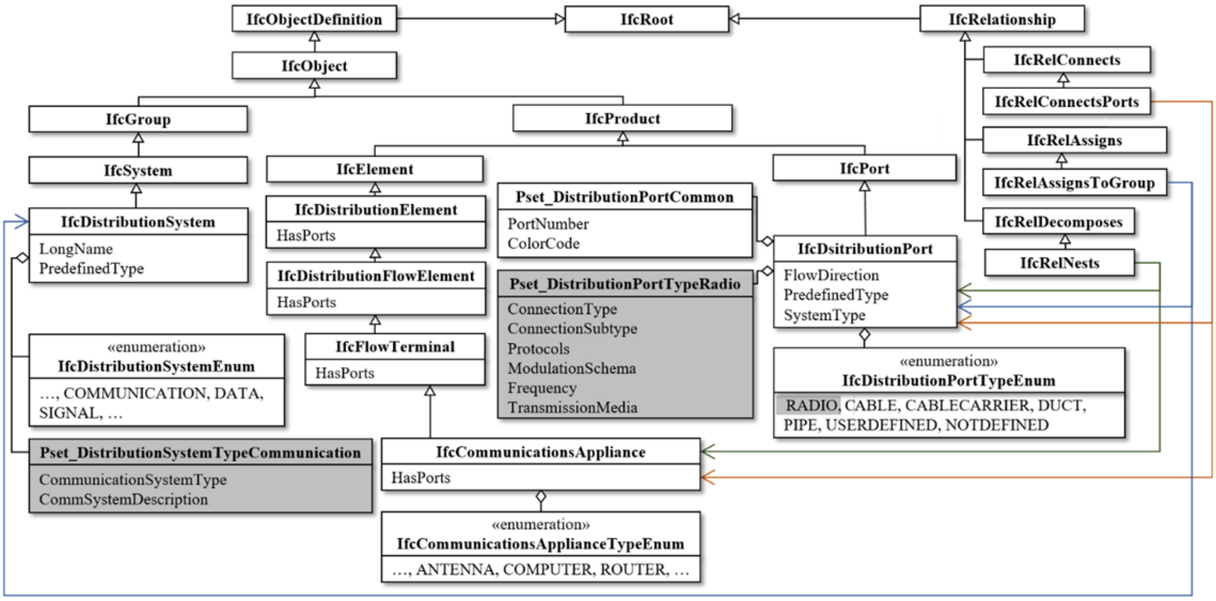

Figure 2: Extract of the extended IFC schema (shaded in gray) for describing communication in cyber-physical systems

To describe *IfcDistributionPort* entities of type "radio" for wireless communication and *IfcDistributionSystem* entities of type "communication" in more detail, the property sets shaded in gray are proposed. *IfcDistributionSystem* entities of type "communication" represent communication systems that are specified by the property set *Pset_DistributionSystemTypeCommunication*. To connect communication ports of different communication units being components of sensor nodes, base stations, and computer systems, the system type predefined by the IFC schema must conform to the *CommunicationSystemType* attribute of *IfcDistributionSystem*. Besides the *SystemType* attribute, *IfcDistributionPort* entities are characterized by the attribute termed *PredefinedType*, such as "radio" for wireless communication ports, and the *FlowDirection* attribute to distinguish between transmitting and receiving ports. To describe transmitters, receivers, and the communication protocols applied in the cyber-physical system, the property set Pset_*DistributionPortTypeRadio* extending the IFC schema is proposed according to the metamodel developed earlier.

4. Example modeling of a prototype cyber-physical system

In this section, to validate the metamodel and the descriptive capacities of the extended IFC schema, a prototype cyber-physical system for monitoring and control of a laboratory test structure is designed. Both the cyber-physical system and the test structure are described through an IFC model that implements the metamodel mapped into the IFC schema.

The wireless prototype cyber-physical system is composed of two wireless sensor nodes of type Raspberry Pi 3 Model B+ (Raspberry Pi Foundation 2017) that are, via Wi-Fi, connected to a computer system in star topology. As shown in Figure 3, sensor node “n1” has two acceleration sensors attached that are fixed to the middle of the first and third story of the test structure. Sensor node “n2” is connected to an actuator controlling the electrical valve of a tuned liquid column damper situated on the top story of the test structure. 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 left of Figure 3, structural components of the test structure are modeled using a conventional BIM software tool.

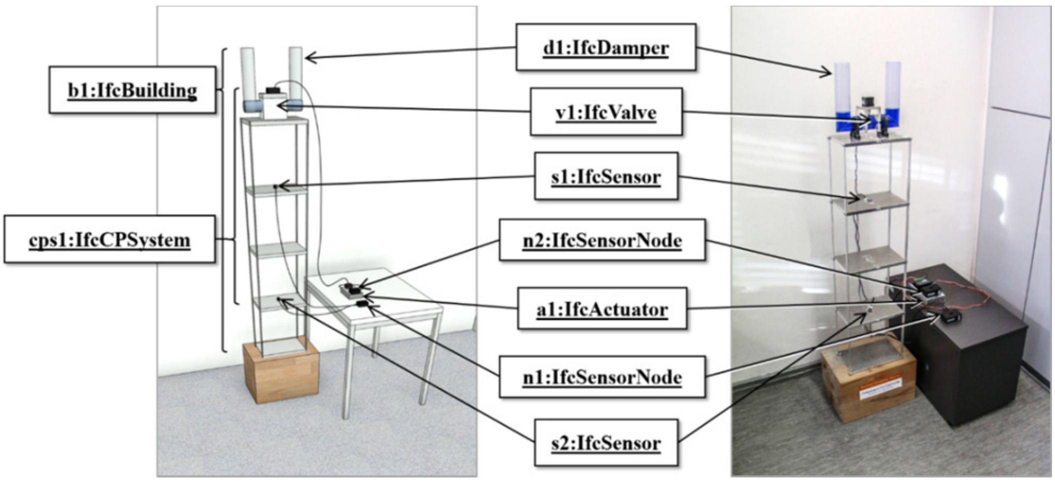

Figure 3: BIM model (left) and physical implementation (right) of the prototype cyber-physical system

To complement the BIM-based structural description of the test structure by monitoring-related and communication-related information, the extended IFC schema is used for manual post-processing of the BIM model. In Figure 4, the IFC model describing the prototype cyber-physical system for SHM and control including monitoring-related information originating from the IFC Monitor extension (shaded in gray) and communication-related information (shaded in blue) is shown. The *IfcDistributionPort* entities representing transmitters and receivers of the sensor nodes and of the computer system are, by means of the *IfcRelAssignsToGroup* relationship, semantically connected to an *IfcDistributionSystem* entity of type communication not shown in Figure 4.

As a result, by describing and implementing the prototype cyber-physical system and the test structure, the metamodel is shown to be suitable for describing and maintaining information related to cyber-physical systems using the extended IFC schema. In the laboratory tests, the cyber-physical system designed upon the metamodel developed in this study is used successfully to measure and to process acceleration data for controlling structural responses of the test structure exposed to manual excitations.

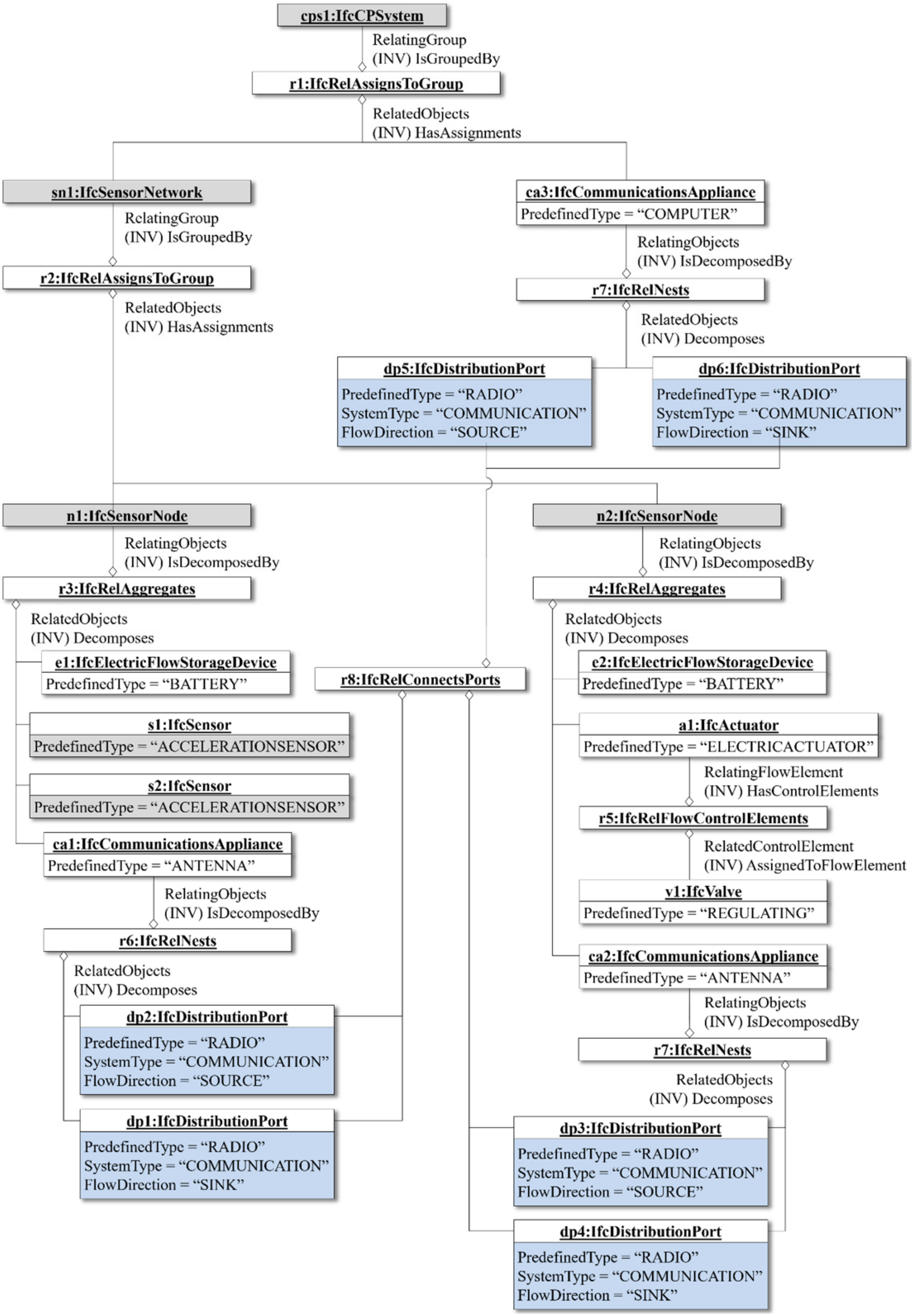

Figure 4: IFC model of the prototype cyber-physical system
(communication-related information shaded in blue)

5. Summary and conclusions

Cyber-physical systems for SHM and control are of increasing importance for operating and maintaining civil infrastructure. Because of the technological heterogeneity of cyber-physical systems composed of sensing, actuating, and processing devices, metamodeling methods facilitating documentation and optimization of cyber-physical systems are needed. In this paper, a metamodeling approach towards formally describing cyber-physical systems with focus on communication has been proposed and applied to a prototype cyber-physical system for SHM and control.

To enable the BIM-based description of cyber-physical systems, monitoring-related and communication-related information has been formalized in the metamodel using UML class diagrams. Subsequently, the metamodel has been mapped into the IFC schema extended by IFC entities for describing monitoring-related and communication-related information. For validating the metamodeling approach, the metamodel has been used to exemplarily describe and setup a prototype cyber-physical system for monitoring and control of a laboratory test structure. In laboratory tests, the prototype cyber-physical system has successfully been used to measure and to process acceleration data and to automatically control the structural response to external loads.

As an outcome of this study, it has been demonstrated that cyber-physical systems for SHM and control can be described following the principles of open BIM in compliance with the IFC standard. In future work, both the metamodel and the extension of the IFC schema may be enhanced by formal semantic representations of sensor data and control sequences, which cannot yet be adequately described using the IFC standard.

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