Towards an Ontological Representation of Condition Monitoring Knowledge in the Manufacturing Domain

Qiushi Cao[1], Cecilia Zanni-Merk[1] and Christoph Reich[2]
[1]*Normandie Université, INSA Rouen, LITIS, 76000 Saint-Étienne-du-Rouvray, France*
[2]*Hochschule Furtwangen University, 78120 Furtwangen, Germany*

Keywords: Industry 4.0, Condition Monitoring, Preventive Maintenance, Ontology, Intelligent System.

Abstract: In the manufacturing domain, machinery faults cause a company high costs. To avoid faulty conditions, the discipline of condition monitoring contributes significantly. The objective of condition monitoring is to determine the correctness of a machine, process or system. This is crucial for improving the productivity and availability of production systems. In most situations, when the tendency of a fault emerges, highly experienced and skilled professionals are capable of providing appropriate decisions about fault alarm launching and maintenance plans. However, production systems are becoming more complicated, and it is more likely that the professionals fail to respond to the faulty conditions timely and accurately.

In this paper, we present an ontological framework, that is used for developing an intelligent system, which can provide decisions about alarm launching and maintenance plans in an intelligent and optimal manner. This framework is based on an ontological representation of condition monitoring knowledge in the manufacturing domain. The framework consists of an ontology structure which includes a core reference ontology for representing general condition monitoring concepts and relations, and several domain ontologies for formalizing manufacturing domain-specific knowledge.

1 INTRODUCTION

Following the trend of Industry 4.0, managing industrial production systems become more and more challenging. The competitive nature of today's manufacturing industry forces manufacturers to respond to the market timely and accurately. Increasing global competition, fast technology evolution and customers' perceptions of product quality trigger the demand for future strategical plans and advanced manufacturing techniques (Rao, 1996). These challenges have brought the issue to manufactures about how to increase manufacturing productivity. In this context, condition monitoring techniques have been accepted as a significant solution to it.

By collecting sensor data from heterogeneous environments, the objective of condition monitoring is to determine whether the condition of a machine, process or system is correct or not. Performing condition monitoring and its associated tasks such as fault prediction and preventive maintenance have shown great success in different subdomains in industry, such as electrical motors (Nandi et al., 2005), wind turbines (Papadopoulos and Cipcigan, 2009) and railway engineering (Schwarzenbach et al., 2010). In the context of Industry 4.0, condition monitoring tasks are facilitated by the vision of cyber-physical systems (CPS), within which information from various environments are closely monitored and synchronized between the physical assets and the cyber-physical space (Lee et al., 2015). As the data generated by sensors and networked machines gets higher in volume, CPSs are required to be more intelligent to handle a variety of complicated situations (Lee et al., 2015). Thus, intelligent CPSs which can automatically perform condition monitoring and related tasks are needed.

The development of such a system requires domain knowledge about system operation and maintenance to be represented in a formal way, thus making this knowledge usable by the intelligent CPS. To achieve this goal, ontologies have shown promising results when formalizing knowledge about condition monitoring tasks in various domains (Papadopoulos and Cipcigan, 2009) (Schwarzenbach et al., 2010). An ontology is a formal knowledge representation of a domain, which captures domain knowledge and provides reusable conceptual resources about concepts and relations. The existence of an ontology provides

Cao, Q., Zanni-Merk, C. and Reich, C.
Towards an Ontological Representation of Condition Monitoring Knowledge in the Manufacturing Domain.
DOI: 10.5220/0006957903120318
In *Proceedings of the 10th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management (IC3K 2018) - Volume 2: KEOD*, pages 312-318
ISBN: 978-989-758-330-8

a common and controlled vocabulary of the domain, which enables different actors and professionals share the same understanding of domain knowledge, thus ease the construction of an intelligent system.

This paper presents an ontology-based framework used for the development of an intelligent condition monitoring system, which aims to perform condition monitoring and its associated tasks on production systems in the manufacturing industry. The framework is proposed based on an ontological representation of condition monitoring knowledge in the manufacturing domain. We present the framework by introducing an ontological structure which includes a core reference ontology for representing general condition monitoring concepts and relations, and a set of domain ontologies for formalizing manufacturing and condition monitoring domain-specific knowledge. The core reference ontology is aligned with the UFO ontology (Unified Foundational Ontology), which is an upper-level ontology providing general concepts and relations at a high abstraction level (Guizzardi and Wagner, 2010). The domain ontologies specialize the core reference ontology into the manufacturing and condition monitoring domains, with representing domain-specific knowledge from different aspects such as context, product, process, and resources.

The rest of the paper is structured as follows. In Section 2, we introduce the related work about existing ontologies that were developed for both condition monitoring and manufacturing domains. In Section 3, we present the ontological framework with its design methodologies. Section 4 concludes the paper and give future perspectives.

2 RELATED WORK

There exist several ontologies focusing on the manufacturing domain, but only a few of them capture domain knowledge about condition monitoring and maintenance. In this section, we introduce most relevant existing ontologies and discuss the suitability of these ontologies for being reused for our purpose.

- The PSL (Process Specification Language) ontology was designed to facilitate the sharing and exchange of process information among manufacturing systems (Gruninger and Menzel, 2003). These ontology models process-related knowledge such as process planning, process modeling, production planning and project management. The PSL ontology provides rich semantics for process-related information in a general point of view. However, it does not describe specific manufacturing processes, such as milling, drilling, and cutting. Thus, to satisfy our needs, this ontology needs to be specialized for having smaller domain coverage.
- The Manufacturing Service Description Language (MSDL) ontology was designed to provide a common semantic model for describing manufacturing services (Ameri and Dutta, 2006). The ontology formally represents key concepts that are essential for describing manufacturing services, such as *Supplier*, *ManufacturingService*, *ManufacturingCapability* and *Process*. This ontology is suitable to be reused in our case since it provides a rigorous conceptualization of manufacturing processes.
- The P-PSO ontology (Politecnico di MilanoProduction Systems Ontology) (Garetti and Fumagalli, 2012) address the manufacturing domain according to four aspects: *Product*, *Physical Aspect*, *Technological Aspect* and *Control Aspect*. The ontology provides a comprehensive definition of important concepts for describing the structure of a manufacturing system.

Most of the ontologies listed above focus on the manufacturing domain and provide representations of manufacturing domain knowledge in a general point of view. However, under the context of condition monitoring in manufacturing, they all lack some expressiveness concerning the representation of knowledge about monitoring and maintenance activities.

There are only a few works address the development of ontologies for condition monitoring and maintenance in manufacturing. Here we discuss two notable examples.

- The ontology for Prognostics and Health Management of Machines (Nuñez and Borsato, 2017) was developed based on a set of international standards. The goal of this ontology is to provide standardization of concepts and terms that are relevant to failure analysis in mechanical components. However, the ontology lacks representation of temporal information. When the machinery faults and failures propagate according to time, this ontology is not capable of supporting temporal reasoning about the propagation of them.
- The sensing system ontology (Maleki et al.,) aims to define the embedded sensing system for smart Product-Service System. The ontology was developed based on the SSN ontology (Semantic Sensor Network ontology) (Compton et al., 2012), and it formally describes sensor knowledge that is related to machine health monitoring service.

This ontology was one of the modules that were used to build the PSS-specific ontology.

However, after reviewing the existing ontologies that are relevant to condition monitoring tasks, the main conclusion is that most of them were only designed to represent a specific portion of knowledge about condition monitoring in the manufacturing domain. Thus, their coverage and scope are limited. In this context, there is a need for an ontology which provides a comprehensive representation of knowledge in both condition monitoring and manufacturing domains. To this end, we introduce in the next section a three-layer ontological framework which captures condition monitoring and manufacturing domain knowledge from different abstraction levels. The ontological framework provides the formalization of knowledge which is essential for the development of an manufacturing condition monitoring ontology.

3 THE ONTOLOGICAL FRAMEWORK FOR REPRESENTING CONDITION MONITORING KNOWLEDGE IN MANUFACTURING

Formalizing knowledge is an essential phase for the development of an intelligent system. The use of formal models such as ontologies is a crucial step in the development work. In this section, we present the ontological framework that will be used for constructing an intelligent condition monitoring system. The framework is demonstrated with an ontological structure which includes a core reference ontology for representing general condition monitoring concepts and relations, and a set of domain ontologies for formalizing domain-specific knowledge.

3.1 The Classification of Ontologies

The development of the ontological framework starts with considering the choice of upper level ontologies. According to (Roussey et al., 2011), ontologies can be classified into four abstraction levels, depending their domain coverage and scope. We modified this classification methodology into a three-layer ontology hierarchy, shown in Figure 1.

In Figure 1, the abstraction level of ontologies becomes more specific from top to bottom. The top level or foundational ontologies define general and basic notions across a wide range of domains. These notions are widely applicable to various environments.

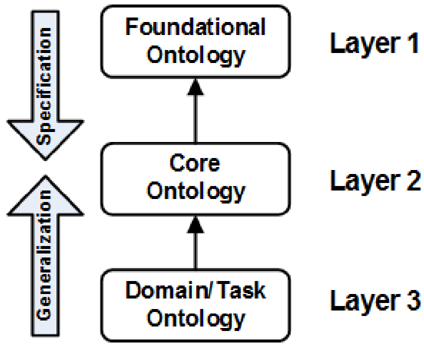

Figure 1: The ontology hierarchy according to domain coverage and scope, adapted from (El Ghosh et al., 2017).

Core reference ontologies are built within the scope of a domain, and they integrate knowledge from different groups of actors and participants in the domain. Normally, a core reference ontology catches central concepts and relations of a domain and is considered as an integration of several domain ontologies. Domain ontologies and task ontologies only focus on a specific domain. When the domain of interest changes, these two types of ontologies are not able to provide sufficient knowledge.

3.2 The Ontological Framework

This section introduces the ontological framework we proposed. We developed our ontological framework based on the ontology hierarchy in the preceding section. Figure 2 shows all layers, that will be desribed in the following sections.

3.2.1 Layer 1: The Foundational Ontology

The development work starts with the choice of a foundational ontology which can enable the integration of core reference and domain ontologies. For our work, we adopted the UFO ontology, since it provides rich descriptions of general concepts and relations which form the foundation for conceptual modeling. The UFO ontology adopts the *Endurant/Perdurant* dichotomy, in which an *Endurant* represents an entity comprising spatial components that is not dependent on any time frame of occurrence, while a *Perdurant* stands for an entity containing temporal components, and it presents only part of its temporal components at different time points.

3.2.2 Layer 2: The Core Reference Ontology for Condition Monitoring

After determining the foundational ontology, we developed our core reference ontology for condition monitoring, named CM-core. The CM-core ontology was developed with using the Middle-Out approach for concept taxonomy construction (Roussey et al., 2011). The idea of this approach is to construct an ontology through the combination of the Top-Down and Bottom-Up approaches. To do this, we first identified central concepts in the condition monitoring domain. The central concepts were extracted from three sources: (i) ISO standards 13372 (ISO, 2012), 9000 (ISO, 2005) and 9001 (ISO, 2000); (ii) the domain ontologies relevant to condition monitoring; and (iii) relevant research papers and textbooks, such as (Schreiber, 2000) and (Kaposi and Myers, 2001). These central concepts were then generalized to the upper level, and the core reference ontology was aligned to the UFO ontology. On the other hand, these central concepts were specialized into different subdomains, for building domain ontologies. In this step, the upper-level concepts were specialized into lower-level ones.

The CM-core ontology contains taxonomies of core condition monitoring concepts such as system, function, behavior, structure, process, state, failure and fault, with their interrelationships. For clarity, we only show a part of the whole ontology that is relevant to our study. Figure 2 presents an excerpt of the CM-core ontology. In the Figure, round boxes are ontology classes, dashed lines stand for object properties among classes, and solid lines represent *is-a* or *subsumption* relationships.

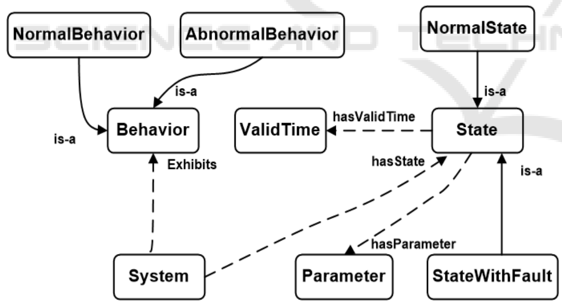

Figure 2: An excerpt of the CM-core ontology.

With the aim of representing conceptual modeling knowledge in a general point of view, the foundational ontology UFO provides a formal structure for the core reference CM-core ontology. Thus it is natural to consider the alignment to the UFO ontology, which can ensure the formalism of the CM-core ontology. We give the descriptions of the ontology classes in Figure 2, and their alignments to the UFO ontology:

- *System*: Set of interrelated elements that achieve a given objective through the performance of a specified function (Stevens, 2016). The definition of this class was adapted from *OntoProg: System*, with slight alteration (Nuñez and Borsato, 2017). The alignment of this class to the upper-level class in the UFO ontology is

$$CM-core:System \sqsubseteq UFO-A:Object, \quad (1)$$

in which the *Object* class (*Endurant*) in UFO ontology represents entities that possess spatial-temporal qualities, such as a person, a building, a tree or a river. The *System* class in CM-core covers different types of physical systems, and they all own spatial-temporal qualities. Therefore, the above alignment was proposed.

- *Parameter*: Variable representing some significant measurable system characteristic. The value of a *Parameter* is measured by sensors that are located at different components of the *System*. The definition and description of this class was adopted from *OntoProg: Parameter*, with alteration. This class was aligned with the *Moment* class in UFO through the alignment

$$CM-core:Parameter \sqsubseteq UFO-A:Moment, \quad (2)$$

in which the the *Moment* class (*Endurant*) is a set of instances that are existentially dependent on the instances of the *Object* class in UFO. The *Parameter* class in CM-core determines interesting *Parameters* whose values are relevant to abnormal status of a *System*, and a *Parameter* can not exist without the presence of a *System*. For this reason, the alignment between these two classes was constructed.

- *State*: The condition of a *System* at a specific time. The condition of a *System* is determined by the values of a set of *Parameters*. The *State* class was aligned to the UFO class *Moment*, by the alignment

$$CM-core:State \sqsubseteq UFO-A:Moment. \quad (3)$$

A *State* is also existentially dependent on an *Object* such as a *System*, thus the *State* class is also aligned with the UFO class *Moment*.

- *ValidTime*: This class represents the valid time entities. It has two subclasses, named *ValidInstant* and *ValidInterval*. The difination of this class was adapted from the *SWRL Temporal Ontology*, with slight adjustment (OConnor and Das, 2010). The proposed alignment for this class is

$$CM-core:ValidTime \sqsubseteq UFO-B:Time\ Point, \quad (4)$$

in which the *Time Point* class (*Perdurant*) is represented as real numbers that provide temporal information (Guizzardi and Wagner, 2010).

- *Behavior*: The *Behavior* of a *System* is represented as a sequence of *States* and transitions among them. The *States* together with transitions specify the evolution in the values of the *Parameters*. For defining this class, we used the definition introduced in (Goel et al., 2009), under the framework of the Structure, Behavior and Function (SBF) model. In the SBF model, a complex *System* could be described by its *Structure*, *Behavior* and *Function*, and the *Behavior* of a *System* is reflected by the *States* and *States* transitions. Based on the definition, the alignment

  $$CM-core : Behavior \sqsubseteq UFO-B : Complex\ Event \quad (5)$$

  was proposed, in which *Complex Event* in UFO is a subclass of *Event* (*Perdurant*). An *Event* represents possible transformations from a portion of reality to another, and it is categorized into *Atomic Event* and *Complex Event*, where a *Atomic Event* has no integral parts, and a *Complex Event* is composed of at least two events. In CM-core, the *Behavior* of a *System* stands for a complex composition of events which happen at different times points, and within different contexts. Thus, the above alignment was proposed.

3.2.3 Layer 3: Domain Ontologies for Condition Monitoring in Manufacturing

A domain ontology represents specific domain knowledge and is only applicable to a certain domain. In this study, the CM-core ontology will be specialized into domain ontologies using the Top-Down approach. Figure 3 shows the whole ontological framework, in which the domain ontologies are presented at the bottom level. In the figure, rectangles are different ontologies or conceptual models, solid lines are subsumption relations, and rectangles with dashed lines indicate different levels of domain scope.

In the ontological framework, the *Manufacturing Condition Monitoring Ontology* plays the central role among all the domain ontologies. This ontology makes use of elements from other domain ontologies and represents knowledge from both manufacturing and condition monitoring domains. The other domain ontologies are included in the framework development phase, but we do not introduce them in details in this paper. We shortly discuss their main usage here: the *Product Ontology* aims to provide a comprehensive representation of manufacturing products and product components. The *Manufacturing Process Ontology* gives a formal representation of manufacturing processes, such as cutting, drilling, milling, and casting. The *Manufacturing Resource Ontology* provides knowledge about manufacturing resources which are physical objects used for executing a range of operations during different manufacturing processes. The *Sensor Ontology* structures knowledge about sensors. This ontology is specialized from the core reference ontology SSN. The *Context Ontology* contains the representations of contextual knowledge, including the formal definitions of context entities such as person, activity, location and time.

The CM-core ontology consists of 42 classes and 15 object properties. In the context of smart factories, the ontological framework was evaluated by domain experts for its expressiveness and quality. It paves the way for the development of an intelligent system, which aims to perform condition monitoring and maintenance tasks automatically.

4 CONCLUSIONS AND FUTURE PERSPECTIVES

This paper presents an ontological framework which is the basis for the development of an intelligent condition monitoring system in manufacturing. The ontological framework was developed using a Middle-Out approach. It includes the CM-core ontology, which is a core reference ontology for representing general condition monitoring concepts and relations, and a set of domain ontologies for gathering and structuring knowledge in both condition monitoring and manufacturing domains. The CM-core ontology was aligned with the foundational ontology UFO, for obtaining a rigorous conceptualization. Also, the CM-core ontology will be specialized into domain ontologies, for integrating and representing domain-specific knowledge.

Currently, we are in the process of developing the domain ontologies that are at the bottom level of the ontological framework. These domain ontologies can be categorized into two types: (i) the ontologies for structuring knowledge in the manufacturing domain; and (ii) the ontologies for structuring knowledge in the condition monitoring domain. The first category of ontologies will provide the formalization of key concepts in manufacturing, such as *Product*, *Process*, *Manufacturing Resource* and *Context*. The second category of ontologies will focus on the representation of concepts that are relevant to machinery prognostics and health management (PHM), especially on the conceptualization of *Fault*, *Error* and *Failure*. Future perspectives include the integration of these domain ontologies with the CM-core ontology, to provide semantic capabilities for an intelligent condition monitoring system. On the other hand, a rule base will be

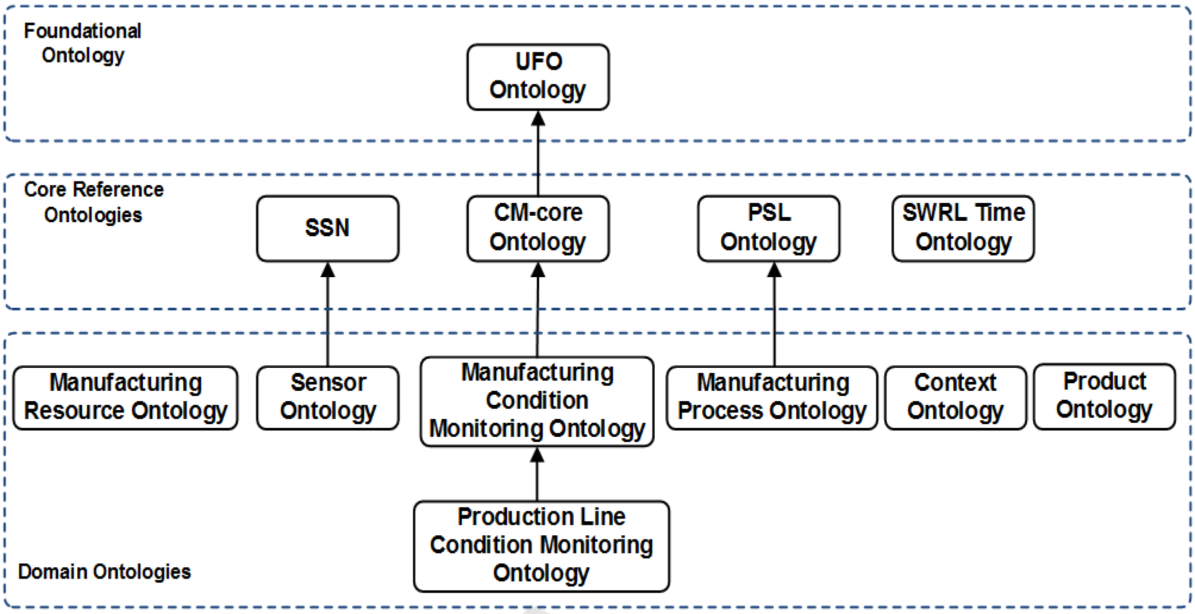

Figure 3: The ontological framework.

constructed to enable reasoning about future fault and failure occurrences. The rule base consists of logical rules that are extracted from the mining of sensor data and from experts' knowledge, and it will be integrated with the ontological framework for developing the intelligent condition monitoring system.

ACKNOWLEDGEMENTS

This work has received funding from INTERREG Upper Rhine (European Regional Development Fund) and the Ministries for Research of Baden-Wrttemberg, Rheinland-Pfalz (Germany) and from the Grand Est French Region in the framework of the Science Offensive Upper Rhine HALFBACK project.

REFERENCES

Ameri, F. and Dutta, D. (2006). An upper ontology for manufacturing service description. In *ASME 2006 international design engineering technical conferences and computers and information in engineering conference*, pages 651–661. American Society of Mechanical Engineers.

Compton, M., Barnaghi, P., Bermudez, L., GarcíA-Castro, R., Corcho, O., Cox, S., Graybeal, J., Hauswirth, M., Henson, C., Herzog, A., et al. (2012). The ssn ontology of the w3c semantic sensor network incubator group. *Web semantics: science, services and agents on the World Wide Web*, 17:25–32.

El Ghosh, M., Naja, H., Abdulrab, H., and Khalil, M. (2017). Using the unified foundational ontology (ufo) for grounding legal domain ontologies. In *9th International Conference on Knowledge Engineering and Ontology Development*.

Garetti, M. and Fumagalli, L. (2012). P-pso ontology for manufacturing systems. *IFAC Proceedings Volumes*, 45(6):449–456.

Goel, A. K., Rugaber, S., and Vattam, S. (2009). Structure, behavior, and function of complex systems: The structure, behavior, and function modeling language. *Ai Edam*, 23(1):23–35.

Gruninger, M. and Menzel, C. (2003). The process specification language (psl) theory and applications. *AI magazine*, 24(3):63.

Guizzardi, G. and Wagner, G. (2010). Using the unified foundational ontology (ufo) as a foundation for general conceptual modeling languages. In *Theory and Applications of Ontology: Computer Applications*, pages 175–196. Springer.

ISO (2012). Condition monitoring and diagnostics of machines–vocabulary.

ISO, B. (2000). 9001: 2008 quality management systems. requirements. *International Organization for Standardization*.

ISO, E. (2005). 9000: 2005. *Quality management systems-Fundamentals and vocabulary (ISO 9000: 2005)*, page 1.

Kaposi, A. and Myers, M. (2001). *Systems for all*. World Scientific Publishing Company.

Lee, J., Bagheri, B., and Kao, H.-A. (2015). A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3:18–23.

Maleki, E., Belkadi, F., Boli, N., van der Zwaag, B. J., Alexopoulos, K., Koukas, S., Marin-Perianu, M., Bernard, A., and Mourtzis, D. Ontology-based framework enabling smart product-service systems: Application of sensing systems for machine health monitoring.

Nandi, S., Toliyat, H. A., and Li, X. (2005). Condition monitoring and fault diagnosis of electrical motorsa review. *IEEE transactions on energy conversion*, 20(4):719–729.

Nuñez, D. L. and Borsato, M. (2017). An ontology-based model for prognostics and health management of machines. *Journal of Industrial Information Integration*, 6:33–46.

OConnor, M. J. and Das, A. K. (2010). A method for representing and querying temporal information in owl. In *International Joint Conference on Biomedical Engineering Systems and Technologies*, pages 97–110. Springer.

Papadopoulos, P. and Cipcigan, L. (2009). Wind turbines' condition monitoring: an ontology model. In *Sustainable power generation and supply, 2009. SUPERGEN'09. International conference on*, pages 1–4. IEEE.

Rao, B. (1996). *Handbook of condition monitoring*. Elsevier.

Roussey, C., Pinet, F., Kang, M. A., and Corcho, O. (2011). An introduction to ontologies and ontology engineering. In *Ontologies in Urban Development Projects*, pages 9–38. Springer.

Schreiber, G. (2000). *Knowledge engineering and management: the CommonKADS methodology*. MIT press.

Schwarzenbach, J., Wilkinson, L., West, M., and Pilling, M. (2010). Mapping the remote condition monitoring architecture. *Research Programme. Rail Safety and Standards Boards (RSSB) LTD. RSSB Core Report*.

Stevens, R. (2016). *Engineering mega-systems: The challenge of systems engineering in the information age*. CRC Press.