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► **To cite this version:**

Qiushi Cao, Cecilia Zanni-Merk, Christoph Reich. Towards a Core Ontology for Condition Monitoring. CARV 2018 - FOMI Workshop, Oct 2018, Nantes, France. pp.177–182, <10.1016/j.promfg.2018.12.029>. <hal-02045053>

**HAL Id: hal-02045053**

**<https://hal.science/hal-02045053v1>**

Submitted on 21 Oct 2021

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International Conference on Changeable, Agile, Reconfigurable and Virtual Production

## Towards a Core Ontology for Condition Monitoring

Qiushi Cao<sup>a\*</sup>, Cecilia Zanni-Merk<sup>a</sup> and Christoph Reich<sup>b</sup>

<sup>a</sup>Normandie Université, INSA Rouen, LITIS, 76000 Saint-Étienne-du-Rouvray, France.

<sup>b</sup>Hochschule Furtwangen University, 78120 Furtwangen im Schwarzwald, Germany.

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### Abstract

Condition monitoring is performed to identify the functioning state of a machine or a mechanical system. It is an important task by which the machine or mechanical system deterioration tendency and the location of a failure can be detected. In recent years, ontologies have shown promising results to enhance knowledge sharing in condition monitoring tasks, while offering a logically defined and controlled vocabulary of domain entities. Motivated by the growing demand for unification and formal representation of useful concepts in condition monitoring, in this paper we present CM-core, an ontology of core condition monitoring entities. It incorporates several ISO standards as sources and also extracts general concepts from a series of domain ontologies. The ontology contains taxonomies of core condition monitoring concepts such as system, function, behavior, structure, state, failure and fault, with their interrelationships. The CM-core ontology has a broader domain coverage than the existing ontologies, and its generality ensures further specification into more specific domain ontologies.

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Peer-review under responsibility of the scientific committee of the International Conference on Changeable, Agile, Reconfigurable and Virtual Production.

*Keywords:* condition monitoring; state of the system or machine; ontology engineering; core ontology; conceptual model

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\* Corresponding author. Tel.: +33 769660272.

E-mail address: [qiushi.cao@insa-rouen.fr](mailto:qiushi.cao@insa-rouen.fr)

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## 1. Introduction

Condition monitoring is a key technique for assuring the proper functioning of machines or mechanical systems. Generally aligned with fault diagnosis tasks, condition monitoring and maintenance has appealed to deep attention from domain experts and engineers. In the context of Industry 4.0, during the machine or mechanical system life cycle, condition monitoring activities are performed by obtaining data from sensors that are located at the components of the machines or mechanical systems, for identifying their operating state.

According to the current state, if any fault or failure exists, a diagnosis can be launched to determine the causes of it. Also, based on the characteristics of the fault or failure, analysis about how they will propagate and evolve over time can be performed. The use of condition monitoring techniques has several advantages, such as improved machine availability, improved production efficiency, and reduced maintenance cost [1, 2].

Recently, machines are connected building cyber-physical systems (CPSs), which are a new class of engineered systems that offer close interaction between cyber and physical components [3]. As the CPSs become more and more complex, the knowledge required for system operation and maintenance increases in complexity. In this context, the need for standard and well-defined models for capturing this complex knowledge is in high demand [4]. Ontologies have had great success with facilitating the formalization of condition monitoring tasks in different domains [5-7]. Ontologies are knowledge models that represent formal, flexible and inter-operable representations of domain concepts. The use of ontologies can streamline the data exchange among different systems, provide services for answering queries about those data, and offer services to improve the interoperability among heterogeneous systems [8].

However, most of the existing ontologies that are used to facilitate condition monitoring tasks are domain-specific, which means that they contain very specific domain concepts and properties, thus not feasible of being reused if the domain of interest changes. Taking account of this, in this paper we present a core ontology, named CM-core. The ontology contains basic concepts, properties, and relationships that are general across a variety of monitoring domains. The development is based on a series of ISO standards and domain ontologies. The generality of the ontology ensures the further specification into more specific domains. By formalizing domain concepts and relationships, the ontology captures and structures manufacturing domain knowledge and makes it usable by an intelligent CPS. The goal of such an intelligent CPS is to facilitate condition monitoring tasks in manufacturing, by providing intelligent decisions about machinery fault or failure prognostics and maintenance plans.

The remainder of the paper is organized as follows. In Section 2, we present related work, in which a set of existing ontologies related to condition monitoring will be discussed. Section 3 shows the design approach for the ontology, as well as the key classes and properties of it. Section 4 presents the conclusion and future perspectives.

## 2. Related work

There exist several ontologies and conceptual models related to condition monitoring. These efforts mainly focus on providing formal representations of concepts such as system, fault, failure, alarm, and measurement, in different specific domains. In this section, we first enumerate some of the most related ontologies and conceptual models existing in the literature.

- The ontology for condition assessment of a power substation apparatus [10] was developed to be one segment of the power system ontology [11]. By modeling key concepts of a partial transformer, the authors argue that this ontology can be used to support a range of important processes such as transformer thermal condition monitoring, remote monitoring and dissolved gas analysis [10].
- Ontoprog is an ontology developed to model the knowledge related to Prognostics and Health Management (PHM) of machines [7]. The authors stated that this ontology could be used to address failure analysis tasks in the context of smart manufacturing. Being used in a real centrifugal pump condition monitoring, the ontology showed its robustness regarding future decision making for condition-based maintenance in real processes [7].

- The ontology for wind energy [12] was developed through a semi-automatic ontology construction process. In the process, the authors used an approach in which the concepts and properties of the ontology were learned from related Wikipedia articles. As an outcome, the frequent phrases were extracted and organized into classes and properties.
- A railway ontology introduced in [13] aims to model contextual information, and also improve the diagnostic performance. The ontology incorporates important concepts in railway subsystems such as system status, symptom, observations, and fault. The developed ontology-based systems have shown satisfactory results in assisting with rolling stock, infrastructure, train operation and traffic management [13].
- An ontology for modeling the integration of Intelligent Maintenance Systems (IMS) and Spare Parts Supply Chain (SPSC) was introduced in [14]. This ontology fulfills the need of a common vocabulary for achieving a proper integration from IMS to SPSC, thus improves the quality of demand prediction in a SPSC.

The ontologies listed above cover specific concepts and properties in certain domains. The scopes of these ontologies are limited in domains such as wind energy, railway system, and supply chain management. Hence, they suffer from the issue of very specific coverage. When researchers or engineers are confronted with an issue in a different domain, a new model for the formal representation of domain concepts may need to be designed, since the existing ontologies do not model sufficient knowledge. The development of a new model may be time-consuming and require a lot of resources. To this end, representations of condition monitoring concepts and properties as general as possible, enabling easy extension and specification for a wide range of domains, tasks, and applications is needed. This is our motivation for developing CM-core, a core ontology for condition monitoring that is presented in Section 3.

### 3. The CM-core ontology

In this section, we present the CM-core ontology. During the development phase, we adapted the iterative ontology development process introduced in [15], and took profit from three knowledge sources: (i) ISO standards 13372 [16], 9000 [17] and 9001 [18]; (ii) the domain ontologies mentioned in Section 2, and (iii) relevant research papers and textbooks, such as [19] and [20]. In the following subsections, we first introduce the general architecture of the CM-core ontology and then enumerate the core classes with their relationships among each other.

#### 3.1. General architecture

The CM-core ontology aims to cover general concepts in condition monitoring that are common to many subdomains. To permit generality, the formal representation of key condition monitoring entities in the CM-core ontology has been made as generic as possible. In this subsection, we provide the terms that will be associated with the classes of the ontology. The CM-core ontology has been aligned to UFO [21], which is an upper-level ontology. We show how the CM-core ontology classes are aligned to UFO, and the general formal architecture of the ontology is presented thereafter.

- *System*: Set of interrelated elements that achieve a given objective through the performance of a specified function [22]. We refined the definition of the class *Ontoprog: System* in [7], by using a qualitative characterization model called Structure-Behavior-Function (SBF) [23]. This class has been aligned with the *Object* class in UFO, through the alignment

$$CM\text{-core: System} \sqsubseteq UFO: Object.$$

In UFO, *Object* (Endurant) represents a set of entities that posses spatial-temporal qualities. In CM-core, the *System* class contains different kinds of physical systems in the manufacturing domain, and they all obtain spatial-temporal qualities. Thus, the above alignment is proposed.

- *Process*: Set of interrelated or interacting activities that use inputs to deliver an intended result [18]. This class has been aligned with the *Complex Event* class in UFO, through the alignment

*CM-core: Process*  $\sqsubseteq$  *UFO: Complex Event*.

In UFO, a *Complex Event* (Perdurant) stands for a set of combined events with each consists of at least two single events. The *Process* class in CM-core represents manufacturing processes that are structured as a series of simple activities. For this reason, the above alignment is 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*. When the domain changes, different *Parameters* could be selected for the condition monitoring task, such as bearing temperature, oil debris, oil pressure, velocity, voltage, .etc. The alignment for this class and the upper-level UFO class is

*CM-core: Parameter*  $\sqsubseteq$  *UFO: Moment*.

In UFO, the *Moment* class (Endurant) is a set of individuals that are existentially dependent on individuals of *Object*, such as color, height and electronic charge. In CM-core, we also define the a *Parameter* to be existentially dependent on a *System*. Thus the proposed alignment is valid.

- *State*: The condition of a *System* at a specific time. The condition of a *System* is associated with the values of a set of *Parameters*. Since a *State* is existentially dependent on a *System*, the alignment

*CM-core: State*  $\sqsubseteq$  *UFO: Moment*

has been proposed.

- *Behavior*: It 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* [23]. According to the definition, the *Behavior* of a *System* is also existentially dependent on a *System*. Therefore, the alignment

*CM-core: Behavior*  $\sqsubseteq$  *UFO: Moment*

has been introduced for the CM-core ontology.

- *Fault*: A *Fault* is defined as a condition of a *System* that occurs when one of its components or assemblies degrades or exhibits abnormally [16]. The representation of this class is adapted from *Ontoprog: Fault* [7], with slight modification. Based on the definition, we propose the alignment

*CM-core: Fault*  $\sqsubseteq$  *UFO: Event*,

for representing a *Fault* as an *Event* (Perdurant) that happens in time.

- *Failure*: Termination of the ability of an item to perform a required function [16]. A *Failure* is a manifestation of a *Fault*. We adapted the definition of the class *Ontoprog: Failure* [7], with minor alteration. We also align this class with the UFO class *Event*, through the alignment

*CM-core: Failure*  $\sqsubseteq$  *UFO: Event*.

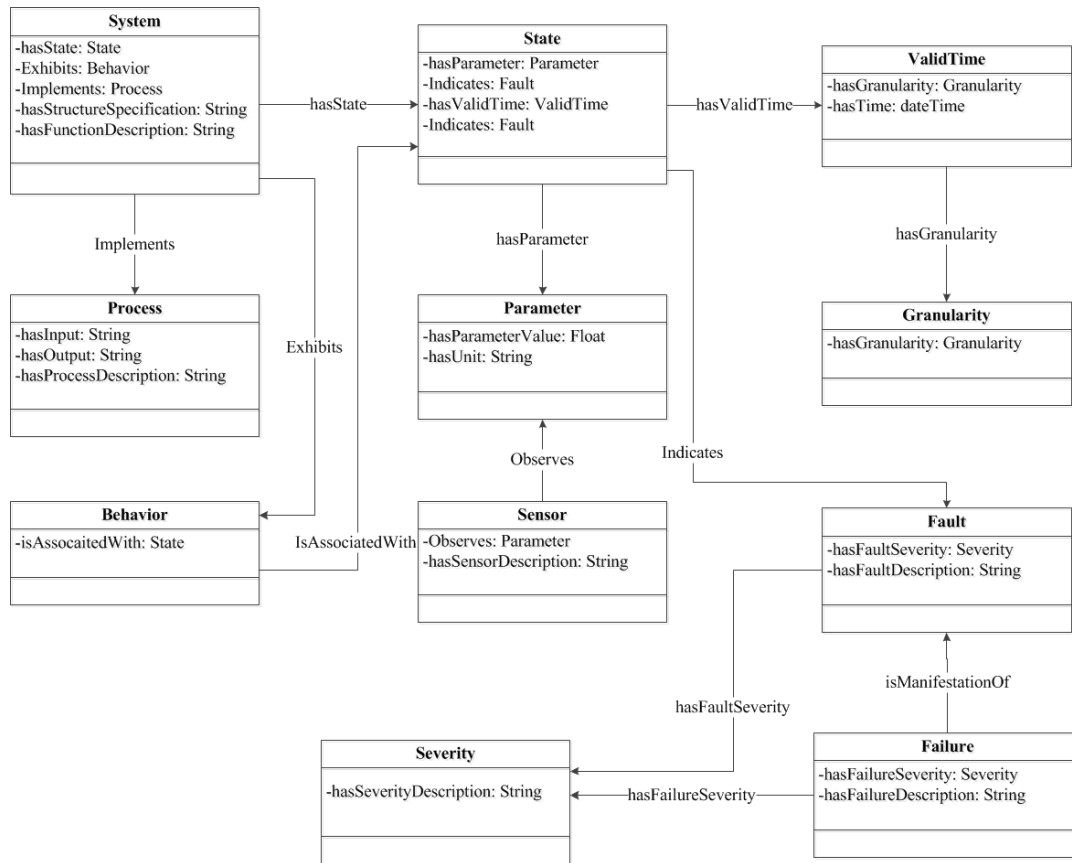


Fig. 1. Global architecture of the CM-core ontology.

Based on these terms, the classes with their object properties and data properties are constructed. A class defines a group of individuals which share some properties, and individuals are instances of the class. Object properties are binary relations between individuals, and data properties can relate individuals to concrete data values. Fig. 1 shows the global architecture of the CM-core ontology. For the purpose of clarity, we only show part of the classes and properties. In Fig. 1, rectangles are classes, solid lines represent object properties between classes.

The “Hermit” reasoner [24] is used to check the consistency of the ontology. The ontology has been evaluated by the experts, for its

#### 4. Conclusions and future perspectives

In this paper, an ontology that models the core concepts and properties for condition monitoring, named CM-core, has been introduced. The ontology contains core concepts related to condition monitoring, such as system, structure, behavior, function, state, fault and failure. The generality of the CM-core ontology ensures the possibility of its specialization into more specific domain ontologies, such as the ontologies for machine condition monitoring in industry. Thus, the CM-core ontology can be extended and customized to satisfy better the needs in individual domains where ontologies need to be used to empower information systems.

Future works will include the extension of the ontology for prognostic purposes. Machinery prognosis is an important aspect of condition monitoring, whose aim is to predict the fault conditions before they occur. To do this, the CM-core ontology will be specialized for the manufacturing domain, to be integrated into an intelligent system [25]. In the intelligent system, a rule base is needed to perform reasoning, for launching alarms about possible occurrences of machinery faults in the future. This rule base can be elicited by mining sensor data, which will learn

normal and abnormal behaviors of the machinery. The intelligent system aims to detect fault conditions and trend of failures of the machinery, thus facilitate decision making such as launching fault/failure alarms and providing maintenance plans.

## Acknowledgements

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

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