MULTIDIMENSIONAL DIH4CPS ONTOLOGY

Damien Nicolas, Christophe Feltus and Djamel Khadraoui
Luxembourg Institute of Science and Technology, 5, avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg

ABSTRACT

Digital Innovation Hub are of utmost importance when they sustain cooperation in innovative technological domains like the Cyber-Physical System. In this paper, we introduce, in a first part, a DIH ontology that we extend with CPS entities. For this, we remind the questions that the ontology must answer, deploy the methodology proposed by Noy and McGuinness, to identify the classes and the associations between classes, and integrate the new CPS ontological extensions. In the second part, we implement the full innovative DIH4CPS ontology within Protégé, and we instantiate it to a real company.

KEYWORDS

Digital Innovation Hub, CPS, Cyber-Physical System, Ontology, Protégé, Network, Capability, SME, Enterprise

1. INTRODUCTION

A Digital Innovation Hub (DIH) is defined by Crupi et al. (2020) as a one-stop shops that can help companies become more competitive with regard to their business/production processes, products or services by using digital technologie. DIH have for purpose to guarantee that all companies, whatever their sizes, can benefit from the advantages of new digital technologies1 and thereby, that they are able to find the appropriate competence regarding digital technologies and IT, which, for Rübmann (2015), is paramount for manufacturing industry. DIH are by essence strongly associated to network of partners, and it is essential for DIH to set up the more efficient tools as possible to support the market in discovering the digital information (technological, business or even scientific) in an accurate and prompt manner since both are essential for the existence of the company. Moreover, has already observed, DIH are especially of utmost importance when they are encouraging and sustaining cooperation (Sassanelli & Terzi, 2022) in cutting-edge technological domains like the cyber-physical system (CPS) (Gunes et al., 2014). In this context, an ontological representation of a DIH4CPS may be perceived as a contribution with high impact since it offers an "explicit specifications of conceptualizations" and, as a result contribute to sustain the networking environment in which DIH behaves. Unfortunately, as far of our knowledge, such ontology for specifying the DIH surrounding the promotion, the strengthening, the cooperation, and the co-development of CPS2 networks have never been developed so far.

Acknowledging this, the paper aims to describe and instantiate the ontology by formalizing the existing knowledge on DIHs competences, organization, experience, technologies, network, and the interoperability requirements of their networks and with their partners. Accordingly, this paper targets the development of the DIH4CPS ontology, including a dimension related to inner consortiums development and cooperation, as well as inner networking activities among the partner from a DIH. As a matter of fact, the target audience of this paper is far beyond traditional academic audience but also target directly project consortiums and the project partners responsible for the development of the DIH4CPS models. Those partners will use the ontological model described in the paper for achieving several development processes later. The paper also allows to understand how the ontology was built and its potential links with existing ontologies. Therefore, in the paper we remind an ontology for the CPS. This ontology has the particularity to be oriented to the surrounding network of the CPS organizational management that is addressed by the lens of Digital Innovation Hub.

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[1] [1] Pan-European network of Digital Innovation Hubs (DIHs). Available: https://ec.europa.eu/digital-single-market/en/digital-innovation-hubs; 2016

[2] A Cyber-Physical System (CPS) is, according to Wikipedia, a computer system in which a mechanism is controlled or monitored by computer-based algorithms

This paper is structured as following: After having remind the related work in Section 2 and put in exergue the lack of existing DIH for CPS ontology, we present an innovative DIH ontology with a CPS extension in Section 3. In Section 4, the complete ontology is validated by means of inferences in the context of a real case study. And Section 5 concludes the paper and propose few future works.

2. RELATED WORKS

While CPS exist for few decades, scientific contributions directly addressing the inter-relation between physical and cybernetic knowledge entities dates from 20 years with an acceleration in the volume of publications since 2018. This includes but is not limited to CPS for a plethora of areas such as traffic light and mobility (Shih et al., 2016), facilities management tools (door opening, conditioning system) (Terreno et al., 2020), robotics and healthcare cyber-robots (Yang et al., 2020; Zhang et al., 2015), mobility and self-driving car (Kim et al., 2013), telecommunication (Kim et al., 2017), etc. Accordingly, and as it is usual to do in the academic field, a large number of authors have produced state of the arts in this field, among which some are very good and well documented, like Jamaludin & Rohani (2018) analyzed CPS through two criteria: CPS's characteristic and architectures, Kumar et al. (2020) that stresses out how attacks on CPS (CPS) continue to grow in frequency and that accordingly, identifies a set of relevant research opportunities or Sun et al. (2018) that specially focus on CPS security and describes future research directions to secure critical CPS. Although the impressive number of existing publications dealing with CPS, little research has been focused so far to the modeling of the CPS system, which is paramount to understand the underlying structure and communication mechanisms between the CPS sub-components. In that regards, Weyer et al. (2016) proposes a framework for modeling and simulation of CPS-based factories and applied it to the automotive industry that the authors consider as the most competitive, advanced and complex industrial sector, Jeon et al. (2012) developed a CPS dedicated Meta Modeler (CMM) allowing to design complex and large scale systems, and Yu et al. (2011) proposed (1) a method to model and analyze CPS using a hierarchical and compositional modeling approach contributing to solve the tight coupling between physical and cyber world and (2) basic transformation rules to translate the CPS model into the networks of timed automata. Apart from these few contributions Weyer et al. (2016), Jeon et al. (2012), Yu et al. (2011), and some other less significant, modeling CPS remains a rather marginal area of research.

Modelling is a power tool to take a picture of the CPS and its environment. The project DIH4CPS goes one step further and proposes the elaboration of an ontologically structured knowledge base allowing reasoning based on CPS entities. Although CPS ontologies have already been proposed in the literature as well (Garetti et al., 2015; Petnga & Austin, 2016; Hildebrandt et al., 2018), the ontology proposed in this paper proposes to enrol a CPS ontology in the context of Digital Innovation Hubs competences and networking environment. As for of our knowledge such integration and integration-based reasoning has never been achieved before.

3. GENERIC DIH ONTOLOGY EXTENSION TO CPS

The DIH ontology that we extend to the CPS has been proposed in deliverable 3.3b of the DIH4CPS project. The global UML model of this DIH4CPS and further details are available in D3.3a and b3. To define the CPS ontology extension, we first had to determine and select the most appropriate method for ontology development. The review of the literature proposes therefore various approaches among which: Uschold & Gruninger (1996), Uschold & King (1995), Grüninger & Fox (1995), but also Methontology (Fernández-López et al., 1997), The Cyc Method (Fernández-López & Gómez-Pérez, 2002), KACTUS (Schreiber et al., 1995), SENSUS (Swartout et al., 1996), On-To-Knowledge2, ISO15504-based (Feltus & Rifaut, 2007; Rifaut & Feltus, 2006) and NeOn methodology (Rübmann, 2015; Terreno et al., 2020). For the CPS ontology, we have decided to work with the methodology proposed by Noy & McGuinness (2001). According to them, the development of ontologies requires the following steps: 1. Determine the domain and scope of the ontology, 2. Consider reusing existing ontologies, 3. Enumerate important terms, 4. Define the classes & class hierarchy, 5. Define the properties of classes, 6. Define the facets of the slots, 7. Create instances.

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[3] All DIH4CPS deliverables are available at https://dih4cps.eu/ and considered by Eslami et al. (2020)

3.1 Determine the Domain and Scope of the Network Ontology Extension

This section aims to determine what the ontology is going to cover, for which purpose, and especially who will maintain and use this ontology. According to Noy & McGuiness (2001), one method to determine this domain and scope is to enumerate a list of question that the ontology must be able to answer afterwards. This list of question has been iteratively determined through working groups meeting. Examples of questions are: Who can give me advice in CPS technology application? Who can give advice for a specific technology? Which university can offer IT support? Which technologies uses organization A for data storage? Who has experience on sensor sensitivity and calibration? Who has expertise in working with Augmented Reality?

3.2 Consider Reusing Existing Ontologies

To extend the ontology to CPS, we have reviewed the state of the art in CPS ontologies, we have extracted the most important concepts, and we have proposed our own integrated model. Nine additional entities have been added to the DIH4CPS ontology to express that a CPS is a type of product, itself being a type of artefact. This CPS extension claims that CPS are composed of a Cyber Process entity, which is a type of Process and of a Physical Resource entity, which is a type of Resource (Zhang et al., 2015). According to Bertoli et al. (2021), characteristics of CPS are Sensors, Actuators, and HMI for the Physical part, and the Computing, The Software Communication and the Data storing and analytics for the Cyber part, as represented in Figure 1.

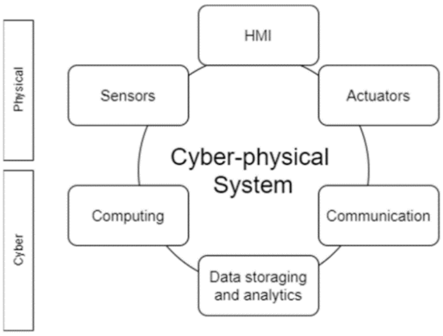

Figure 1. Key CPS characteristics extracted from Bertoli et al. (2021)

3.3 Enumerate Important Terms

Table 1. CPS terms

Concepts	Definition - Explanation
CPS	CPS are the key technology enabling Industry 4.0 and can be applied on different levels in the modern value chain (Bertoli et al., 2021). According to University of Yichita[4], CPS are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components.
Cyber Process	According to Guo (2017), a cyber process system is a huge system with mass components an complex communication protocol.
Physical Resources	The Physical Resource system correspond to the integration of the physical components or mechanical parts of the CPS.
Computing	The realization of a set of algorithms having an impact on the stat and behavior of the physica system.
Software Communication	The exchange of messages between end-devices and a central network.
Data storing and analytics	The activity of analyzing, holding, deleting, backup organizing, and securing information to b compute to the purpose of the CPS.

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[4] https://www.wichita.edu/research/netcpsreu/CPS.php

Sensors	A physical device that detects information form inputs from the physical environment and generate the expected responds.
Actuators	A physical device that achieves physical behavior in response to a cyber or physical order or command.
HMI	The hardware or software through which an operator interacts with a controller[5].

Based on these definitions and explanations, the hereabove concepts have been gather in an integrated ontology as represented on Figure 2.

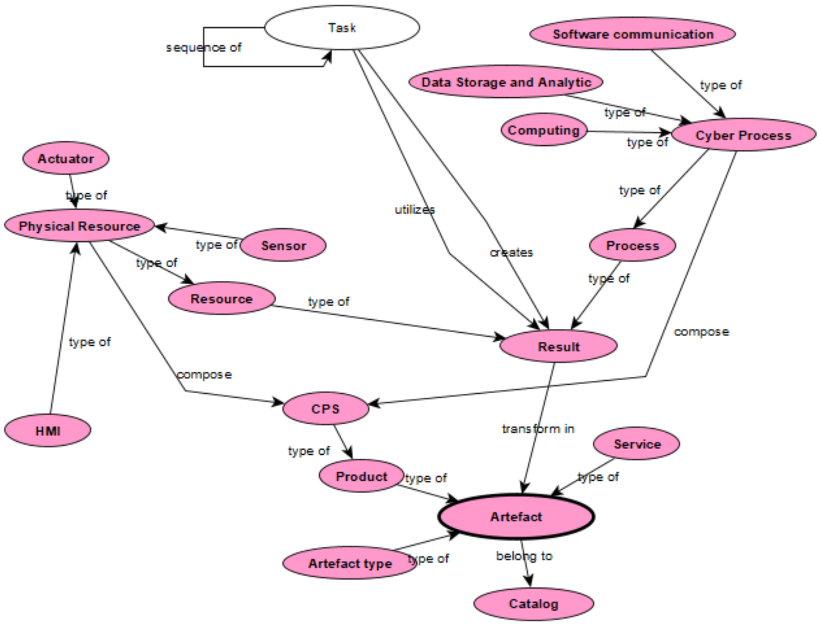

Figure 2. Integrated CPS ontology extension

3.4 Define the Classes & Class Hierarchy

Based on the important concepts enumerated in Table 1, the list of class and class hierarchy is the following: CPS are `type of` Product, Physical Resource and Cyber Process `compose` the CPS, Sensor, Actuator and HMI are `type of` Physical Resource, Data Storage and Analytic, Communication and Computing are `type of` Cyber Process, Physical Resource are `type of` Resource, Cyber Process are `type of` Process, and Sponsor `is an` Organization type.

3.5 Define the Properties of Classes

According to Noy & McGuiness (2001), the classes defined in section 3.3 do not contain enough information to fully and correctly answer all the questions listed in 3.1. Therefore, in this section, the methodology foresees to describe the internal structure of each concept. This step is important and has already partially been achieved in previous section. For instance, the structure of the Network concept has been explained based on the Network-type, the functioning rule and Status, and the relation with the Organization. It will not be further extended here.

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[5] https://csrc.nist.gov/glossary/term/human_machine_interface

3.6 Define the Facets of the Slots

The cardinality defines, among others, the cardinalities and values a class may have. Accordingly, in this section, we will focus on defining the classes and associations cardinalities, as explained in Table 2.

Table 2. CPS cardinalities

Cardinality	Concepts	Association	Cardinality	Concepts
1	CPS	Type of	1	Product
1	Actuator, Sensor, HMI	Type of	1	Physical Resource
1	Data Storage and Analytic, Communication, Computing	Type of	1	Cyber Process
1	Physical Resource	Type of	1	Resource
1	Cyber Process	Type of	1	Process
1	Physical Resource	Compose	0 to n	CPS
1	Cyber Process	Compose	0 to n	CPS

3.7 Create Instances

This last step in the methodology is addressed in next section.

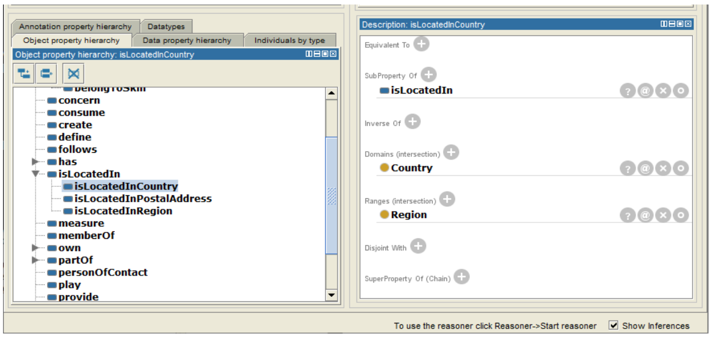
4. OPERATIONAL ONTOLOGY

The instantiation of the ontology for the one concrete company is realized with the tool Protégé, and the Luxembourg Institute for Science and Technology was chosen to test the instantiation of the DIH4CPS ontology because it covers a large set of services, competencies, domains, and skills.

4.1 Implementation in Protégé

According to Stanford University[6], Protégé is a “free, open-source ontology editor and framework for building intelligent systems”, moreover, “Protégé is supported by a strong community of academic, government, and corporate users, who use Protégé to build knowledge-based solutions in areas as diverse as biomedicine, e-commerce, and organizational modelling”. Using Protégé to support the exploitation of the DIH4CPS ontology, first, the 67 classes and 49 object properties have been encoded in Protégé.

In protégé, the relations between classes must be defined as object properties. For instance, as illustrated on Figure 3, the association name “is located” that associate the class “Region” and the class “Country” is the property named “isLocatedInCountry” and this property has for Domains Country and for Ranges Region. Given that all associations with a same name (e.g., “is located”) have different Domains and Ranges, we must create as many associations as there exist cases. Therefore, for the “is located”, we have three different properties: “isLocatedInCountry”, “isLocatedIn- PostalAddress”, and “isLocatedInRegion” (cf Figure 3).



Equivalent To

SubProperty Of
isLocatedIn

Inverse Of

Domains (intersection)
Country

Ranges (intersection)
Region

Disjoint With

SuperProperty Of (Chain)

To use the reasoner click Reasoner->Start reasoner ☑ Show Inferences

Figure 3. Example of property

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[6] https://protege.stanford.edu/

4.2 Business Case Validation Using Inferences

To validate the ontology and to illustrate how it is possible to use it to infer new knowledge, we illustrate how an instance of the PME concept may also be an instance of an RTO using the inference mechanism. To do so, first we have created the individuals (instance of concepts) and data properties of these individuals in section 4.2.1, then, we have created rules in section 4.2.2, afterwards, we have launched the reasoning in section 4.2.3, and we have analyzed the new created knowledge base in Section 4.2.4.

4.2.1 Creation of Individuals

The creation of a new individual consists in defining a new direct instance of a class. For instance, we created an instance of the class PME by selecting the targeted class concept on the top left frame and pushing the mauve lozenge in the bottom left frame.

After the individual being created, it is possible to assign it with Data properties. Data properties need to be defined before being assigned. Therefore, in Protégé's Data property frame, we have defined 3 instances:

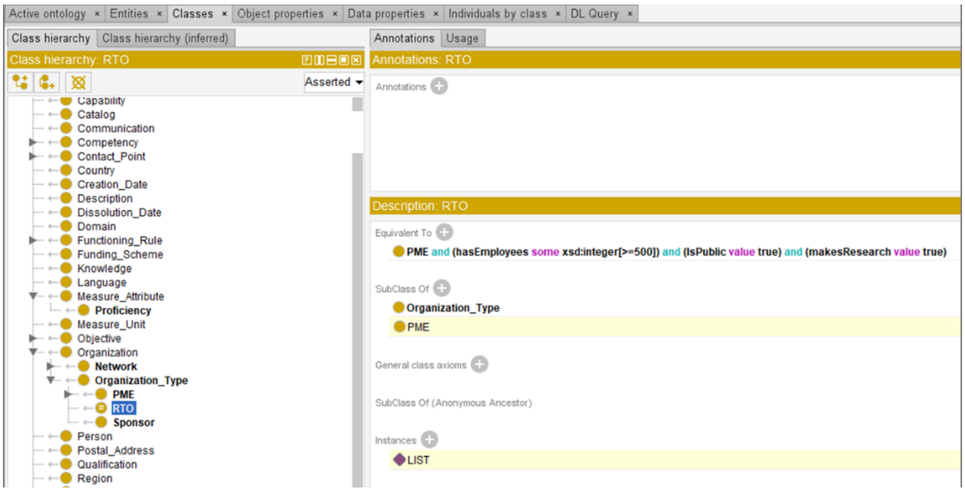
1. makesResearch, which is a property that may be assigned to a PME or an RTO, and which is of a type Boolean (True or False)
2. isPublic, which is a property that may also be assigned to a PME or an RTO, and which is of a type Boolean (True or False)
3. hasEmplosees, which is a property that may also be assigned to a PME or an RTO, and which is of a type integer.

Finally, these data properties may be asserted to created individuals. For example, we have asserted that LIST makes research, is public and has 750 employees.

4.2.2 Creation of Rules

The second step to create inference consists in generating inferring rules. There exist various options, therefore. In this paper, we have decided to express an "Equivale To" rule in the description of the RTO class. This rule, illustrated on Figure 4, shows that an RTO is equivalent to a class with the following characteristics: It is an individual of a class "PME" and it has, as data properties: to have more than 500 employees, to be public, and to make research. As illustrated on Figure 4, this is expressed by:

```
PME and (hasEmploees some xsd:integer[>=500] and (isPublic value true)
                  and (makesResearch value true)
```



Equivalent To
PME and (hasEmployees some xsd:integer[>=500]) and (IsPublic value true) and (makesResearch value true)

SubClass Of
Organization_Type
PME

Instances
LIST

Figure 4. Example with inference

4.2.3 Reasoning

The last step in inferring new knowledge from the ontology consists in launching the reasoner. Before doing so, we observe that the RTO has not LIST individual as direct instance although LIST is an individual of PME.

To launch the reasoning, it is necessary to run a reasoner from the top menu of Protégé. In our case, we have worked with Pellet inference engine (reasoner) (Singh & Karwayun, 2010).

4.2.4 New Knowledge Base

After this reasoning, new inferences are automatically detected and ad to the existing knowledge base. For instance, in the case of LIST, Pellet has detected and a PME may also be considered has a subclass of RTO and that LIST fulfils the 3 conditions to be RTO, to know: to be public, to make research and to employ more than 500 employees. As illustrated on Figure 4, the newly inferred knowledge is highlighted in light yellow.

5. CONCLUSION AND FUTURE WORKS

This paper describes, as main result, the first part of the DIH4CPS ontology presented in D3.3, including its two dimensions, to know: competence and organization. In the second part (Section 3) we have developed the third area of the DIH4CPS ontology dedicated to networking. Therefore, we have reminded the questions the ontology is required to answer, we have developed the methodology proposed by Noy & McGuinness (2001), to identify the class and their associations, and we have integrated this networking area with the competence and organizational areas. Then, we have extended the Artefact Ontology with a CPS description using the same methodology than for defining the network one (Section 4). Finally, in the fourth part, we have encoded the full DIH4CPS ontology within Protégé, we have instantiated it to a real company case (to know: LIST), and we have validated its usability by means of inferences.

Based on the outcomes of this instantiation, updates on the DIH4CPS model could be foreseen if needed following by the instantiation of all the DIH4CPS network. This paper could also be used as a baseline for the development team of the DIH4CPS platform and for further use cases with other companies, and considering other technologies like the blockchain (Imeri et al., 2018).

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