Internet of Things Ontology for Digital Twin in Cyber Physical Systems

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***Abstract*—The Digital Twin is one of the most important concepts in the Cyber Physical Systems (CPS) era. It can bring benefits such as simulation, monitoring or management once it joins the physical and the virtual through the Internet of Things. This concept is being adopted more and more in the academia and in the industry, but there is still a lack of methods to define and formalize the representation of the Digital Twin, as for example semantic models. Ontologies are a way of representing knowledge that can be shared between different entities, allowing a common understanding about a information. In this sense, this work proposes an ontology to represent Digital Twin in the context of CPS and embedded systems. These concepts are implemented through a proposed architecture. The proposed ideas are being evaluated with industrial case studies and some of the preliminary results are described in the paper.**

I. Introduction

The embedded systems and network applications are becoming a part of our life. In production, embedded system is an important support to industrial infrastructure [1]. The main objective of embedded system applications is that these equipment and products need digitization, intelligence and network. Recently, emerging technologies are being introduced into the manufacturing environment, which results in the new industrial revolution (Industry 4.0) [2].

Industry 4.0 [3] or Smart Factory [4] will transform the manufacturing and production. It is a technological evolution from embedded systems to Cyber-Physical Systems (CPS) [5].

A Cyber Physical System is a kind of embedded systems and can be described as a set of physical devices, objects and equipments that interact with a virtual cyberspace through a communication network. The cyber model of each physical entity can be seen as a digital representation of the real entity, thus it is sometimes called “Digital Twin”[6]. The Digital Twin (DT) can monitor and interact with the physical entity, device or system [7].

These technologies form the edges of the Internet of Things (IoT) [8] bridging the gap between cyber space and the physical world of real things, and are crucial in enabling the Internet of Things to deliver its vision and become part of bigger systems in a world of systems of systems [9].

According to [10], effective collaboration and integration between industrial devices and their virtual representation are considered a challenge in this domain. Management of real-time embedded components is a challenge to the designing of complex and critical embedded systems. Thus, approaches to map physical devices into models, with easily user management, can contribute to design, development and adoption of Digital Twin and Semantic Models in embedded systems.

This paper presents an ontology to represents the Digital Twin in the context of CPS and IoT and solve the problem to bring together the physical and virtual worlds. The next section discusses related work and theoretical background. In section III, an architecture for digital modeling and the proposed ontology are explained; section IV describes the case study to clarify and validate the proposal; finally, in section V conclusions are drawn, and future work directions are signaled.

II. Theoretical Background and Related works

A. Internet of Things

IoT is characterized by the adoption of interconnected objects which involves physical, software and embedded technologies. These elements are able to interact and cooperate between each other in order to reach a common objective [8].

This concept can be divided into three generations [11]:

- of tagged objects
- of things interconnection through web technologies
- of social objects, semantic data representation, and cloud of things

These three generations show the evolution of IoT and allow to identify and understand the characteristics of this concept nowadays, avoiding a misunderstanding or possible rejections [11]. The IoT generations are essential information to explore the maximum potential of this idea.

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Different researches have been presenting the combination of IoT, semantic models and Digital Twin. In [12] an AutomationML model is proposed to represent Digital Twin. The work uses this model to exchange data between heterogeneous devices through an IoT platform.

In [13] it is proposed an architecture for Digital Twin based on the IoT concept. It presents an idea that every physical device has a cyber thing in the cloud.

B. Digital Twin

The term "Digital Twin" was brought to the general public for the first time in [14] and [15] as "an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, to mirror the life of its corresponding flying twin".

With the Cyber Physical System concept, the Digital Twin can be understood as a virtual representation of the physical product, a digital shadow that contains all information and knowledge of it [16].

In the context of data and information, a Digital Twin includes both static as dynamic information [12]. Static information can be geometrical dimensions, bill of materials, processes, while dynamic information is the one that changes with time along the product lifecycle.

Digital Twin can bring benefits such as simulation, monitoring or management once it joins the physical and the virtual through the Internet of Things.

- Simulation: ontologies provide a formal way to write rules that can be applied to the model. From these rules, simulation methods can be created.
- Monitoring: from an ontology, it is possible to create communication interfaces that allow devices to send and receive data. In [17] it is presented this idea of creating interfaces automatically from an ontology. Since the ontology can be always updated with the devices status it is possible to make decisions based on this information.
- Management: from an ontology it is possible to create a management system for the Digital Twin. It is possible to model storage information, authentication, communication interfaces, Human machine Interface (HMI) and all these components make up the management system

In [13] it is proposed a reference architecture and affirms the importance of the 'cloud' to the CPS. The article contributes with an analytical description to model a reference architecture for cloud-based cybernetic systems (C2PS), where each physical element accompanies a cyber-hosted element in the cloud, which is the digital twin.

Sierla [18] presents a modeling description for Digital Twin based on digital product description. The Digital Twin is able to gain access to all production resources and to orchestrate them, thus realizing our proposed product-centric control concept.

C. Semantics models - Ontologies

Ontologies provide a generic way to represent domain knowledge for an agreed understanding among applications [19]. It can also be understood as a formal and explicit specification of a shared conceptualization [20]. Ontologies enable to create a common vocabulary of a domain, the meaning of the terms and the relations between them [20].

Classes in ontologies can be related to the concept of class as in object-oriented programming. Objects from real world are grouped and they are composing sets of elements with similar characteristics [21].

A property is a relationship between the individual and a value. This value can be data or another individual. Properties provide attributes for individuals, which are similar to object-oriented programming where one has have methods for accessing object data, but the ontology provides greater re-usability by relating a property with multiple classes [21].

Individuals represent instances of the classes described in the ontology. These instances are similar to objects in object-oriented programming, but they have no associated methods. Individuals can represent both virtual concepts and physical objects [21].

In this context, the work of [17] proposes an approach to integrate industrial devices using ontologies and an IoT middleware. Devices are mapped into an ontology and interfaces are automatically generated based on the semantic model.

An approach to data management for smart products is presented in [22]. It is proposed a flexible, dynamic and semantic content considering both physical product as well as the digital product twin. Ontologies have been used in this work to describe the main concepts in this topic.

In [23] it is presented a combination of UML and Ontologies to find a generic system-level semantic model. The authors propose a way to have a communication through human-readable text and computer-readable models that is important for engineering experts, software developers and decision makers.

III. Architecture and Ontology for Digital Twin Modeling

This work aims to contribute with a semantic model to Digital Twin in the context of CPS. Therefore, an architecture has been developed to identify the main elements of this context. Figure 1 depicts the proposed architecture to combine Digital Twin and IoT concepts.

The main idea of this proposal is to provide a manner to represent Digital Twins through a semantic model. As it can be observed in Figure 1 the first step is responsible to map components of the Physical World to the semantic model (called Domain Knowledge). In this approach, semantic model can be dynamic complemented by users (step 2) and it allows to improve the way that data is shown on applications. For example, users can define how an attribute should be presented to them in order to highlighted important properties.

A group of similar devices is represented by a class and each device is individually modelled in this class. For example, a set of valves can be represented by a class called "Valve" and each single valve can be represented by an individual of this class, like "valve1", "valve2" and so on.

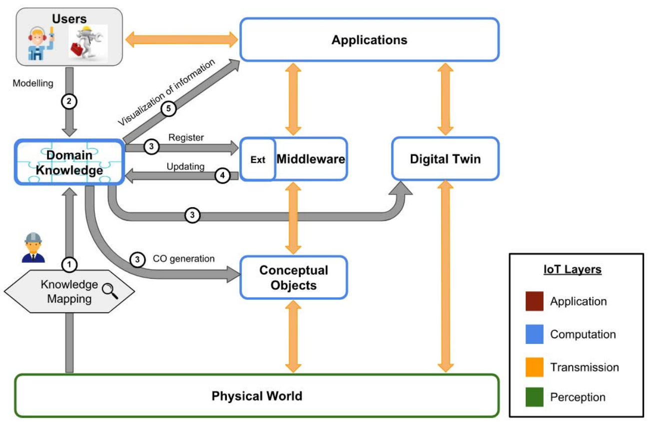

Fig. 1. Proposal Architecture for Digital Twin based on Ontologies

Since the ontology is ready and physical devices are mapped, it will provide the necessary information to the middleware do the registration of the industrial elements. This integration, between the Domain Knowledge, physical devices and IoT concepts is shown in the step 3. At this step, it is also generated interfaces called as Conceptual Objects which provide a way which devices can communicate to the middleware. These interfaces are source code generated from the proposed ontology.

Digital Twin is an important concept to Smart Factories once it brings several benefits to these companies. Therefore, still at step 3, the Domain Knowledge is applied to represent how data should be shown in Digital Twins. The main idea is to describe data information in high level description.

In the Domain Knowledge it is possible to create different rules in SWRL in order to be executed in Digital Twins. This allows users to create behaviors of a real device into a Digital Twin as, for example, it is possible to create an alarm if temperature is higher than an specific value.

The middleware will keep the ontology updated (step 4) through the extension. This is possible because the Concept Objects contain an identifier of each class in the ontology and each individual is represented by an instance in the Conceptual Objects which has an identifier as well.

At the step 5 the Domain Model is used to provide a better manner to show information to users through the end-users applications. There are several architectures available in the literature that can satisfy the needs of this problem [24]. In this research, a four-layers architecture has been selected since it provides a logical and intuitive division of the elements:

- **Perception layer**: it is a set of sensors and actuators which enables the physical object to perceive;
- **Transmission layer**: it is the layer after perception and it has the task to transmit the information to the upper layers;
- **Computation layer**: it is responsible for receiving and processing data, and making decisions;
- **Application layer**: it receives the information from the lower layers and provides tactical understanding of it.

This architecture allows the integration of heterogeneous devices and the detailing of these features. In this integration semantic models have been adopted.

A. *Semantic Models - Ontology for Digital Twin*

Semantic models have been considered an important way to achieve interoperability between different elements [25]. In the IoT context, ontologies can also be adopted for managing access, discovering resources and producing useful results [25].

There are several ontologies in the literature for the most diverse areas and with different scope, granularity and generality. Therefore, these concepts can be used to system integration [25]. The adoption of ontologies in Digital Twin applications allows to add more information to users. Moreover, it can be used to improve the visualization and understanding of object's data [26].

There are also generic ontologies which can be extended for different domains. For example, one lightweight ontology is IoT-Lite [27]. It is an instantiation of the Semantic Sensor Network (SSN) ontology [28] and its purpose is to describe key IoT concepts. This ontology contains concepts of System, Device, Tag, Service, Sensor and Attribute which are the main concepts in this area.

One of the contributions of this research is the elaboration of an ontology for Digital Twin. Thought the proposed research it is possible to represent Digital Twins of devices in an IoT system. To achieve this, IoT-Lite has been extended with classes related to virtual twin of devices. Figure 2 presents the elaborated ontology that was used for development of the work. IoT Lite ontology is presented in gray and the new classes are presented in orange.

The proposed ontology specifies that a Digital Twin have one application programming interface (API). It means that external applications and systems should access to the Digital Twin functionalities via a well defined protocol. API is a set of specifications to allow external elements access some provided functionalities. For example, the API may allow external applications to query the current state of the virtual model or to trigger a simulation start.

The Digital Twin can also have storage, events generation, methods execution and access control to its resources. Moreover, it can provide HMI to its users. These components support the implementation of most functionalities of a Digital Twin. Following, it is listed a brief explanation of each of these components and indicate how it can be used:

- **Storage**: a Digital Twin may be able to maintain a historical log of modifications to the device model and generated events. The historical record of a device operation is essential to some applications, specially those involving big data analytics and predictive maintenance. This component can be implemented as a local file record, a local database or a connection to a remote database.

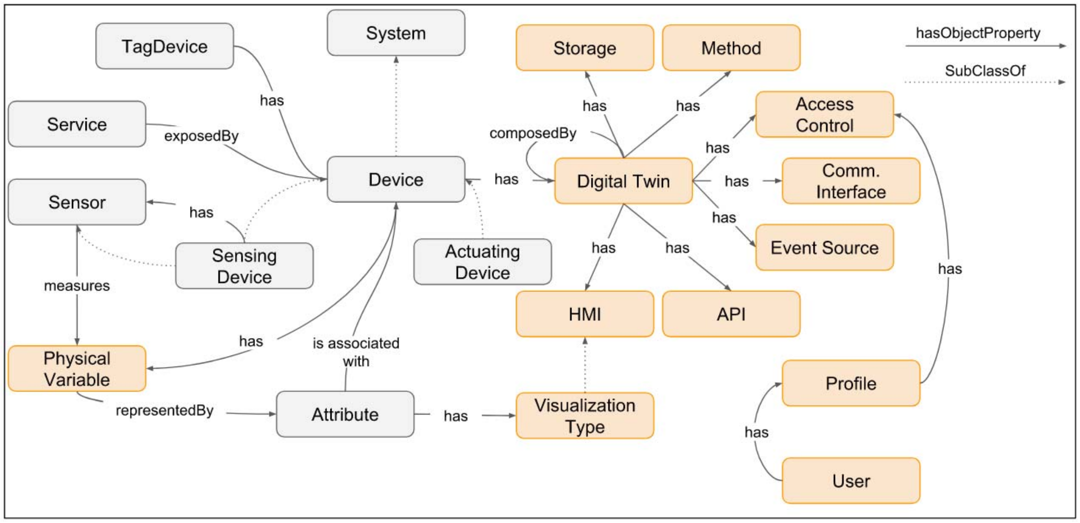

Fig. 2. Digital Twin Ontology with IoT-Lite

- **Events**: a Digital Twin may generate events to indicate that something has happened or a given condition has been met. Examples of events are change in some device model property, an alarm indicating that the value of a sensor is above a specified threshold.
- **Methods**: a Digital Twin may have functionalities that can be accessed by applications or users. These functionalities are modeled as methods, which are callable objects that implement a set of instructions. Methods can be used to control the device, execute simulations, run diagnostics, etc.
- **Access control**: a Digital Twin may implement security measures to restrict access to its functionalities and to the device model information. In order to maintain flexibility these measures were not modeled as required, but in practice they are essential to guarantee security, specially when the Digital Twin is accessible via internet. Access control measures can include the implementation of user authentication, access control list, or can be delegated to a dedicated framework.
- **Human machine interface (HMI)**: a Digital Twin may provide interfaces such that humans can easily visualize the device virtual representation and interact with it. This can be implemented for example as a simple graphical user interface or with advanced augmented reality techniques.
- **Communication Interface**: a Digital Twin may provide communication interface with the physical device. It is responsible to update properties of the Digital Twin. These interfaces make a bridge between the physical device and its virtual representation.

The Digital Twin can be composed by other Digital Twins as shown by the reflexive composition in Fig. 2. This allows complex twins to be created by aggregating smaller ones in a hierarchical structure. For example, the Digital Twin of a factory can be composed by Digital Twins of its machines, which in turn can be composed by the Digital Twins of its parts. It is defined that the set of functionalities provided by a parent Digital Twin should at least contain an individual functionalities of its children Digital Twins. Nevertheless, higher level functionalities can be added in higher hierarchical levels.

In addition, a class which is related with information visualization have been added to make possible to model how data should be presented to users. For example, temperature of an equipment can be shown as a chart and it can describe its data history or it can be presented in simplified form (only with the current value).

B. *Digital Twin Visualization Based on Models*

For the present proposal, it is intended to extract information from semantic models that can serve as input for the visualization of information for the users.

This idea can be applied in many domains, in industry for instance, there are different types of users, and they may have different needs regarding the information of a system. For example, the person in charge of maintaining equipment will need to view the history of the equipment to identify possible faults or problems. However, the operator may only need the current status of the equipment and the functionalities of that equipment.

In this context, this work presents a strategy to support these characteristics enabling the visualization of information in a way that is more convenient for each kind of user.

IV. Validation - Valve Actuator Industrial Case Study

A case study in industrial domain is presented in order to show the initial contributions of this research. It includes

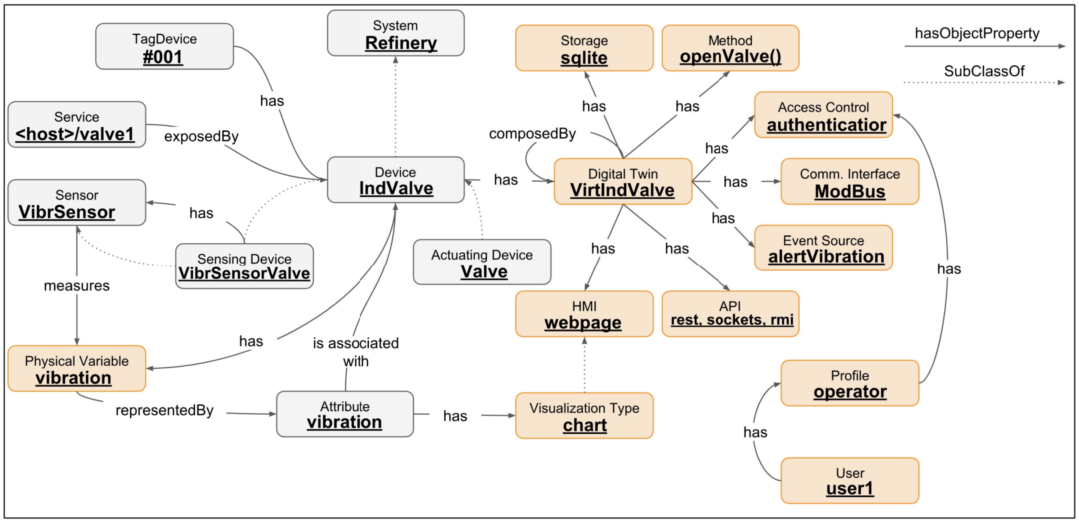

Fig. 3. Digital Twin Ontology with an Industrial Valve Actuator

concepts from the modeling of the physical components up to the top layer (application) that serves as the interface for users.

For the Physycal World layer, an industrial valve has been modeled. It can open and close which allows something to pass though it or not. The Valve has sensors to monitor its health such as: vibration, battery level sensor, temperature sensor, pressure sensor and also a torque sensor which measures this attribute when the valve opens and when it closes.

Data used for simulation were captured from an electric valve actuator model CS06, produced by Coester, a partner company from Brazil, and because of that it was possible to bring the simulation closer to a real scenario.

Figure 3 shows how it can be modeled with the proposed ontology.

This Valve has been modeled, as a Device, to show that the proposed ontology can be applied to this kind of systems covering the most important concepts. It contains a sensor which measures vibration of the valve. This vibration is represented by an attribute with the same name which has visualization type as chart. It means that this attribute should be shown as a chart.

The Device has a Digital Twin which is a virtual representation of the physical device. In the model is defined that its data will be stored in a Sqlite database. This virtual device has methods like "openValve" to manipulate the virtual entity.

In the computation layer, the FIWARE middleware was used to receive and store the information which was received from the lower layers. An extension of the middleware was implemented so that one could work on ontologies at this level.

The Digital Twin has been created based on the ontology which is updated by the middleware extension. As visualization form, a 3D model of the valve has been used in the Collada format. Figure 4 shows this model with the attribute vibration.

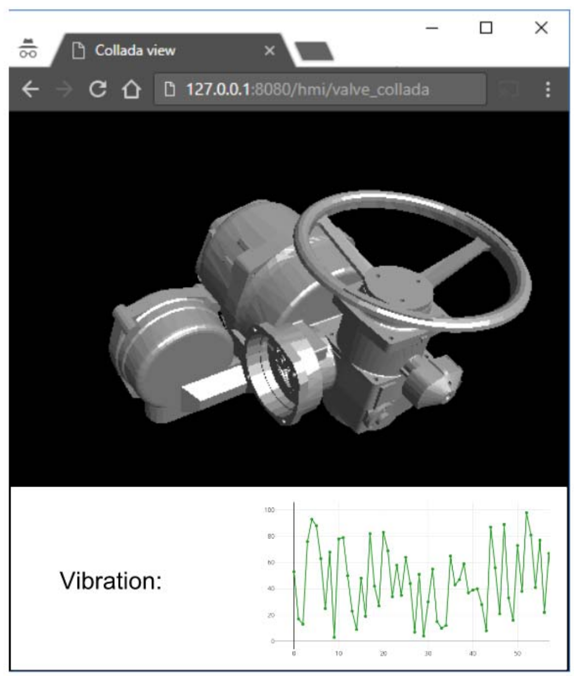

Fig. 4. Case Study of an Industrial Valve Actuator

As modeled in the ontology, the vibration attribute should be shown in a chart format. It is possible to create visualization forms that final users can model and choose wich best fit with their needs.

V. Conclusion

In this research, it is proposed an ontology that contains the basic concepts for DT modeling in the context of CPS and embedded systems. This ontology used concepts already existing in the literature, such as the IoT-Lite ontology.

The case study has demonstrated that the ontology covers the main concepts for the mapping of physical devices as well as the concepts involved in the development of DT. It was also possible to verify that the ontology can be used for graphic visualization of the digital twin. This feature allows you to not only map the physical devices, but also configure how their attributes should be presented visually.

The proposed ontology seeks to highlight the main concepts involving Digital Twin, however it can be extended to more complex systems or with specific peculiarities. As future work, we intend to explore the SWRL rules to generate even richer models semantically. In addition, it is intended to detail each concept that integrates the Digital Twin to apply this concept to other scenarios.

References

[1] J. Wan, H. Cai, and K. Zhou, "Industrie 4.0: enabling technologies," in *Intelligent Computing and Internet of Things (ICIT), 2014 International Conference on*. IEEE, 2015, pp. 135–140.

[2] S. Wang, J. Wan, D. Li, and C. Zhang, "Implementing smart factory of industrie 4.0: an outlook," *International Journal of Distributed Sensor Networks*, vol. 12, no. 1, p. 3159805, 2016.

[3] I. . W. Group *et al.*, "Securing the future of german manufacturing industry: Recommendations for implementing the strategic initiative industrie 4.0," *Federal Ministry of Education and Research of German*, 2013.

[4] D. Zuehlke, "Smartfactorytowards a factory-of-things," *Annual Reviews in Control*, vol. 34, no. 1, pp. 129–138, 2010.

[5] E. A. Lee, "Cyber physical systems: Design challenges," in *2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)*, May 2008, pp. 363–369.

[6] M. Grieves, "Digital twin: Manufacturing excellence through virtual factory replication," *URL http://www. apriso. com*, 2014.

[7] G. Schroeder, C. Steinmetz, C. E. Pereira, I. Muller, N. Garcia, D. Espindola, and R. Rodrigues, "Visualising the digital twin using web services and augmented reality," in *Industrial Informatics (INDIN), 2016 IEEE 14th International Conference on*. IEEE, 2016, pp. 522–527.

[8] L. Atzori, A. Iera, and G. Morabito, "The Internet of things: A survey," *Computer networks*, vol. 54, no. 15, pp. 2787–2805, 2010.

[9] I. Ungurean, N.-C. Gaitan, and V. G. Gaitan, "An iot architecture for things from industrial environment," in *Communications (COMM), 2014 10th International Conference on*. IEEE, 2014, pp. 1–4.

[10] U. Eliasson, R. Heldal, P. Pelliccione, and J. Lantz, "Architecting in the automotive domain: Descriptive vs prescriptive architecture," in *12th Working IEEE/IFIP Conference on Software Architecture, WICSA 2015, Montreal, QC, Canada, May 4-8, 2015*, 2015, pp. 115–118.

[11] L. Atzori, A. Iera, and G. Morabito, "Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm," *Ad Hoc Networks*, vol. 56, pp. 122–140, 2017.

[12] G. N. Schroeder, C. Steinmetz, C. E. Pereira, and D. B. Espindola, "Digital twin data modeling with automationml and a communication methodology for data exchange," *IFAC-PapersOnLine*, vol. 49, no. 30, pp. 12–17, 2016.

[13] K. M. Alam and A. El Saddik, "C2ps: A digital twin architecture reference model for the cloud-based cyber-physical systems," *IEEE Access*, vol. 5, pp. 2050–2062, 2017.

[14] M. Shafto, M. Conroy, R. Doyle, E. Glaessgen, C. Kemp, J. LeMoigne, and L. Wang, "Draft modeling, simulation, information technology & processing roadmap," *Technology Area*, vol. 11, 2010.

[15] ——, "Modeling, simulation, information technology & processing roadmap," *National Aeronautics and Space Administration*, 2012.

[16] R. Rosen, G. von Wichert, G. Lo, and K. D. Bettenhausen, "About the importance of autonomy and digital twins for the future of manufacturing," *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 567–572, 2015.

[17] C. Steinmetz, G. Schroeder, A. dos Santos Roque, C. E. Pereira, C. Wagner, P. Saalmann, and B. Hellingrath, "Ontology-driven iot code generation for fiware," in *Industrial Informatics (INDIN), 2017 IEEE 15th International Conference on*. IEEE, 2017, pp. 38–43.

[18] S. Sierla, V. Kyrki, P. Aarnio, and V. Vyatkin, "Automatic assembly planning based on digital product descriptions," *Computers in Industry*, vol. 97, pp. 34–46, 2018.

[19] B. Chandrasekaran, J. R. Josephson, and V. R. Benjamins, "What are ontologies, and why do we need them?" *IEEE Intelligent Systems and their applications*, vol. 14, no. 1, pp. 20–26, 1999.

[20] W. Borst and W. Borst, "Construction of engineering ontologies for knowledge sharing and reuse," Ph.D. dissertation, University of Twente, Netherlands, 9 1997.

[21] L. W. Lacy, *OWL: Representing information using the web ontology language*. Victoria BC, Canada: Trafford Publishing, 2005.

[22] M. Abramovici, J. C. Göbel, and H. B. Dang, "Semantic data management for the development and continuous reconfiguration of smart products and systems," *CIRP Annals-Manufacturing Technology*, vol. 65, no. 1, pp. 185–188, 2016.

[23] K. Yacout, V. Ebrahimipour, and S. Yacout, "Ontology based modeling of a complex real time system," in *IIE Annual Conference. Proceedings*. Institute of Industrial and Systems Engineers (IISE), 2014, p. 3361.

[24] A. J. Trappey, C. V. Trappey, U. H. Govindarajan, A. C. Chuang, and J. J. Sun, "A review of essential standards and patent landscapes for the internet of things: A key enabler for industry 4.0," *Advanced Engineering Informatics*, vol. 33, pp. 208–229, 2017.

[25] M. Ganzha, M. Paprzycki, W. Pawłowski, P. Szmeja, and K. Wasielewska, "Semantic interoperability in the internet of things: an overview from the inter-iot perspective," *Journal of Network and Computer Applications*, vol. 81, pp. 111–124, 2017.

[26] S. Mayer, J. Hodges, D. Yu, M. Kritzler, and F. Michahelles, "An open semantic framework for the industrial internet of things," *IEEE Intelligent Systems*, vol. 32, no. 1, pp. 96–101, 2017.

[27] M. Bermudez-Edo, T. Elsaleh, P. Barnaghi, and K. Taylor, "IoT-Lite: a lightweight semantic model for the internet of things," in *Ubiquitous Intelligence & Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People, and Smart World Congress (UIC/ATC/ScalCom/CBDCom/IoP/SmartWorld), 2016 Intl IEEE Conferences*. IEEE, 2016, pp. 90–97.

[28] M. Compton, P. Barnaghi, L. Bermudez, R. GarcíA-Castro, O. Corcho, S. Cox, J. Graybeal, M. Hauswirth, C. Henson, A. Herzog *et al.*, "The SSN ontology of the W3C semantic sensor network incubator group," *Web semantics: science, services and agents on the World Wide Web*, vol. 17, pp. 25–32, 2012.