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Open semantic modeling for smart production systems

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Abstract

Conventional production systems are evolving through cyber-physical systems and application-oriented approaches of AI, more and more into "smart" production systems, which are characterized among other things by a high level of communication and integration of the individual components. The exchange of information between the systems is usually only oriented towards the data content, where semantics is usually only implicitly considered. The adaptability required by external and internal influences requires the integration of new or the redesign of existing components. Through an open application-oriented ontology the information and communication exchange are extended by explicit semantic information. This enables a better integration of new and an easier reconfiguration of existing components. The developed ontology, the derived application and use of the semantic information will be evaluated by means of a practical use case.

Keywords: Ontology;Semantics;Modelling

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1. Introduction

The advancing fourth industrial revolution leads to an evolution of classical production systems through cyber-physical systems (CPS) to interconnected systems, which are connected via the Internet of Things (IoT) [1]. Application-oriented solutions using artificial intelligence (AI) enable the evolution of cyber-physical production systems (CPPS) into smart production systems [2]. The resulting spanned network of cyber-physical components requires a high degree of communication for the interconnective interaction among each other to exchange information within the system. Thus, the construction of the information network involves an exchange of data, which usually focuses on the content of the factual data. In this process, the semantics of the exchanged data is usually only implicitly considered. However, the system's data's semantics plays an essential role since the extended requirements, such as mutability and flexibility within production, make a basic semantic understanding within the involved components necessary [3]. The interoperability [4-6] is of particular importance because, on the one hand, existing components can be extended. On the other hand, new components have to be integrated dynamically into the overall system.

In this work, an application-oriented ontology architecture for a CPPS is developed. For this purpose, first, a methodology is presented by which the existing system components, particularly the cyber-physical system, are extended by the semantic information. Based on this additional semantic component, the extended communication below the different elements of the CPPS (purely immaterial components and hybrid components, e.g. CPS) is enabled.

Based on this structure, dynamic and intelligent sequence controls can be implemented in addition to integration and reconfiguration [7].

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2. Literature review

This section describes the general use of ontologies and the use of semantic models and information in the context of smart production systems.

2.1. Use of ontologies

There are comprehensive approaches to the use of ontologies in the production engineering environment. A good overview can be found in Usman et al. [8]

In principle, it is possible to distinguish between the
- the meta-oriented,
- the general-oriented,
- the domain-specific and
- the task-oriented

approaches.

Meta-oriented approaches take the approach of modeling the structure of semantics on a higher level. For example, Cabral [9] presents an ontology for modeling business processes. Meta-oriented approaches are only suitable for the application field to a limited extent since the relatively high abstraction level does not support a simple usage for the intended use cases well.

The *general-oriented* ontology approaches attempt to formulate a comprehensive ontology the application domain. For example, Lemaignan et al. [10] provide MASON, a relatively comprehensive ontology for the manufacturing domain. Other examples of comprehensive ontologies are the MOSES ontology [11], CIMOSA ontology , and the FDM ontology [12]. However, the breadth of the approach in general ontology approaches is contrasted by the closed nature of the approaches, as well as the low extensibility in some cases.

The *domain-oriented* approaches are characterized by a limitation to a specific application area. This containment refers either to a particular application domain (functional-vertical) or to a specific application level (functional-horizontal). For example, the FLEXINET ontology [13] supports global production networks and the ARO ontology [14] supports the assembly domain. An ontology related to a specific application layer is, for example, the Automation I4.0 ontology [15], which describes the semantic model within communication networks, such as OPC UA. Domain-oriented approaches are usually characterized by the depth in the application field. This depth may be too extensive for the application in the real environment if necessary. Furthermore, due to the specific character of the ontology, the connectivity to other ontologies is challenging to realize since semantic mappings may have been made differently (content and structure).

With the *task-oriented* ontologies, defined tasks are placed in the center of the consideration. For example, in the approach of Svetashova et al. [16], the ontology forms the basis for machine learning, in this case, limited to the technology of welding. In Cao et.al. [17], states within the manufacturing process are queried and monitored based on the ontology. One possible use is the definition of a structural application domain, such as the description of the production resource's capability, which Järvenpää et. al. [18] perform with the MaRCO ontology.

2.2. Use of semantic models and information

Every ontology needs semantic information and models as a basis to apply to data. To be able to use the ontology uniformly, a formalization is necessary. The *Web Ontology Language* (OWL) [19] s often used as a formal description language.

Ontologies are used in the application context either as analysis or as decision-making tools. For example, semantic information is extracted from augmented sensor data [3, 20, 21]. In this context, the saving of semantic data can be a particular problem, especially when data volume is high [21].

An architecture for the extension and consideration of semantic information, models, and ontologies can be found in Cho [22]. The integration and use of semantic information are shown over various levels of Industry 4.0 components.

In addition to the data-oriented analysis use, ontology also becomes for decision making or decision support. Here, fewer transaction data, but rather a structure and property data are relevant. Thus, using the approach of Järvenpää et. al. [18], manufacturing resources with the corresponding capability can be determined.

2.3. Use of semantic models and information

For the use of ontologies in CPSs and CPPSs, on the one hand, a large variety of relevant ontologies are only redundant to a limited extent, and, on the other hand, the special nature of their use becomes apparent. To maintain or strengthen the autonomy of CPSs, they should be able to access ontologies consistently. Thereby, the semantic information is implemented on the CPS, and an access possibility to semantic information of other CPSs has to be enabled. Due to the different use cases, a single comprehensive ontology does not seem to be sufficient. Thus, access to multiple ontologies available to a hybrid (e.g., CPS) or purely virtual information systems (classical IT systems or, e.g., digital twins) must be enabled. In Figure 1 the ontology-based approach in comparison to pure data or information driven approaches is shown.

2.4. Need for ontologies in smart production systems

Smart production systems are increasingly characterized by a decentralized network structure that enables them to react flexibly to changes from inside and outside [23]. For coupling the smart production system units, knowledge structures are needed in addition to pure data and information exchange to draw the appropriate conclusions. Ontologies enable effective knowledge representation [24], which supports the analysis of the application field, the actual representation as well as the sharing through open interfaces. The benefits of the approach

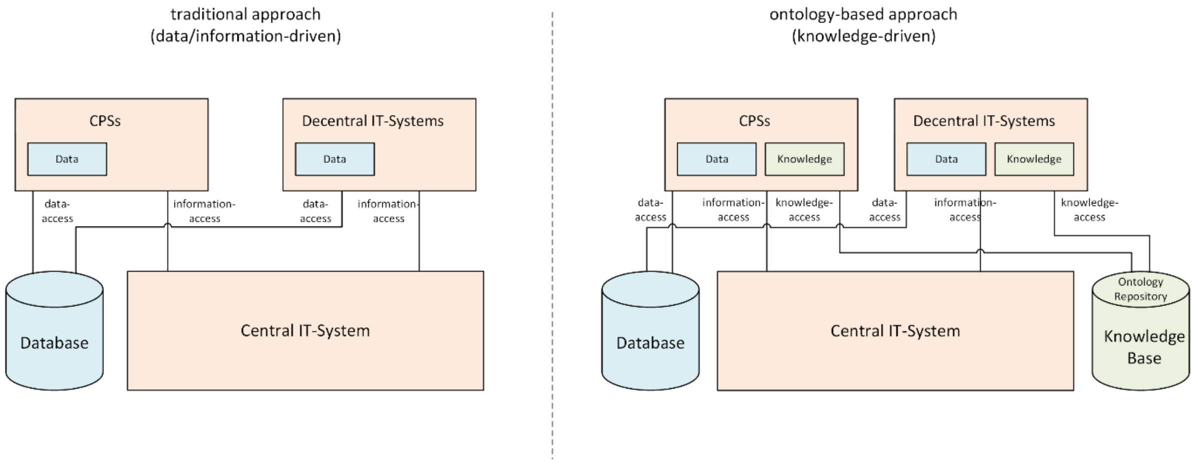


Fig. 1: Ontology based approach vs data/information-driven approach

exceed the disadvantages of the increased effort and the need for a (uniform) definition compared to the pure data or information-oriented approaches significantly [25, 26].

3. Methodology of ontology development and usage for CPPS

The development of an ontology is classically done according to Sure et. al. [27] in the following steps:

1.) Feasibility study
2.) Kick-Off
3.) Refinement
4.) Evaluation
5.) Application & Evolution

It is usually assumed that the ontology is developed from scratch-up.

Since there are already existing ontologies in the application field, as described above, which are to be used and the CPS are also already available, the following modified approach is recommended, divided into the domain-oriented and IT-technical area.

Table 1: Approach

Process-Tasks	Information-Technology
1.) Identify and analyze Use Cases	1.) Setting standards (Language, Communication)
2.) Scan existing Ontologies	2.) Build an Ontology-Repository
3.) Choose, create, or adopt an Ontology	3.) Implementing CPS specific semantic information
4.) Evaluate Ontology	

3.1. Specialist implementation steps

Identify and analyze use cases

To use semantic information, the first step is to analyze and identify the relevant business processes. The use of semantic information always makes sense when either the data or the decision structure exceeds a certain complexity. These can be assignment or selection problems as well as extended analysis questions.

Scan existing ontologies

Concerning the selected problem, it is checked whether there are already existing ontologies in the application domain. For CPS, the ontology has to be chosen according to the technologies realized in the CPS. Here, not necessarily a complete technology has to be adopted in breadth, but only the technology area that is covered by the CPS. In addition to hybrid systems, task-oriented ontologies are usually used for purely virtual systems. These are generally also restricted to a specific task area according to the purpose of the system components.

Choose, create, or adopt an ontology

If no corresponding ontology can be found, an own ontology must be created. The ontology structure is again based on the amount of information and the decision logic of the considered system. For the creation of the ontology, the approach of Sure et. al. [27] can be fallen back.

3.2. IT implementation steps

Setting standards

The standards to be used should be determined before the ontologies are formed and selected. Primarily, the description language in which the ontology is to be defined should be chosen. Due to the extensive use of OWL (see 2.2) in the production-oriented ontologies, this language should usually be the first choice. If existing ontologies are found during scanning (see 3.1.2), which are to be used, it should be ensured

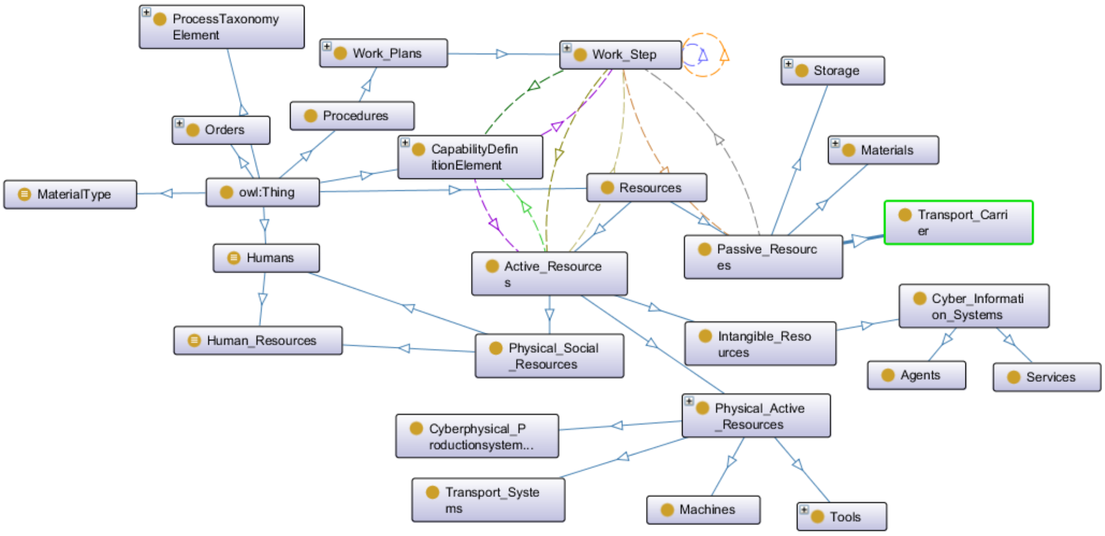


Fig. 2. “Reutlingen Smart-Production-System Ontology” created for use case

that these ontologies can be described in the selected language. The query language for retrieving the semantic information should also be specified in addition to the description language. A prominent representative here is the query language SPARQL (a recursive acronym for SPARQL Protocol and RDF Query Language) [28]. Suppose "intelligent" rule-based decision logic is planned within the overall system or in subsystems. In that case, the language can additionally be specified with which new knowledge can be deductively derived from existing knowledge and logical rules. Based on OWL, the Semantic Web Rule Language (SWRL) [29] offers the best option.

Ontology repository

The entirety of the ontologies must be made available for use by the individual elements of the CPPS. For this purpose, an ontology repository is built where the separate ontologies' formal definition is available. This repository can also store the semantic information of the individual system elements (as instantiated OWL classes). In this case, the ontology repository can be used as a "Semantic Digital Twin" used in a centralized structure. The respective standards defined above must be provided in the ontology repository.

As an alternative to centralized use, the respective semantic information can also be provided in a decentralized manner on the individual system components. In this case, the CPSs have a higher degree of autonomy, but this is countered by more significant implementation effort.

Implementation of CPS-specific semantic information

After the standard has been defined and the ontology repository has been made available, the semantic information is implemented on the individual system components, particularly the CPS. This provides the CPSs with a semantic layer utilizing which information can be made available to others in an extended scope. Also, the CPSs can access other elements in the CPPS and obtain semantic information from them or, in the extended case, deductively derived knowledge. Since there is no restriction to a specific ontology, task-specific semantic information can be used in a high breadth. This further strengthens the autonomy and extensibility of the CPSs.

3.3. Evaluation

After implementing the ontology and the semantic access layer on the individual system components, the overall system should be evaluated. The evaluation should include the examination of test cases for the validation of the existing processes and the examination for extensibility of the ontologies and robustness. Due to the system structure's open nature, increased dynamics compared to closed systems are to be expected. In particular, extended requirements for the CPPS, such as flexibility or mutability, require high-quality communication based on semantic information [30].

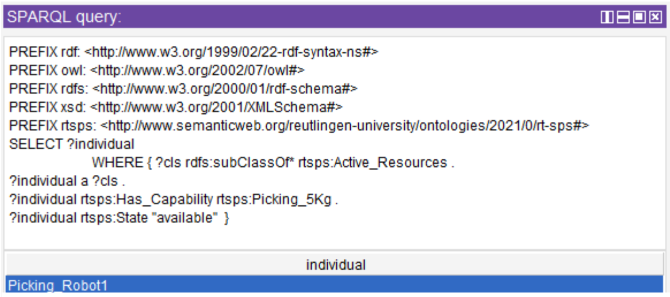
4. Application within the use case

The use case and the application of the Semantic Layer within the use cases are presented below. The use case can be applied and executed within the framework of *Werk150*.

4.1. Initial Situation

The next order to be produced within a street scooter manufacturing plant is determined using a scheduling system. The order determined in this way is forwarded to the first work step stored in the work plan. The following work step sequences apply to the scenario:

1. picking for assembly
2. assembly of the order
3. packing



```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rtsps: <http://www.semanticweb.org/reutlingen-university/ontologies/2021/0/rt-sps#>
SELECT ?individual
              WHERE { ?cls rdfs:subClassOf* rtsps:Active_Resources .
?individual a ?cls .
?individual rtsps:Has_Capability rtsps:Picking_5Kg .
?individual rtsps:State "available"  }
```

```
individual
Picking_Robot1
```

Fig. 3.Sample SPARQL Query to determine active resources

Each of these work steps is performed on one workstation. Each of the workstations can process a maximum of one job. The workstations exist as CPSs that can send and receive information via the IoT.

A scheduling node receives a new job in this scenario. Based on the current processing step in the routing context, the order is scheduled to the station in the routing.

4.2. Use case

The system built this way is not flexible in enforcement. To achieve dynamic enforcement within manufacturing, the scheduling node must know which possible CPSs are available for the next/active processing step. For this purpose, the requirements for the machining step must be made known.

4.3. Technologies used and selection of the ontology

Once the use case has been analyzed, the next step is to define the standards. In this scenario, the IoT framework used is the basis for the communication between the CPS and the virtual (software) components. Protege [31] is used as a tool to describe the ontology. The tool can be used to create and edit ontologies and check queries for SPARQL. As a result, the ontology can be exported to OWL. For the scenario, an ontology for describing a smart production system is created. Figure 1 shows an excerpt of the used ontology.

For the classes used, the requirements were defined as ObjectProperty and the data fields as DataProperty. The properties defined in this way can be queried in the individuals and assigned values. Thus the following requirement for the processing step can be formulated as a condition: Determine an active resource via the next operation, which has the ability to perform the process and is available.

The ontology created in this way will then be exported as OWL in the format RDF/XML and made available. In addition, the MaRCO ontology [18] will be used to determine the capabilities of manufacturing resources.

4.4. Introduction ontology repository

To make the ontology available, an ontology repository is introduced in the Virtual Layer. This repository contains the available ontologies. The scheduling node, as well as the CPS, connect to the repository through the IoT framework. The nodes can query semantic information related to the associated ontology by connecting the nodes to the ontology repository. The repository must also create, read, update, and delete methods for individuals in the ontology.

4.5. Introduction of the semantic layer

Based on the processing step's requirements, the scheduling node matches the assignment to the appropriate CPS. By introducing the semantic layer on the physical layer, semantic information is added to the CPS. For this purpose, the following information is created in the CPS:

1. associated ontology
2. class of ontology
3. call CRUD methods for individual

This information enables the mapping of individuals, which can be queried regarding their requirements. The semantic layer also provides the ability to query the ontology repository. In this way, the scheduling node can query the CPS via the semantic layer.

4.6. Dynamic determination of next CPS

With the available information, it is now possible for the scheduling node to send a request to the ontology repository. For a processing step, the scheduling node can send the ontology repository a request to determine all suitable CPSs for the processing step. The determined set of CPSs are valid and can be selected by the scheduling node as the processing step's target. The processing step is sent to the CPS via the IoT. In this way, a dynamic, request-dependent assignment is achieved utilizing semantic information. The semantic information goes beyond the possible alternatives within a structured work plan.

5. Summary and outlook

In the article, the decentralized ontology-based approach to support CPPS was presented. In contrast to previous approaches, which usually focus on one specific ontology, which is usually only available on one system component, the proposed approach shows how multiple ontologies can be used simultaneously. Furthermore, the semantic information is not exclusively provided centrally, but decentrally on the individual system components such as CPSs.

Based on this approach, both individual CPSs and the overall CPPS system can now be made smarter and more open, supporting decentralized coordination and flexible configurability as key Industry 4.0 features [32].

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