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Dynamic adaption in cyber-physical production systems based on ontologies

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Abstract

The paradigmatic shift of production systems towards Cyber-Physical Production Systems (CPPSs) requires the development of flexible and decentralized approaches. In this way, such systems enable manufacturers to respond quickly and accurately to changing requirements. However, domain-specific applications require the use of suitable conceptualizations. The issue at hand, when using various conceptualizations is the interoperability of different ontologies. To achieve flexibility and adaptability in CPPSs though requires overcoming interoperability issues within CPPSs. This paper presents an approach to increase flexibility and adaptability in CPPSs while addressing the interoperability issue. In this work, OWL ontologies conceptualize domain knowledge. The Intelligent Manufacturing Knowledge Ontology Repository (IMKOR) connects the domain knowledge in different ontologies. Testing if adaptions in one ontology within the IMKOR provide knowledge to the whole IMKOR. The tests showed, positive results and the repository makes the knowledge available to the whole CPPS. Furthermore, an increase in flexibility and adaptability was noticed.

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Keywords: Cyber-Physical Production Systems (CPPSs); Ontology; Adaptability; Flexibility

1. Introduction

Technological advances and a paradigmatic shift towards flexible and decentralized solutions in the field of production systems, have been triggering the development of new approaches [1].

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In building modern production systems with Cyber-Physical Systems (CPSs) and IoT technologies as essential structural elements, the first step was to focus on fundamental design and functionality. Likewise, corresponding architectural approaches (e.g., RAMI 4.0 [2]) have evolved to provide an appropriate structural framework for the functionality and design of the systems. However, within the systems underlying semantic information is mandatory for flexibility, and the corresponding decision logics, are often realized statically in rigid data and decision models. To meet the flexibility requirements, a limitation to the adaptability to the existing data and decision structure is not sufficient. To overcome this limitation, both an explicit mapping of knowledge [3] and the structural adaptability of the knowledge base are necessary. In contrast to existing approaches, which usually rely on one knowledge base, the following approach uses multiple knowledge bases that are used simultaneously to solve a problem.

This paper is organized in five sections. Section 2 provides background on the use of ontologies in the application context of CPPSs. Section 3 describes the use case, considering an adaption across multiple knowledge bases. The fourth section includes the summary and presentation of the results and Section 5 concerns the conclusion and the outlook.

2. Background

This section outlines the necessary background emphasizing the potential benefits of providing semantic information within Cyber-Physical Production Systems (CPPSs). Interconnected machines and software systems in CPPSs lead to ubiquity and omnipresence of data [4]. As a result, the need for approaches that derive useful information from this data, like Data Mining and Machine Learning arises. Even though, the latter technologies are promising for autonomous pattern recognition and prediction, the approaches do not assert meaning to data. Therefore, semantic information technologies are used to provide domain-specific conceptualized and formalized knowledge. Such knowledge representation is indispensable for self-aware cognitive systems [5], which dynamically and autonomously act and react to changing conditions [6].

2.1. Semantic Information in CPPS

Current systems with capsulated information within their control units are limited and are neither extensible nor reconfigurable without a considerable effort [7]. Incorporating new machinery to a production line accordingly means adapting control interfaces manually to integrate the system into a heterogeneous environment. Such implementations require specific domain and engineering knowledge [8]. The use of ontologies increases autonomy and flexibility in future systems. As ontologies are description logic-based machine-readable knowledge conceptualizations they improve the modularity of CPPS [9]. Some advantages are the easy extensibility, inference of knowledge, and semantic reasoning [10].

2.2. Ontologies and interoperability issues

In the manufacturing domain, including its logistics and design disciplines, ontologies generate a significant amount of interest. [9,11–14] provide overviews of existing approaches. Usman et al. [11] state that there is a need for a reference ontology, to enable mutual understanding of different domain conceptualizations, like design or production, in the manufacturing domain. Cao et al. [12] conclude that ontologies potentially solve the interoperability issue in the manufacturing domain but focus on using domain knowledge for condition monitoring applications. Whereas others like Negri et al. [9] focus on extending existing ontologies. Negri et al. [9] develop an internal logistics extension to the Manufacturing Systems Ontology (MSO) concentrating on providing resource concepts, as they identified a lack of production logistics concepts in the MSO. Knoll et al. [15] analyze 67 ontologies focusing on production and internal logistics to develop an internal logistics ontology for process mining. In a previous work[14] categorize different manufacturing ontology approaches regarding their orientation and specification. The four established categories are meta-oriented, general-oriented, domain-specific, and task-oriented. They point out that using ontologies with a distinct purpose and vocabulary is beneficial for different fields of applications, but also results in interoperability issues in a mutual CPPS [14]. Shilov et al [13] clearly point out, that the different approaches have specific advantages, and that there is a need for solutions to integrate different manufacturing ontologies. They respectively present a research framework to build ontology-based decision support models and methods.

Task-oriented ontologies like the logistics extension to the MSO [9] focus e.g. on resources, whereas others like Knoll et al. [15] focus on processes but yet conceptualize the same domain. Consequently, the statement that ontologies solve the interoperability problem in heterogenous production systems as Fumangalli et al. [7] advocate, accounts certainly true within one ontology. However, a manufacturing system needs different ontologies for different purposes.

2.3. Flexible Reasoning through Ontologies

Ontologies as knowledge representation use underlying description logic and thus have the ability to infer knowledge. The Web Ontology Language (OWL) is a widely accepted standard in the Semantic Web, which is built on Research Description Framework (RDF) and RDF-Schema (RDFS) and provides strong reasoning capabilities. OWL organizes information in sets of triples and is represented in graphs [16]. In contrast to relational or non-relational query languages, the inference ability of RDF allows not only querying data, but also allows inferring relationships in the data using semantics. Inserting new knowledge elements using semantic linking does not require changing the data storage structures such as tables or objects. Lemaignan et al. [16] among others demonstrates the usability of OWL for the conceptualization of manufacturing domain purposes.

To retrieve information from ontologies the SPARQL Protocol And RDF Query Language (SPARQL) is used. SPARQL matches graph patterns [17] and allows querying and updating ontologies. Furthermore, adding, and deleting entities is possible.

2.4. Interoperability issue approach

Any given CPPS consists of various CPSs, each with a proprietary knowledge concept, consequently, the interoperability issue presented in section 2.2 occurs naturally in heterogeneous systems. [14] introduces an ontology repository in the application layer, this repository's name is Intelligent Manufacturing Knowledge Ontology Repository (IMKOR). Within the IMKOR, ontologies are linked to provide various concepts for a decentralized ontology based CPPS. The OWL's intrinsic capabilities allow to infer knowledge. Consequently, this knowledge is automatically included in existing SPARQL queries. Accordingly, the approach demonstrates the simultaneous use of different ontologies. For this demonstration, the Reutlingen Smart Production System Ontology (RTSPSO) [14] was developed and integrated into the IMKOR. To further investigate the approach, MaRCO [18] is a suitable candidate for early inclusion in the IMKOR. Besides this ontology's open availability, the approach envisions the modeling of combined capabilities within a detailed yet comprehensive task-oriented manufacturing domain conceptualization. Besides the focus on the capability concept, MaRCO likewise includes a resource, product, and process taxonomy model which allows generic modularization of entities.

3. AGV control in Werk150

Section 3 shows that using the IMKOR and expanding ontologies within it, increases the flexibility and adaptability of a production system. Accordingly, a system was developed and implemented to satisfy such characteristics. Adjusting the control principles in Werk150 demonstrated the adaptability of the whole control system.

For this purpose, this section starts first with describing the initial situation in Werk150. Second, it describes the methodological approach regarding system environment and tools together with system design and development. The third subsection is concerned with the implementation within the use case in Werk150. The subsequent use case demonstrates selecting an Automated Guided Vehicle (AGV) to execute a material transport using semantic information stored in the IMKOR. Furthermore, this investigation expresses semantic information to integrate new AGVs into Werk150's logistics infrastructure. Finally, in this section adapting an ontology in the IMKOR shows the system's extensibility regarding the selection criteria.

3.1. Use case: AGV control in Werk150

In Werk150, various means of transportation perform the material flow of scooter manufacturing. Transport aids, transport containers, and other mechanical and physical properties characterize these means of transportation. The following transportation resources are considered for this application:

1. BeeMini with rack structure
2. BeePallet with pallet pick-up device
3. Neobotix 400 platform
4. KollRo

The BeeMini with rack structure is an AGV that transports material boxes in its rack structure. The BeePallet with pallet pick-up device is an AGV that uses pallets as transport aids. The maximum payload restriction limits the autonomous transport capability. The Neobotix 400 platform is a platform that transports boxes directly from the warehouse to their destination. For loading and unloading these three AGVs require manual execution. The KollRo 4.0 is a collaborative tugger train developed and used in Werk150. The prototype combines an AGV with a collaborative robot to autonomously load and unload suitable transport boxes. All described AGVs' purpose is material supply. Various types of transport aids to store and transport the materials needed for scooter manufacturing exist. These have specific characteristics describing their dimensions as well as their object structure for picking and placing. The following list presents the existing transport aids:

1. Medium size black transport boxes (bm)
2. Medium size gray transport boxes (gm)
3. Small size gray transport boxes (gs)
4. Large size gray transport boxes (gvb)
5. Pallets

Table 1 provides an overview of the restrictions regarding the capacitive transportation capability of the AGV mapped with the dimensions of the boxes holding the materials:

Table 1. Overview of transport cability

Means of transport	bm	gm	gs	gvb	pallet
BeeMini rack	Yes	Yes	Yes	Yes	No
BeePallet	Yes	Yes	Yes	Yes	Yes
Neobotix	Yes	Yes	Yes	Yes	No
KollRo	Yes	No	Yes	No	No

3.2. Design and development of the system

3.2.1. Tools and System Environment

Covering all OWL2 specifications, Protege Desktop v5.5.0 serves to develop and adapt all ontologies in the scope of this project. Furthermore, Protégé allows the development of more than one ontology within the same workspace, which is indispensable for the IMKOR test environment. [19,20]

Werk150 is a Learning Factory environment designed with Smart Factory principles. The factory's purpose is to offer a research environment for the "design, implementation, optimization, and digitalization of partially automated assembly and logistics systems" [21]. Werk150 has AGVs, state-of-the-art ICT- Technologies, 3D- Printers, Collaborative Robots and, lightweight robot systems. With such equipment, the integration of different technological maturity levels envisions learning to master complex high-tech infrastructure challenges. [21]

3.2.2. Proposed System Design

A suitable systems design enables achieving increased flexibility, autonomy, and an optimized material flow in a short-term scope. Fig 1 outlines the system design and illustrates the information flow process. The Logistic Agent is the interface designed to process material transportation requests. As a chatbot, it generates SPARQL queries to retrieve information from the IMKOR, where semantic information is hold within ontologies. An adapted capability ontology is used for conceptualizing transportation capabilities and requirements of the AGVs in Werk150.
The RTSPO describes the CPPS. After retrieving the information, the Logistics Assistant passes it to the Scheduler,

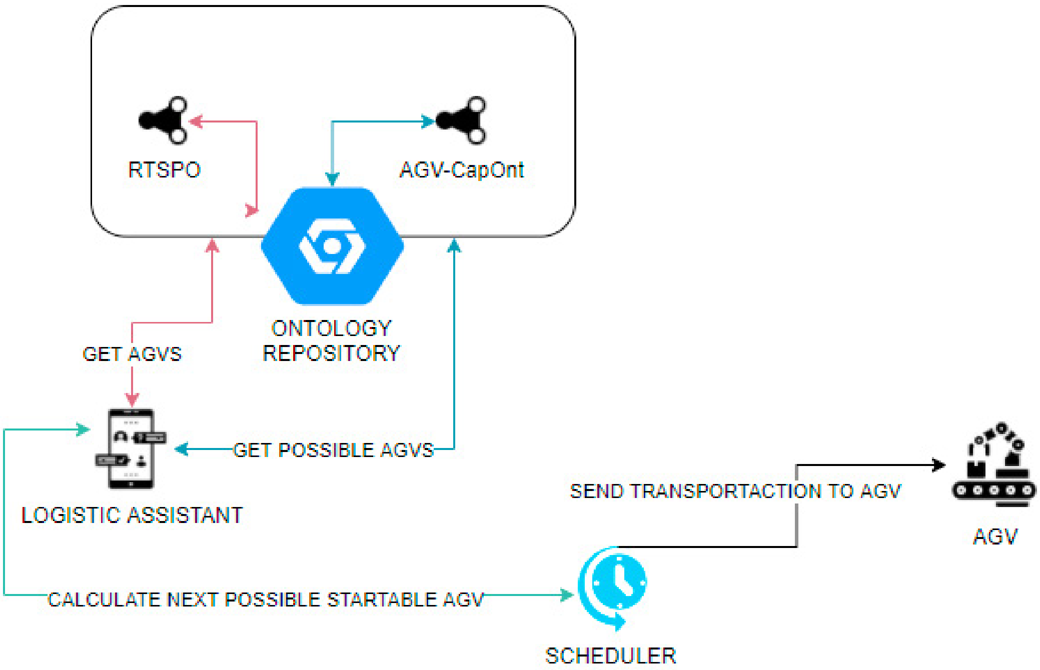

Fig. 1 Process for transport request of a material with AGV selection via the IMKOR and the Scheduler

which selects a suitable AGV and further distributes respective decisions and information.

To develop a suitable ontology for the transportation concepts, the modified approach of the Ontology Engineering Methodology [14] suggests following two different tracks. Accordingly, following the domain and process oriented track led to identifying the MaRCO [18] as a suitable base ontology for the capability-based selection of AGVs. Even tough MaRCO presents exhaustive generic capability concepts, and precise domain vocabulary, adapting the ontology still is indispensable for the AGV modeling. The resulting capability-based ontology hereafter is called AGV Capability Ontology (AGV-CapOnt). Fig. 2 shows the Resource and Capability classes with their instantiated individuals. Asserting data and object properties to individuals defines the individuals' capabilities.

3.2.3. Implementation of the System

After developing the system design and the respective software components, the resulting software in Werk150 was integrated. Adapting transport orders for AGVs considering their capabilities was carried out in a second implementation phase. Completing this phase enables selecting AGVs with specific capabilities that are suitable for specific transportation tasks through mapping to certain orders.

Following, we describe the process execution at the shopfloor. An employee sends a material request via the Logistics Assistant. To identify the transport box type, the system uses the requested material. Based on the transport box, the transportation properties required to execute the transport are derived. Through the ontology, SPARQL is used to derive the transport properties for the transport box. Within a second SPARQL query, the accordingly derived properties are used for the capability checking of the AGV. As a result, the SPARQL query returns a list of suitable

AGVs. The Scheduler receives the data to schedule and execute the selection of an AGV. This selection is based on the scheduling constraints from the passed list. The wizard gets the AGV and displays the scheduled delivery date. Fig. 3 shows the communication of the whole AGV requesting, selecting, and executing process between worker and the Logistics Assistant wizard.

3.2.4. Extension of the System

The in section 3.2.3 implemented capability ontology is extended with new capabilities. The latter enables the CPPS to consider those new capabilities. A new AGV is introduced effortlessly as an individual within the ontology. The AGV provides the properties to the CPPS and updates the ontology around the new individual. It is thereby automatically considered by the SPARQL queries used. For new capabilities, two steps must be performed. First, the new capability must be modeled within the ontology. After the capability is modeled, the expression of the capability must also be supplied by the CPPS. This means that the CPPS must have these new properties assigned as *hasCapability* object property.

An example of this scenario is the introduction of a payload property. In the ontology we are using, we need to insert a subclass *Payload* below the *Capability* class. Next, an instance for *Payload* must be created. In this example, the properties *light_capablity, medium_capablity, heavy_capablity*. Next, we define the object property that the transport boxes will occupy. In this example, the property *hasAllowedBoxWeight*. The properties *light_capability, medium_capability*, and *heavy_capability* get this *hasAllowedBoxWeight* property and allocate the transport boxes. Next, a new *hasCapability* property is created and assigned to the individuals with *light_capability medium_capability* or *heavy_capability*. In this way, the *Payload* capability is now automatically considered during the selection process. Adapting and updating the semantic information at the ontology and CPPS level results in a flexible, capability-oriented selection and extensibility of AGVs.

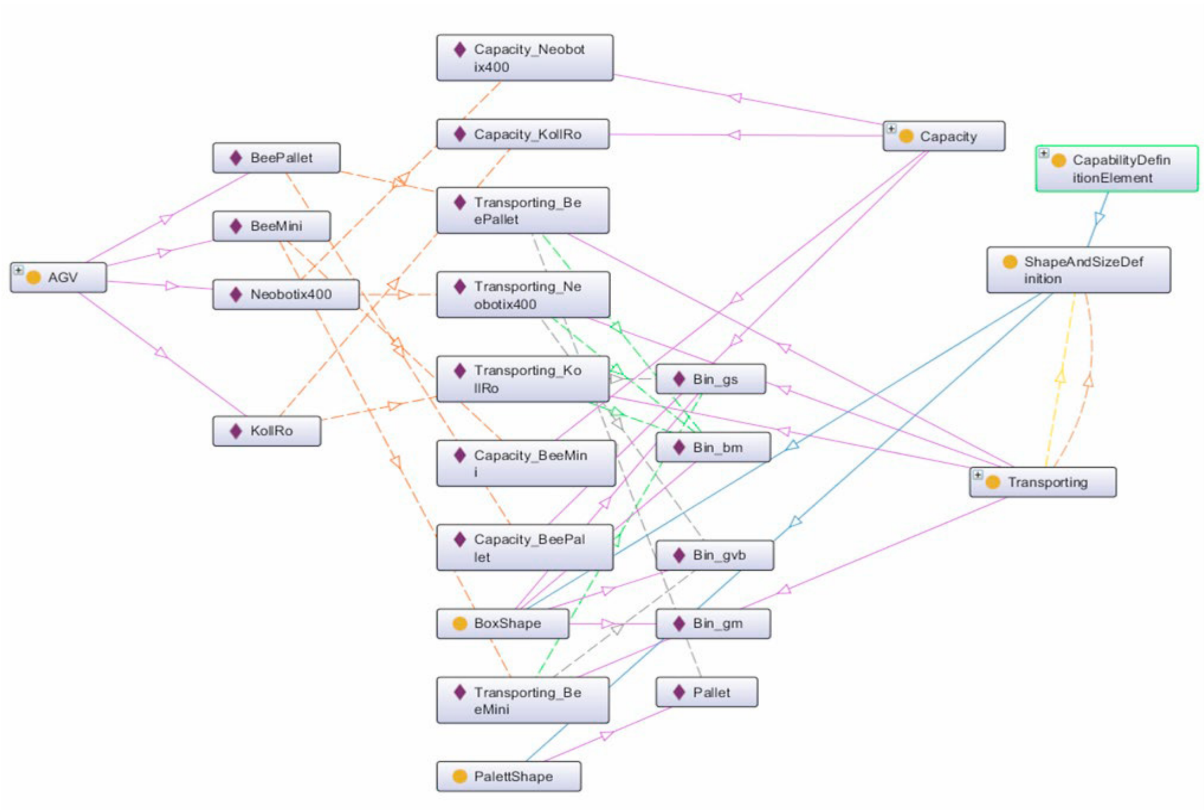

Fig. 2 AGV-CapOnt in Werk150

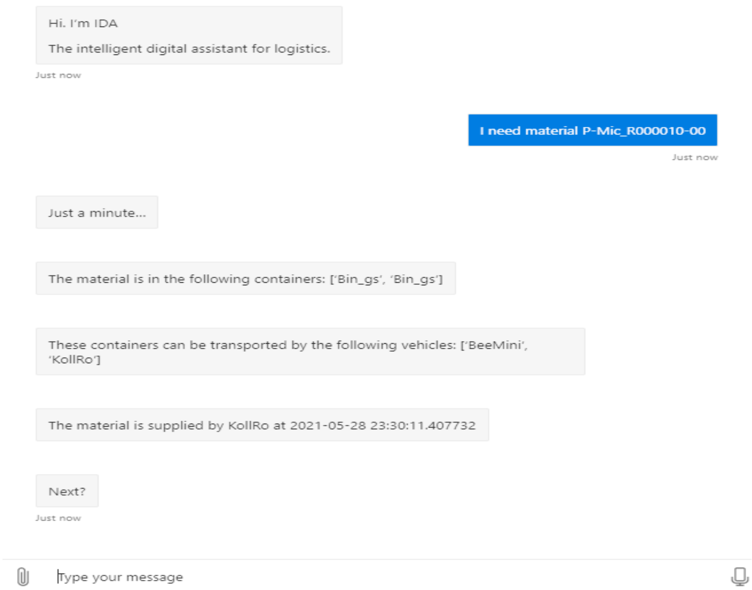

Fig. 3 Result of AGV selection for a transport order via Logistics Assistant

4. Results and Discussion

This work presents the dynamic adaptation within CPPS with the help of ontologies based on the use case "Selection of a suitable AGV." Including RTSPSO and AGV-CapOnt in the IMKOR, demonstrates that querying and incorporating ontologies with distinguished conceptualizations achieves easy adaptability of the CPPS. First a query retrieves the types of the means of transportation and materials from the RTSPSO. A second query uses the accordingly obtained individuals to map their properties and capabilities with the semantic information in the AGV-CapOnt. Subsequently, the Logistics Assistant passes the information to the Scheduler. This corresponds to a dynamic, capability-based assignment of CPSs within the CPPS.

Furthermore, using ontologies and the IMKOR shows that dynamically extending the dynamic constraints is possible. Modeling and assigning a new capability in the AGV-CapOnt demonstrates the latter purpose exemplarily. In contrast to non-semantic storage structures, the maintenance and implementation effort is reduced. A model extension and a query considering the semantic context enables easy addition of new structures.

However, semantic modeling itself is challenging. Furthermore, application scenario limits the use case. Therefore, further investigation in the context of other scenarios in manufacturing, planning, or control is of great interest.

5. Conclusion

Technological changes and more and more flexible solutions within production systems create the challenge of dynamic adaptation within CPPS. The presented approach gives a potential answer for the required flexibility and the constant change of CPS components in a CPPS. Furthermore, ontologies are a part of Machine Intelligence [22] and thus offer an approach for other technologies, such as ML as a pre-or post-process.

However, the approach also shows that an increase in modeling effort in and thus the need for extensive domain-knowledge. Another limitation is the still open integration of the CPS with the IMKOR and the CPPS. Furthermore, the currently small repository limits the semantic information.

However, this work also represents the start of a future platform. The platform idea will help to expand end extend the IMKOR. The growing semantic structure will further enhance, an intelligent, flexible, and decentralized adaptation.

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