Automatic Data Representation Analysis for Reconfigurable Systems Integration

Jiayi Zhang, Bilal Ahmad, Daniel Vera, Robert Harrison
Automation Systems Group, WMG
University of Warwick
Coventry, United Kingdom
{Jiayi.Zhang, B.Ahmad, D.A.Vera, Robert.Harrison} @warwick.ac.uk

***Abstract*—Digital factory modelling based on virtual design and simulation has emerged as part of the mainstream activities geared manufacturing digitalisation and Industry 4.0. Some commercial product and manufacturing process modelling tools are currently integrated via semantic modelling technologies to match product with required processes and resources to achieve production requirements such as volume, cost etc. Despite these achievements, product design is still dependent on the knowledge of designers and do not benefit from existing process and resource knowledge, which are in separate domains. This paper therefore presents an integration method based on semantic technologies and PPR ontologies to reuse existing process and resource knowledge and automatically map it with product attributes and production requirements. The approach will help in improving efficiency of the response to frequently changing products and production requirements.**

Keywords—ontology, semantic, knowledge-based system, system integration

I. INTRODUCTION

Due to the growing need for personalisation and customisation in high volume products, the existing engineering approach to design and manufacture products, and change management is becoming a bottleneck to achieve business goals [1]. To realise customisation and personalisation in high volume products, there is a need for new engineering approaches for managing changes in product and production requirements over the entire lifecycle of manufacturing systems.

Current engineering approach, including complete sets of methods, models and designs covering entire lifecycle, are mostly fragmented and cannot meet requirements of product lifecycle management efficiently and cost effectively [2]. Especially, changing existing manufacturing facility (i.e. manufacturing processes and resources) require significant resources in terms of knowledge and human resources. Additionally, modification of highly complex systems can result in unpredictable conflicts between various aspects of a system. Many researchers proposed to tackle such problems using component-based system design such as reconfigurable or flexible manufacturing systems. Reconfigurable manufacturing system design relies on the reuse of existing knowledge in order to decrease the required skills and configuration, both physical and software, and time to manufacture new products.

To reduce the time to market and risks, a number of digital modelling and simulation tools are adopted by industry to visualise, validate and optimise manufacturing system design. However, for quick iterative design, these tools lack reuse of existing knowledge and data from product, process and resource domain due to the lack of software components integration and semantic meaning mapping. Consequently, the existing engineering approach requires product, process, mechanical and control engineers to carry out a number of design iterations before finalising product and manufacturing system design.

Some applications share editable resources but details may be lost during the data conversion. Usually large amount of data cannot be shared or transferred effectively between different systems, which results in the use of labour-intensive and ad hoc methods for data exchange across different engineering domains [3]. To address this, a systematic and integrated approach is required to help in predicting the impact of design change on manufacturing processes and resources before carrying out physical changes. Thus, a semantic-based data transform approach is used to integrate product, process and resource data in this paper.

In the following sections the authors reviewed ontology and data representation methods and tools to support reconfigurable manufacturing systems' design. Based on previous research and literature review, an integrated knowledge-based design approach is proposed and developed to enable rapid changes in manufacturing systems using a semantic-ontology methodology. A Festo Test Bench is used to evaluate PPR ontology with automatic semantic data representation.

II. LITERATURE REVIEW

A. Reconfigurable Manufacturing System

Flexibility and reconfigurability require capability to change both hardware and software of a system [4, 5]. Modular design concepts are widely used to enable quick changes in both software and hardware. For example, modular processing stations have common input and output connectors based on standard specifications. Typically, modules are designed in a way to perform a specific task autonomously but can be integrated with other modules in various configurations in a plug & play manner to perform a manufacturing process.

Thus, a manufacturing line can be configured from a combination of interacting modules. Each module provides specific functions / services. All possible combinations of these actions / services represent capability of this manufacturing line. Any future requirement can be achieved by adding new modules or reconfigure existing actions / services. Where necessary, modules can be swapped or upgraded to manufacture new products. Additionally, modular resources allow to reduce maintenance and upgrade costs.

However, there are still a number of issues that need to be addressed. For example, a reasonable granularity of modules will improve the performance of the automation system. Excessive granularity in production lines will result in a large number of control interfaces that increase the complexity of mechanical, control and software system, therefore increase maintenance and upgrade costs [6]. Therefore, integrity of reconfigurable automation system relies on a stable and reliable integration strategy.

B. Ontology Technology

Ontology as a conceptualised logic specification is being extended from Artificial Intelligence (Computer Science) to a number of research areas [7]. At the same time ontology is being widely used in the Semantic Web and the World Wide Web. Ontology-based systems are suitable for rapid update of knowledge system, such as dynamic scheduling, Integrating the Internet of Things (IoT) metadata and flexible manufacturing systems [8]. This method is also constantly being evaluated in product design and manufacturing field via the sharing of information and engineering knowledge. Ontology specialises in knowledge management, re-use knowledge and the ability to handle complex dependencies between different engineering domains. Ontology-based methods provide an excellent opportunity to share information at application and system level.

Ontology provides a common language to describe the concepts in different domains and focus on the relationship between those concepts to assist in the information sharing and knowledge translation [9]. It is also defined as a set of terms and categories which gives specific attributes and relationships in a particular field or domain [10]. Some existing Reconfigurable Manufacturing Systems (RMS) are using ontology-based design method to integrate manufacturing resource and real-time task management. Such as Manufacturing Cyber-Physical System (MCPS) reconfiguration[11], Capability-based Framework[12]. However, current ontology design methods are focus on a particular scenario which cannot be widely used in other systems.

To reuse other ontology in assembly system, GRACE system use the Java Agent Development Framework (JADE) to extract information and map data with ontology[13]. Although this solution solved information mapping issues, all generation classes and rules are created by hard coding. The flexibility of GRACE system has a limitation when facts are changing. Thus, semantic-ontology methodology is able to address automated information extract and match.

C. Semantic Transformation Tools

Despite on the advantages of ontology technology, traditional industry data are still stored in SQL or NoSQL database which are difficult to represent at the ontology [14]. Semantic transformation tools enable sharing and reuse of knowledge structures to support the integration and analysis of existing data sets. Thus relational databases-based conversion tools became an ideal method to improve ontology development efficiency, such as DB2OWL, RDB2Onto. The tools address the time-consuming ontology development process faced by knowledge engineers [15].

DB2OWL is a conversion tool that can automatically generate ontologies from relational databases via mapping database tables and description logics using OWL-DL language [16]. In DB2OWL, data are translated to equivalent ontology components. For example, tables are represented as classes in ontology description; columns and rows are represented by properties and instances; the relations in database schema are relationships between ontologies domains. The advantage of this tools is to automatically generate records for logging ontology mapping processes including (1) each corresponding description for ontology components, (2) conceptual relationships between ontologies and databases, and (3) mapping history of instances and attributes [17]. However, this tool cannot translate semantic rules to ontologies. As a result, engineers still need to create rules for each components by hand.

The automatic generation of ontologies are usually focused on mapping relational databases with ontology concepts, such as DB2OWL, D2R and R2O [18]. RDB2Onto is a SQL query-based RDF/OWL translation tool which can be used to transfer existing data to ontology templates using only SQL queries [19]. To analyse XML schema in ontology template, data is merged to an ontology data format. This tool is developed in JAVA using Sesame and Jena library which support SPARQL to connect an ontology with a MySQL database, but it can also be used for other relational databases. The advantage of this solution resides in its simple and easy operation through a graphical user interface [20]. RDB2Onto also provides an excellent opportunity to customise instances and create decision-making rules using ontology library. But current tools are focus on data mining and analysis. For reconfigurable systems, semantic-ontology methodology has to include automatic rules generation for assembly system.

III. Development of Semantic-Ontology Methodology

In this section, a knowledge-based design framework is described to support a semantic-based predictive methodology. Additionally, a detailed system ontology design is also presented for supporting the semantic part in this methodology. PPR integration which enables building advanced predicting algorithms is explained in the last part of this section.

A. Requirements for an Integrated Knowledge-based Design

Based on the analysis of existing design methods and flexibility of ontology and semantic method to support design and reconfiguration of manufacturing systems, the authors propose that product design combined with a robust integrated reconfigurable design architecture should meet the following requirements:

- The integrated design methodology to support efficient reconfiguration should incorporate product, process and resource models, so that designers can make use of these knowledge sets at an early stage of product design. In addition, to evaluate actual design and manufacturing processes, processes must be decomposed into elementary activities and associated with product components and features. This will allow one-to-one mapping of product model to the process model and vice-versa. This will help in modularising product, process and resource design and improve the efficiency and reuse of such models.

- Decision making modelling (such as process prediction modelling) capabilities should be embedded in the early stage of product design to perceive the impact of product design on processes and resources. In order to evaluate different product design concepts based on existing processes and resources, such process prediction models should support methods for assessing uncertainty and risk in decision making. It should also reflect on the changes associated with complex and varied processes due to lack of appropriate resources, increased workload, etc.
- This methodology should support the agile semantic query using semantic technologies. Based on natural language analysis, data query should not limit on SQL query format which is difficult to understand for end users. Intelligent search engine can translate user query to SPARQL query automatically by semantic translation.

B. Methodology Development

Data acquisition is the first step and aims at collecting data from independent database or file system. Fig. 1 provides a data map for system integration and decision-making tools. Data collection focuses on gathering any relevant data and models from manufacturing systems which may contain different formats, languages, and even file types. In order to accurately locate the knowledge, semantic transformation is a key step to define suitable concepts, categories, and domains using semantic technology. Then, data integration focuses on checking the existing knowledge library and add new knowledge to expand the existing information system. Meanwhile, knowledge integration reduces redundant data for saving data analysis costs and decreasing ontology mapping difficulty.

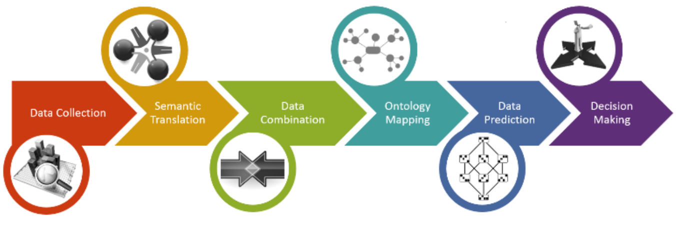

Fig. 1. Data Process Flow

Ontology mapping takes advantages of ontology and semantic technology to achieve automatic linking of data with ontology structures in order to implement a rule-based relational knowledge model. Furthermore, reasoning engines can attach unknown logic and relationships to a known knowledge system in order to analyse possible changes and related restrictions. Rule-based data prediction modules is an important step in implementing artificial intelligence for this framework. A well-built rules development, therefore, would be completed by experienced engineers for product design, process assembly, and resource planning areas. Typically, decision are made by human relying on their knowledge. Through the analysis of existing models and data, intelligent engineering integration provides more robust and reliable decision-making suggestion based on requirements and available resources. Besides, ancillary decision-making system will reduce the cost of decision making and the need for expert knowledge required by decision makers.

The vueOne manufacturing process planning tool set is an update of the lightweight system integration tools, previously called Core Component Editor (CCE) tool set. CCE tool set provided a powerful 3-D simulation engine to simulate manufacturing process with minimum cost and also integrates product, process, and resource data which is a suitable platform to achieve a new generation of industrial solutions. However, vueOne tool was only designed to achieve integration of product, resource and process information. Besides, product import and model export follow the traditional data storage models which is recognised based on a specific attribute (product type or concept classification) and cannot distinguish same product with different expression, such as product name or file name. Furthermore, there is no explicit relationship between products, processes and resources. Process engineers have to manually provide process states, transitions, and conditions with for each product and resource. This problem is common to most manufacturing engineering environments. DELMIA integrates a large amount of industrial data and has achieved knowledge-based manufacturing process model. But a lot of manual process and, user experience and industrial knowledge is required to build models.

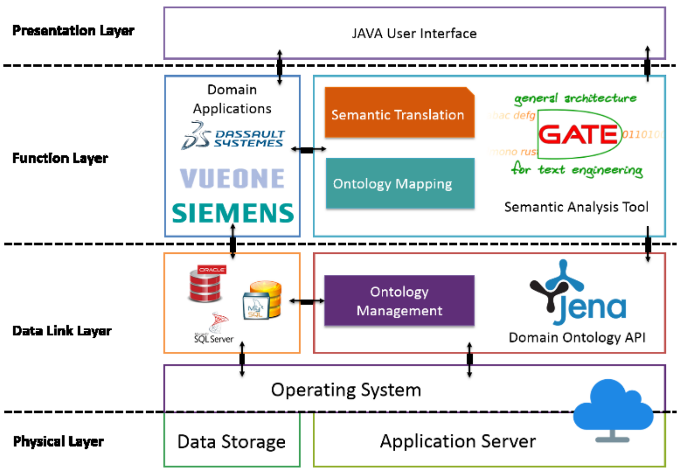

Fig. 2. Reconfigurable System Structure

C. Rapid Reconfigurable Automation Framework

The rapid reconfigurable automation framework uses an ontology-based semantic model to integrate different engineering domains and their corresponding data sets, including product geometry, process sequence and resource capabilities (see Fig.2). The semantic translation model translates simulation models of assembly systems to semantic data that can be uniquely identified. After mapping semantic data with ontology, product data is linked with relevant process and resources data. Thus, each change in the product model automatically link and identify its impact on relevant process and resource data.

The knowledge can be retained by the inherited methods and can be enhanced by reconfiguring and analysing manufacturing systems. Rapid reconfiguration is does not just allow integration of the data models, but also enables the generation of new processes and resource requirements for new product variants.

D. High-level PPR Ontology

The high-level PPR ontology is defined as follows: Business Case, Component Role, Component Type, Process Component, Product Component, Cost Component, Delivery Method, Liaison, Liaison Type, Product Volume, Required Test, Resource Component, and Scenario (see Fig. 3).

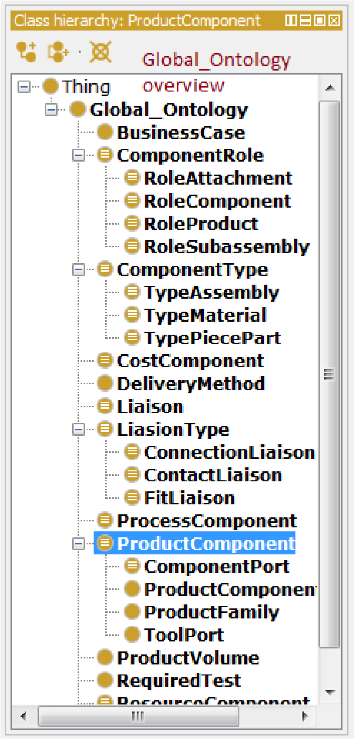

Fig. 3. Global Ontology Overview

Business Case contains all automation system and business logic for each automation system which is also a human readable index of global ontology to help ontology developers to find the correct ontology library and instance. The product ontology describes the details concepts for business case and product specification under the manufacturing system framework. The process ontology explains the process definitions and process requirements for each process steps. The resources ontology is used to outline all available resources and the capability models with specific manufacturing process requirements. Most important, the system environment is set up as a small cloud services platform to facilitate access for different users.

IV. Case Application

To verify this ontology-based PPR integration, a Festo test bench was used as the first case study to define the basic manufacturing concepts and verify the modelling of ontology integration and semantic transformation. This section provides an overview of the implementation of basic ontology design and data representations based on the methodology presented in previous sections with a focus on the Festo Rig case study.

A. Festo Rig Assembly System

The Festo test bench, shown in Fig. 4, used for this cause study is a scaled down version of a realistic automation system with sufficient complexity to represent a real manufacturing process used within industry for effective evaluation of the research concept. The test bench consists of four stations, i.e. Distribution, Buffering, Processing and Handling stations. The test bench can handle a number of part variants and perform a number of manufacturing processes which are carried out through various resources (i.e. actuators and sensors). Typically, a number of changes are required to manufacture a new variant of a product. These changes have impact on the associated processes, resources and their performance. One of the major goals, therefore, is to integrate product design data with factory system analysis and simulation, so that production line analysis can be done at an early design stage.

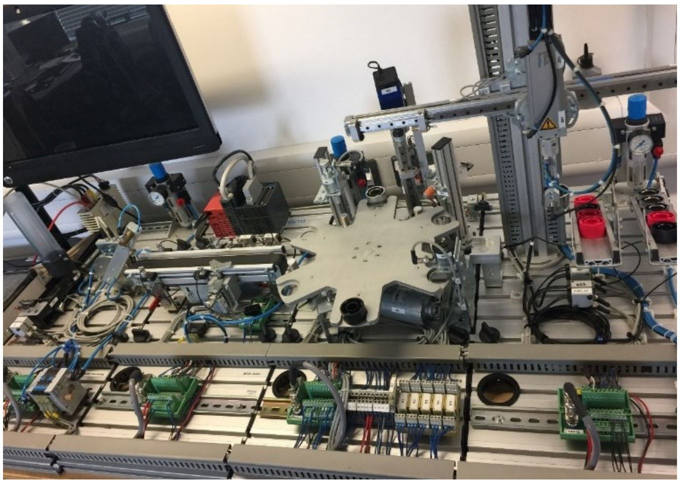

Fig. 4. Festo Didactic Test Bench

In this case study, integrated product, process and resource ontologies were used to support decision making in terms of product design and to predict processes and resources requirement changes after product design changes. All data and the structure of ontologies were changed based on different requirements, for example actuators' cycle time, high volume processes, and process costs. The main aim for this case study is to create a suitable and extendable ontology structure for automation system process to test the capability of ontology integration compared to traditional manufacturing 3D simulation approaches. Moreover, case evaluation focus on SPARQL query evaluation and product-process-resource-requirement ontology validation.

B. Semantic Translation Data

Real-time data processing and exchange are possible based on advanced web technology and network support. However semantic-based information exchange is still in a development stage in the existing operating system layer and application layer. Semantic web provides an extension of the web technology which gives an accurate meaning of information in different semantic contexts to enhance computer and human interoperability. Machine readability improves the comprehensibility of information and improve the accuracy of information dissemination. Machine readable data describes metadata of resource for retrieval, filtering, or inheritance of human knowledge.

The objective of semantic data is to translate data to meaningful data, so that semantic software can recognise and process intelligent queries, knowledge representations and predictions. To understand the meaning of data, semantic software is required to accurately understand the meaning of each word, sentence, and paragraph. Therefore, three basic things are considered in the semantic web: language, grammar, and query process. The detailed elements for representing semantic data on this case study are described in the following sections.

Semantic Language provides an automated translation method and gives the meaning to the data based on ontology structure. Ontology structure is a pre-defined knowledge representation including concepts, semantic logic and basic relationships (see Fig. 5). With the help of semantic language, ontology can be accurately identified, analysed and connected to a single domain or different domains of interest. The shared ontology is integrated into a robust ontology unit to support expansion and compatibility with certain projects. In order to achieve automatic semantic translation, semantic language already supports artificial intelligence using semantic dictionaries to define the logic of the topic data and terminology as well as the rules to automatically retrieve information and establish the relationship between each data to implement intelligent learning and expansion. An ontology is developed and used using semantic language for the following purposes:

- Reuse knowledge: reusing ontology to expand the previous version, transpose ontology to support another problem in different context;
- Share knowledge: sharing information structure or semantic layout for other domains of ontologies.
- Simulate a domain: building a pre-designed ontology library and verify the feasibility of the solution.

In this research, semantic language is used for retrieving information from product-process-resource XML files and utilise each component for explicit PPR data representation on the process simulation tool. Semantic language can enhance the automatic capture and identification of information, including but not limited to text documents, tables, CAD files etc. Informal ontology structure obstructs reusing and sharing ontology, so ontology is usually encoded as a common format which software can understand and maintain easily. In this case study, RDF is used as the default ontology structure which can be edited and described by semantic software (GATE).

C. Document Processing

The Information resources describe a series of related documents in the same domain or project, such as text documents, CAD files. These documents describe ontology specific events, time and relevant resources. Electronic documents used for this case study are in XML formatted files that contains extensible product, process, and resource information. Thus, standardised information modelling is necessary for establishing a unified and structured information exchange standard. In industry, textual information is usually captured from the software export file, process planning table file, word documents, etc. This section will explain the document processing for semi-structured XML files and transforming it into plain text.

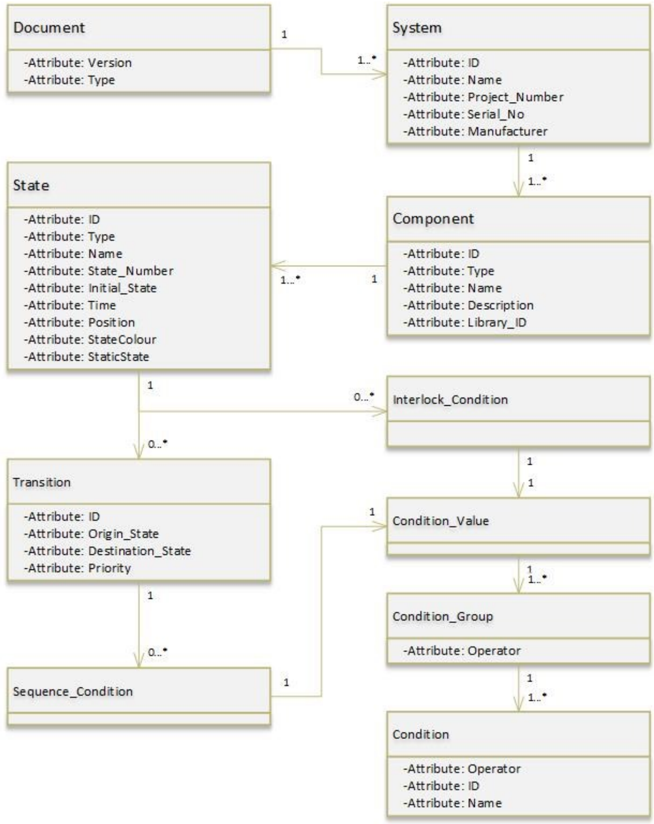

Fig. 5. Ontology Data Structure

The pre-processing task consists of automatically transforming irregular structures into a machine-readable unified text structure using semantic analysis model. Through the analysis of unstructured XML tags, text information can be translated as elements, components, and attributes. Based on components' type, the properties of components are assigned as product, process, and resource. The attributes are also different for each component types. For example, process component has States which contain Initial State, Time, Position, Transitions, etc. In order to improve the robustness of the semantic analysis model, the semantic analysis of XML tags is based on the text itself rather than XML parsing. Therefore, this model can also be applied to normal language text analysis and structured data analysis.

D. Parsing and Filtrating

In this case study, documents represent a collection of systems and components including product, process and resource. If S is a system, S will be split into several components after pre-processing. As an extensible mark-up language, customised labels can be presented in different forms or languages to help in human's readability. This increases the difficulty of automatic computer identification and classification. Thus, each label is treated as a phrase or as a sentence. Syntactically, a sentence is composed of several words which have the weakest semantic relationship but are the most easily identified and divided from documents. The part-of-speech (POS) of each word is the key to address syntactic and semantic meaning. In addition, part of speech is usually divided into eight parts, but the basic grammar and industry documents can focus on five important parts of speech, such as the noun, the pronoun, the verb, the preposition, and the conjunction. Therefore, automatically tagging POS and tagging related semantic tags are the first step in semantic analysis.

POS Tagging: In natural language analysis, POS and text can be automatically tagged and prepared for higher level analysis. Although POS tagging is not the first step in text analysis, it is important in many scenarios, such as POS disambiguation, knowledge management, and sentence reconstruction. Rule-based POS tagging as an automatic natural language analysis tool is used in this case study. Other automatic identification methods include probability method, statistical method, neural network method and Markov chain model. Due to availability and scalability, rule-based POS tagging method is the primary method of analysis and it can achieve document analysis requirements.

Gazetteer Identification: Gazetteer is a predefined customised term and phrase list which contain a set of words with major instead of information extracted from current document. Majors are used to tagging phrases, such as location, date, and product name. Users can define gazetteer list as a dictionary to describe each system or production line. Each gazetteer list includes major category, minor category, language, and annotation type. Feature type and attribute value explain the property of each word or phrase for further ontology generation.

V. Conclusion and Future Work

This paper provides an overview of the features of current reconfigurable manufacturing system and semantic-ontology tools. Based on each component (product, process and resource), manufacturing data can be stored in ontology format, but data transfer is not simple task for engineers. To enable data transfer and integration, this paper proposes a semantic-ontology methodology to improve reconfigurable system integration. This method not only transfers PPR data to semantic data, but also integrates PPR data into an accurate ontology category and property for predicting system changes based on change in product and production requirements.

In the future, this method will be integrated into vueOne 3Dsimulation tool to provide flexibility of re-configurability during system design. Also, an editable gazetteer library will be embedded into vueOne editor to support additional manufacturing systems' design.

Acknowledgment

The authors gratefully acknowledge the support for this work from UK EPSRC, through the Knowledge-Driven Configurable Manufacturing (KDCM) research project under the Flexible and Reconfigurable Manufacturing Initiative.

References

[1] Malheiros, P., P. Costa, A.P. Moreira, and M. Ferreira. Robust and real-time teaching of industrial robots for mass customisation manufacturing using stereoscopic vision. IECON'09. 35th Annual Conference of IEEE. 2009.

[2] Demoly, F., et al., Product relationships management enabler for concurrent engineering and product lifecycle management. Computers in Industry. 64(7): p. 833-848, 2013.

[3] Wu, Y., F. He, D. Zhang, and X. Li, Service-oriented feature-based data exchange for cloud-based design and manufacturing. IEEE Transactions on Services Computing, 2015.

[4] Brusaferri, A., A. Ballarino, F.A. Cavadini, D. Manzocchi, and M. Mazzolini. Cps-based hierarchical and self-similar automation architecture for the control and verification of reconfigurable manufacturing systems. Emerging Technology and Factory Automation (ETFA), IEEE. 2014.

[5] Yousuf, S. and A. Gordon-Ross, An automated hardware/software co-design flow for partially reconfigurable fpgas. p. 30-35, 2016.

[6] Cavin, S. and N. Lohse. Multi-level skill-based allocation methodology for evolvable assembly systems. Industrial Informatics (INDIN), 12th IEEE International Conference. 2014.

[7] Pradhan, A.M. and A.S. Varde. Ontology based meta knowledge extraction with semantic web tools for ubiquitous computing. Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), IEEE. 2016.

[8] Cheng, H., L. Xue, P. Wang, P. Zeng, and H. Yu. Ontology-based web service integration for flexible manufacturing systems. Industrial Informatics (INDIN), IEEE 15th International Conference. 2017.

[9] Giovannini, A., A. Aubry, H. Panetto, M. Dassisti, and H. El Haouzi, Ontology-based system for supporting manufacturing sustainability. Annual Reviews in Control. 36(2): p. 309-317, 2012.

[10] Guarino, N., D. Oberle, and S. Staab, What is an ontology?, in Handbook on ontologies. 2009, Springer. p. 1-17.

[11] Wan, J., et al., An ontology-based resource reconfiguration method for manufacturing cyber-physical systems. IEEE/ASME Transactions on Mechatronics, 2018.

[12] Antzoulatos, N., et al., Towards a capability-based framework for reconfiguring industrial production systems. IFAC-PapersOnLine. 48(3): p. 2077-2082, 2015.

[13] Leitão, P., N. Rodrigues, C. Turrin, A. Pagani, and P. Petrali. Grace ontology integrating process and quality control. IECON 38th Annual Conference on IEEE Industrial Electronics Society. 2012.

[14] Tan, D.-P., L. Li, Y.-L. Zhu, S. Zheng, and X.-Y. Jiang, An embedded cloud database service method for distributed industry monitoring. IEEE Transactions on Industrial Informatics, 2017.

[15] del Mar Roldan-Garcia, M., J.J. Molina-Castro, and J.F. Aldana-Montes. Ecq: A simple query language for the semantic web. Database and Expert Systems Application. DEXA. 19th International Workshop. 2008.

[16] Altowayan, A.A. and L. Tao. Simplified approach for representing part-whole relations in owl-dl ontologies. IEEE 12th International Conferen on Embedded Software and Systems (ICESS). 2015.

[17] Jayakumar, P. and P. Shobana. Creating ontology based user profile for searching web information. Information Communication and Embedded Systems (ICICES). 2014.

[18] Barrasa Rodríguez, J., Ó. Corcho, and A. Gómez-Pérez, R2o, an extensible and semantically based database-to-ontology mapping language. 2004.

[19] Octaviani, D., A. Pranolo, and S. Othman. Rdb2onto: An approach for creating semantic metadata from relational educational data. Science in Information Technology (ICSITech). 2015.

[20] Laclavık, M. Rdb2onto: Relational database data to ontology individuals mapping. in Proceeding of ninth international conference of informatics. 2007.