INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

ONTOLOGY IN DESIGN ENGINEERING: STATUS AND CHALLENGES

Lim, Soon Chong Johnson (1); Liu, Ying (2); Chen, Yong (3)
1: Universiti Tun Hussein Onn Malaysia, Malaysia; 2: Cardiff University, United Kingdom; 3: Shanghai Jiao Tong University, China

Abstract
Nowadays, the wide adoption of affordable ICT hardware and software solutions has fundamentally changed how product design information is being created, shared, stored and retrieved. Due to numerous issues related to heterogeneous system implementation and design information retrieval, ontology has been identified as a feasible modeling solution for rich design information and knowledge representation. From the literature, ontology has been widely applied in various areas of design engineering, both in the academia and industry applications. In line with the latest development in both fields, this paper attempt to provide the status quo on ontology applications for design information and knowledge management. We report our reviews and findings in a number of perspectives, that includes ontology engineering, major applications of ontology in design engineering and the state of ontology adoption in the industry. Based on these outcomes, a number of challenges, research issues and potential directions of research concerning the application of ontology in design engineering have been discussed and suggested.

Keywords: design informatics, Design engineering, Knowledge management, ontology

Contact:
Dr. Soon Chong Johnson Lim
Universiti Tun Hussein Onn Malaysia
Dept. Of Engineering, Faculty of Technical & Vocational Education
Malaysia
johnson@uthm.edu.my

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Since the early 60's, computational support tools and technologies such as computer-aided design (CAD) and drafting, computer-aided engineering (CAE) and parametric design has helped design companies in achieving speed, accuracy and cost reduction in their design process. With the advancement in information and communication technology (ICT) peripherals and relatively lower cost of ownership, design companies nowadays are able to gain competitive advantage from these tools. The adoption of various computational support tools by design companies have shaped how product design information is being created, shared, stored and retrieved. Design information refers to information generated during the course of a design process, such as design specification, functional description, material list, manufacturing planning and production data. With the sheer amount of information generated from computerized design tools and stored in product database systems, organizations are faced with the challenges in managing these large amounts of design information. The main purpose of managing these information is for efficient storage, retrieval, as well as to discover meaningful knowledge for timely decision making.

Nevertheless, before these aims can be fulfilled, there are two main issues that need to be addressed from our perspective. Firstly, design companies commonly adopt heterogeneous design systems. Given different system solutions that are offered in the market, it is not uncommon for a design company to implement more than a single system. In fact, it was revealed that a typical design organization may implement 7 to 12 information systems (IS) that are tailored for different needs (Hicks et al., 2006). Information exchange between systems is usually difficult due to different proprietary data format and model representation. While open standards for geometrical data exchange such as IGES and STEP offer a plausible solution, design parameters and design intent are usually lost in the conversion process. Data management wise, product data management (PDM) is a widely implemented database tool that enables quick and secure access for multiple stakeholders. Similar to PDM, product lifecycle management (PLM) is the successor of PDM that allows a more comprehensive view of a product’s lifecycle.Since both PDM and PLM systems are essentially document-oriented database systems,they are limited in capturing the dynamic design process (e.g., design history) and know-how (Catalano et al., 2009). In other words, PDM and PLM systems focus on managing file operation and are unable to fully cater the needs of designers during the design process. Current PDM or PLM systems mainly support document-based retrieval and are still not fully capable of discovering information (e.g., design knowledge or insights) that are essential towards a successful design.

Secondly, computational tools should be able to cater for designers' needs during a product design process. Typically, design engineers spend a significant amount of time searching for the right information during the design process. From previous literature, it was discovered that more than 75% of design activity comprises reuse of previously existing knowledge (Hou and Ramani, 2004), and design engineers often sought solutions from past design cases in solving their design problems where they spent 20% to 30% of their time retrieving and communicating design information (Court et al., 1998). All these findings suggest that a decent design information search and retrieval system that supports both experienced and novice designers in identifying key information during the design process is essential. Apart from this, it is increasingly common that designers need to consider other non-product information, such as public opinion or economic census data, to make better decision on their product offerings. However, the challenge here lies at how these “open data” can be best amalgamated with existing product know-how to maximize organizational benefits.

In order to address these two pressing issues, a unified information model that allows interoperability of design information across different IS for efficient search, navigation and retrieval is essential towards streamlining the design process. With respect to all these requirements, ontology is identified as a feasible information modelling approach that possesses rich knowledge representation capabilities for comprehensive design information and knowledge management. Ontologies are the basic building blocks of Semantic Web where it allows the mapping of information across different perspectives. The ability of ontology to describe multiple semantic relationships between concepts and entities within ontology, as well as to other ontologies, allows design information to be semantically modelled and promote new perspectives of design knowledge reuse.

We have previously presented a critical review on ontology applications in design engineering in the year 2011 (Liu and Lim, 2011). From our last paper, we have anticipated the rising interests and efforts in realizing the Semantic Web for design engineering using ontology in the design community. In line with our predictions, there are already a substantial number of works that have illustrated the advances of ontology modelling and applications in different areas of design engineering. Modelling wise, there are a number of works that have focused on domain ontology design (Catalano et al., 2009, Liu and Hu, 2013) and new ontology development approaches (Chen et al., 2013, Cross and Bathija, 2010). In terms of applications, ontology is also being used in new areas such as design rationale (Liu and Hu, 2013) and design problem formation (MacLellan et al., 2013). While the number of research works have been growing in the academia, we have also begin to witness efforts from the industry where ontology is being embedded in several design software applications (IHS, 2013, Dassault Systemes, 2014) as well as notable industrial efforts towards standardizing ontology design for design applications (Teijgeler, 2013).

In light with the latest development both in the academia and the industry, we reckon that there is a need to review the latest development, issues in ontology development and applications, as well as identifying possible future research directions and applications in the design engineering domain. In this paper, we attempt to provide an overview on the status-quo of ontology for information and knowledge management in design engineering. The rest of this paper is organized as follows: In Section 2, we present an overview of ontology engineering approaches. Key applications of ontology in design engineering are summarized in Section 3. Section 4 is focused on elaborating the rising adoption of ontology in industrial design engineering systems. Section 5 discusses about the challenges and research issues surrounding various aspects of ontology applications in design engineering. Finally, Section 6 concludes.

2 ONTOLOGY ENGINEERING

Ontology consists of a set of concepts, axioms, and relationships that describe a domain of interest, and can be regarded as an explicit specification of a shared conceptualization, that can be taxonomically or axiomatically based (Gruber, 1995). We view the ontology design perspective from two angles: design for formalization of generic engineering knowledge and design for specific domain of engineering applications. The first perspective involves efforts to create ontologies that conceptualize generic knowledge. These ontologies are mostly developed based on extensive domain literature studies that aimed for representing domain specific knowledge at a higher level of abstraction for knowledge generalization. Some of the examples are such as the Cyc ontology and WordNet. In contrast, some of the early related works of ontology application in design engineering domain are meant for the purpose of systematizing specific domain knowledge, that includes defining and developing ontology for product configuration (Soininen et al., 1998), part and assembly port ontology (Liang and Paredis, 2004) and ontology of functional knowledge (Kitamura and Mizoguchi, 2003). On the other hand, there are also application specific ontologies. Not intended for comprehensive knowledge generalization, these ontologies are created based on the needs to solve specific issue in design engineering. For instance, the creation of ontology for camera product family by Nanda et al.(2006), ontology for shape processing (Catalano et al., 2009) and ontology for capturing evolving design rationale (Liu and Hu, 2013). The ontology developed in this way presented a more specialized area of knowledge representation for certain intended purposes towards a domain of interest.

Ontology development process can be generally classified in two perspectives of development: top-down and bottom-up. In top-down ontology development, ontology is usually created based on domain literature. The definition of ontological concepts and instances are based on knowledge conceptualization from extensive domain references. In the area of library science and computer science, there are several early studies that proposed ontology development that are top-down in nature. Among the notable ones are such as design principles for ontology development by Gruber (1995), methodology for building and evaluating enterprise ontologies (Gruninger and Fox, 1995, Uschold and King, 1995) and ontology development 101 (Noy and McGuinness, 2001). Although all these studies have presented practical guidelines in ontology building in the design engineering domain, there are also a number of methodology proposed for building ontology from the design engineering domain. For instance, Ahmed et al.(Ahmed et al., 2007) have proposed a generic methodology for ontology development using four root concepts: design process, function, issue and product in their engineering design integrated taxonomy (EDIT). However, their methodology does not explicitly study the complex inter-relations among the root concepts. Other methodologies of development witness the use of knowledge engineering (KE) approach (e.g., the use of predefined templates) which is practical and avoid the pitfalls of heterogeneous property and conceptual understanding. For example, Domain Knowledge Acquisition Process (DKAP) by Sarder et al.(2007) and template with predefined elements by Pavkovic et al.(2013). The main characteristic of top-down approach is manual development to ensure non-trivial relationship and concept definition. However, this approach also takes considerable amount of resources (e.g. human efforts) to complete ontology. As opposed to top-down approach, bottom-up approach advocates ontology building from basic element of ontology such as triples. A triple is expressed in the form of *subject-predicate-object*, where it is the basic relationship definition in ontology, particularly in the resource description framework (RDF) format. Modelling wise, bottom-up approach can be done either manually or automatically. An example of manual approach is formal concept analysis (FCA) where concepts are derived from studying a collection of ontological entities and their associated properties. Nanda et al.(2006) applied FCA in their methodology to develop domain specific ontology for a product family. Ahmed and Storga (2009) proposed an empirical, user-centric approach towards developing ontology through ontology merging. They have suggested ways to identify common concepts, concepts that present in one of the two ontologies and to identify relationships between concepts.

Another way of modelling triples is either through semi-automated approach or automated learning algorithms (i.e., ontology learning). In semi-automated approach, ontological concepts and relationships are discovered from multiple sources of design information, e.g. customer reviews, and suggested to human annotators during the ontology development process. We have previously proposed a methodology for building a semantically annotated multi-faceted ontology for product family modelling using such an approach (Lim et al., 2011). Automated learning, also known as ontology learning, learns ontological concepts and relationships automatically from multiple sources of design information. Usually, techniques such as natural language processing (NLP) and machine learning are used to elicit important topical words and frequent terms. Given a significant number of annotated triple relationships, ontology concepts can be derived automatically to form the concept hierarchy. For instance, Cross and Bathija (2010) advocates bottom-up ontology development through ontology reuse and adaptation. Algorithms such as concept relevance are used to determine whether a concept belongs to the base ontology. Hsieh et al. (2011) proposed a quick ontology construction method using extraction of concepts, instances and relationships from handbook. Chen et al. (2013) proposed an ontology learning approach to automatically translate customer needs into customer needs ontology, and to account for non-taxonomic relations.

3 RESEARCH AND APPLICATION OF ONTOLOGY IN DESIGN ENGINEERING

This section highlights some of the existing works on ontology applications in design engineering, emphasizing on the perspectives of information and knowledge management. To proceed, we have attempted to review selected papers from journals centered on design engineering and practice while acknowledging that this is by no means a complete list on the subject. The related papers are obtained via online database on selected journals, e.g., Journal of Mechanical Design, Research in Engineering Design, Journal of Engineering Design, using keywords, such as “Ontology”, “Semantic Web”, and so on. Based on the papers we obtained, we have summarized these applications into three major categories as in Figure 1: (a) design information annotation, search and retrieval; (b) design knowledge representation and (c) design information federation and interoperability. The detailed descriptions on each of the applications are described in the following sections.

3.1 Design Information Annotation, Search and Retrieval

One of the most widely preferable use of ontology in design engineering is for the annotation, search and retrieval of design information. We view this area of application in two perspectives: one is where ontology functions as the knowledge structure to aid designers in annotation process, and the other one is where the ontology itself is the underlying knowledge structure (e.g., schema, metadata) for intelligent retrieval by designers and engineers. In the first perspective, ontology aids designers to identify suitable tags of information usually by means of conceptual similarity matching. For instance, Li et al. (2009) used a pre-defined engineering ontology to semi-automatically create semantic metadata of textual engineering documents. Catalano et al. (2009) proposed a product design ontology that enhances the shape processing, search and retrieval during automobile design workflows. Pavkovic et al. (2013) applied ontology as an indexing structure that links to design documentation improve traceability of information (e.g., historical events) and search according to user's context. Ontology-based annotation ensures a more efficient indexing and retrieval of design information where ontology can function as the semantic indexing structure.

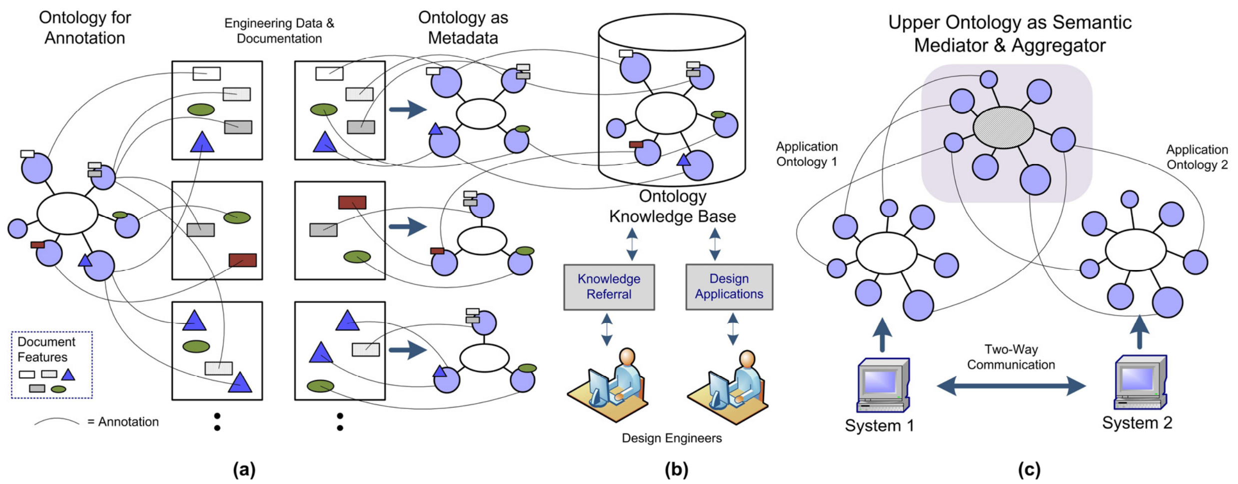

Figure 1. Summary of Ontology Applications in Design Engineering: (a) Design Information Annotation, Search and Retrieval; (b) Design Knowledge Representation; (c) Design Information Federation and Interoperability

Second perspective, on the other hand, focused on creating ontology (usually RDF schema) based on design information to enable semantic-based search and retrieval. Example studies are: Zhao and Liu (2008) have proposed an ontology-based methodology for encoding EXPRESS-driven product information model to web ontology language (OWL) and Semantic Web rules language (SWRL). Jung et al. (2010) proposed the formation of ontology based on user query that includes methodology for query ontology building, mapping and update using Bayesian network inference. Crowder et al. (2012) used RDF triples as a metadata for design knowledge acquired from engineers to enable semantic search in the aerospace domain.

3.2 Design Knowledge Representation

The second application of ontology witnesses its use as a representation of design knowledge. Harnessing the semantic modelling capabilities of ontology, ontology can represent complex inter-relationships that are discovered from design information which provide users with a powerful knowledge base to complete various decision support tasks. For example, ontology can be used as functional knowledge base for functional knowledge retrieval by designers in different viewpoint (Kitamura and Mizoguchi, 2003). Groose et al. (2005) used an ontology-based knowledge base named ON-TEAM to effectively share information on engineering analysis model among engineering organizations. Chakrabarty et al. (2009) studied and developed an ontology-guided knowledge retrieval system for timely suggestions during an automobile assembly process. Liu et al. (2013) proposed a design methodology for ontology-based faceted component analysis, selection and optimization in product family design. MacLellan et al. (2013) developed a software environment named Problem Formulator to assist designers in early design problem formulation using ontology as guidance. Zheng et al. (2013) proposed an ontology-based part obsolescence knowledge modeling for obsolescence prediction using historical sales data and rule-based query. Romero et al. (2014) used ontology as a knowledge-base for recursive case-based reasoning (CBR) system where ontology concepts are used to guide the CBR process. Majority of the works discussed here used ontology features such as reasoning and rule-based query to retrieve relevant knowledge from the knowledge base.

3.3 Design Information Federation and Interoperability

The formal conceptualization of domain knowledge defined in ontology makes it a useful reference for interoperability among heterogeneous knowledge base or applications. In this regard, ontology functions as a common mapping structure that also commonly known with the "upper ontology" concept, where semantic ambiguities are resolved by providing common terms or vocabularies at a higher level of abstraction. The aim is to promote information exchange and sharing among different systems. An example on this topic is to apply feature ontology for solving the interoperability between a computer-aided design (CAD) and computer-aided process planning (CAPP) application (Dartigues et al., 2007). Another study by Cho et al. (2006) adopted a meta-ontology in part libraries integration where it is used for unified search among distinct part libraries. Oh and Yee (2008) presented a method to enable semantic mapping of different business documents by utilizing ontology as the semantic gateway. It is noted that most of these mappings between ontologies are achieved manually via specific tools. The interoperability feature of ontology is an important enabler for federating multiple sources of design information. In this context, an upper ontology function as a central reference for mapping of heterogeneous design information sources, enabling a unified view of information. This is different from what we have discussed in the previous section where ontology is used to promote better information search but not integration. For instance, Bellatreche et al. (2006) used an ontology to automatically integrate electronic catalogues to ensure consistency in data semantics. Eddy et al. (2014) used ontology to federate knowledge base from four different domains: engineering design, sustainability standards, multi-criteria decision making and lifecycle analysis to perform multi-faceted considerations during design. Sun et al. (2010) defined a product knowledge model as upper ontology to integrates four knowledge types: resource description knowledge, organization competence knowledge, product technology knowledge and business process knowledge.

4 ONTOLOGY APPLICATIONS IN INDUSTRY

In the industrial settings, there are already a number of companies that have incorporated ontology and semantic search capabilities in their design applications. Either through acquisition or collaborating with companies with these capabilities, it has been witnessed that majority of these companies are advancing towards cloud-based applications that are powered by Semantic Web technologies. For instance, Autodesk® proposed a cloud-based approach for PLM system called Autodesk® PLM 360. Through a web interface, PLM 360 is able to manage on-premise PDM (e.g., in-house Autodesk® Vault™ PDM) separately. Autodesk's PLM 360 is based on semantic search technology from an acquired startup company named Inforbix in 2012 that focused on cloud-based semantic search applications for manufacturing companies (Franzon, 2012).

Another notable example is EXALEAD Cloudview™ from Dassault Systèmes which utilizes natural language processing (NLP) techniques, semantic query processing and ontology representation in their search-based application (SBA) named EXALEAD OnePart (for design data and parts management) and EXALEAD OneCall (for customer relationship management, CRM). A software toolbox named semantic factory is able to analyse structured and unstructured data using NLP techniques for data federation purpose. The platform also applied ontology representation that enables accelerated search indexing and semantic query in their mashup builder software component (Dassault Systemes, 2014). All these enabled EXALEAD OnePart to find and reuse existing design parts and perform intelligent feature-based comparison for design companies during parts selection and verification process. Besides the discussed two examples that are more focused in PLM systems, ontology is also being applied in decision making system that used ontology as structured knowledge base. The software, IHS™ Goldfire®, is a decision making software platform that helps design companies in solving problems through their semantic search, innovation trend analysis and problem solving tools such as TRIZ in their Goldfire Innovator (IHS, 2013).

Realizing the importance of adding semantics to data, another significant effort in the implementation of ontology in design engineering is the addition of Semantic Web component in the ISO 15926 standard. ISO 15926 is a standard for data integration, sharing, and exchange between different industrial automation system. The addition of Semantic Web component is initiated in the year 2005 with the addition of part 7 (or ISO 15926-7 in short), and later part 8 and 9 that is focused on OWL implementation and standards of semantic web service respectively. ISO 15926-7 essentially describe a template methodology that is based on ISO 15926-2 on data model and ISO 15926-4 on reference data library to define the data schema used in describing different entities. The template is essentially a standard of ontology class definition to assist users in creating object information models (OIMs, i.e., ontology entities) when defining an RDF triple. Later, ISO 15926-8 is introduced to further extend the ontology description using a more expressive OWL schema (Teijgeler, 2013). ISO 15926-9 is focused on Facądes, which is a web server for storing RDF triples.There are a number of companies that support the ISO 15926 standard. Bentley Systems Inc.® (Bentley Systems, 2011) is among the first company that made ISO 15926 standard commercially available in their line of software, including OpenPlant PowerPID and OpenPlantModeler, that allows two-way access of plant design information with other applications using the same standard. Intergraph® supports ISO 15926 in their SmartPlant Enterprise integrated solution (Intergraph, 2012). Autodesk® is a member of the ISO 15926 standard committee and are also incorporating this standard in their plant design products such as AutoCAD Piping and Instrumentation Diagram (P&ID) and AutoCAD Plant 3D.

5 CHALLENGES AND RESEARCH ISSUES

From the previous discussions on applications of ontology, it is clear that ontology can be useful in enabling intelligent design engineering support. For practical deployments, explicitly defined ontologies are crucial. However, to achieve this, a few challenges are identified from the generic aspects of ontology engineering. We discuss these challenges as follows.

(a) **Ontology Creation and Population:** from the perspective of ontology creation, we note that ontologies can be either manually defined based on domain literature studies, or by using automated ontology learning approach. While the later offers feasible solutions, most of the reviewed works created RDF-based ontologies from documents that are primarily serving as semantic metadata. Nevertheless, this is only possible for explicit information that is already coded in documented format. In design engineering, there is also tacit information, i.e., implicit information that is difficult to be explicitly coded in written forms, such as design experience or process know-how. The challenge lies in embedding such information during the creation of ontology, which is an important enrichment apart from machine processable information. On the other hand, we note the challenges of populating ontology. Current works proposed the use of upper ontology as the main mapping structure to other ontologies. Given the sheer number of machine-processed ontologies created, we are interested in learning how an upper ontology can be enriched and economically managed, e.g. reduced efforts in including or excluding ontologies over time to ensure timeliness. For scalability, we reckon that this is an important issue towards the realization of Semantic Web paradigm in design engineering. We suggest the use of intelligent approaches to suggest and assess semantic relatedness between concepts, entities and properties of different ontologies for semi-automated or automated mapping. Secondly, given the efforts in the industry, we recommend the co-creation of ontology by design applications during the design process that follows a standardized template such as ISO-15926. In this way, mapping of ontology can be a much simplified process due to property standardization.

(b) **Ontology Evaluation:** evaluation is an essential step in ensuring the validity and consistency of ontology. However, we found that this part of research is rarely reported in previous studies. Among the suggested evaluation and validation approaches are empirical approaches (e.g. survey & interviews) (Ahmed et al., 2007), domain knowledge inspection for merged ontology (Ahmed and Storga, 2009) or using experimental approach such as completeness and accuracy test (Li et al., 2009). The process of evaluating ontology is complicated and commonly involves manual judgments from domain experts. Under this perspective, we see the challenge lies in how an evaluation process can be efficiently performed with multiple domain experts involved. We anticipate that developing ontology in a collaborative manner can be a feasible direction. Human annotators can be assisted with ontology learning algorithms during the ontology development process through annotation and relationship suggestions, and also achieve a consensus collaboratively on the validity and comprehensiveness of ontology. This will help to reduce the errors of annotation and improve the trustworthiness of ontology. However, the challenge still lies in the process methodology, metrics and effectiveness of the proposed collaborative processes.

(c) **Ontology Evolution:** From our literature survey, we have also noticed that there are not many related works that research on managing changes and further evolution of ontology, for instance, the work by Jung et al. (2010). While a generic domain ontology with generic knowledge representation may not require much changes, other ontologies such as product specific ones are subject to changes when design information changes. The challenge here lies in the feasible method to capture and represent these changes, and how these changes can successfully populate the existing ontology, taking into account the evaluation process. We believe this is an important issue as changes in design information can trigger the “chain effects” in design, i.e., affecting the downstream design activities. It is desirable to study the evolution of ontological structures due to design information changes, and its impact towards the whole design process.

(d) **Ontology Visualization:** visualizing ontology can have many advantages that enable innovative solutions to problems such as semantic search. Due to the differences between a hierarchical tree structure and ontology, visualizing ontologies are more challenging compared to only visualize a taxonomic structure due to multiple annotated properties, relationships and inheritance. In general, the challengeis to search for the best visualization that is able to present the richness of ontology intuitively, and allows substantial user control over the content. For this, we have previously presented a user interface design for product family ontology using a multi-touch user interface (UI) (Lim et al., 2010). We believe the future lies in designing a good UIthat enable users to perform ontology creation, edit and manipulation with ease.

6 CLOSING REMARKS

Ontology is identified as a feasible modelling solution for knowledge rich scenarios, such as design information and knowledge management. The practical applications of ontology in design engineering have presented a great promise in the design information and knowledge management perspective. This study provides a survey on the state-of-the-art application of ontology in design information and knowledge management, both in academia and industry settings. We have discussed on various perspectives of how ontology can be designed, and also major approaches and methodology for building ontology. Application wise, we have summarized three major categories of ontology applications in the design engineering domain: (1) design information annotation, sharing and retrieval; (2) interoperability and design information federation; and (3) design knowledge representation. Besides academia, we have also covered the state of ontology application in recent industrial applications. A number of challenges and research issues on ontology research and applications in design engineering are discussed and highlighted in this paper.

ACKNOWLEDGEMENTS

The work described in this paper was partially supported by a research grant from the Ministry of Education, Malaysia (Grant Ref: RAGS/2013/UTHM/TK01/2) and was partially supported by a research grant from the Natural Science Foundation of China (Grant No. 51375301).

Disclaimer: Commercial software systems that are mentioned in this paper are solely for illustration purpose and does not imply recommendation or endorsement by the authors; nor does it imply that the products identified are necessarily the best available for the purpose.

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