Robotics and Computer-Integrated Manufacturing 28 (2012) 681–693

Contents lists available at SciVerse ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

A mereotopological product relationship description approach for assembly oriented design

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ARTICLE INFO

Article history:
Received 8 June 2011
Received in revised form
5 December 2011
Accepted 30 March 2012
Available online 9 May 2012

Keywords:
Integrated design
Assembly modelling
Product relationships
Ontology
OWL description language
Product lifecycle management
Mereotopology

ABSTRACT

This paper describes a novel approach for integrated assembly modelling and planning. The main objective is to make assembly information accessible and exploitable by data management systems and computer-aided X tools in order to support product architects and designers. Product information and knowledge as well as the related assembly sequence require a logical foundation in order to be managed consistently and processed proactively. In this context, product relationships are considered and described in the part-whole theory supported by mereology and its extension, mereotopology. Firstly, past and current research work are presented on concurrent product design and assembly sequence planning approaches; existing assembly relational models; and spatio-temporal mereotopology. A background of previous research work is also included in order to highlight the current research problem. Then, a mathematical description approach of product relationships based on mereotopology and temporal relationships is introduced. Finally, an ontological implementation of the proposed description using OWL DL and SWRL is presented and illustrated in a case study describing a mechanical assembly, enabling hence, reuse and collaborative exploitation of the assembly knowledge in the different product lifecycle phases.

1. Introduction

Nowadays, the definition and management of product information and knowledge at the beginning of its lifecycle is crucial for delivering lifecycle friendly products (i.e. assembly friendly products, green products, services oriented products, etc.). This major objective therefore requires from the product architects and designers an appropriate awareness and a complete understanding of all product intra-engineering processes (i.e. sequential, parallel, closed-loop, feedback-loop, etc.) and information flows along its lifecycle. To fulfil these product lifecycle requirements, the challenge is to provide a new way of representing and exploiting the product relationships, which supports product architects and designers in concurrent product design and assembly sequence planning stages [1].

To overcome current problems encountered in lifecycle engineering – such as combinational, reasoning, definition and evaluation – researchers have been inspired by nature, mathematical theories, philosophical investigations, cognitive science, techniques used in medicine and biology, etc.

A similar trend is followed in this paper, in which the research objective is to represent product relationships in a mathematical form. Thus, the authors consider the part-whole mathematical and philosophical theory supported by mereology and its extensions with topology such as mereotopology primitives, theorems and axioms, and temporal relationships. Indeed, the management of product information and its related assembly sequence requires a logical foundation, in order to be managed consistently and processed proactively by data management systems and computer-aided X (CAX) tools.

Firstly, the paper states, in Section 2, past and current research works on concurrent product design and assembly sequence planning (ASP) approaches, existing assembly relational models and space-time mereotopological theories. A background of previous research work is also included in this survey, highlighting hence the research problem to be tackled. In Section 3, a novel approach – called PRONOIA[1] (PROduct relatioNships description based On mereotopologIcAl theory) – for defining product relationships based on mereotopological theory and temporal relationships is proposed and described in detail. Finally, in Section 4,

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[1] PRONOIA was an Okaenid nymph of Mount Parnassos in Phokis (central Greece). She was the wife of the Titan Prometheus, and the goddess of foresight. Today this word means forethought and provident care.

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http://dx.doi.org/10.1016/j.rcim.2012.03.003

an ontological implementation of the proposed approach by using Ontology Web Language-Description Logic (OWL-DL) and Semantic Web Rule Language (SWRL) is described with a mechanical assembly, in order to demonstrate the potential benefits for product engineering of such a qualitative description approach.

2. Literature review

This section aims to give a brief overview of the significant amount of reported research work on concurrent product design and ASP, assembly relational modelling, and mereotopological theories including spatio-temporal issues, so as to provide the foundation for the proposed approach based on current status and challenges.

2.1. Concurrent product design and assembly sequence planning

The issue of concurrent product design and ASP [2–4] has received much attention in research works during the last decade [5]. These efforts aimed at tackling difficulties and weaknesses encountered in Design for Assembly (DFA) and ASP approaches by introducing the concept of ‘‘Assembly-Oriented Design (AOD)’’ [2,6].

Actually, most of the research work performed and reported in the field of DFA can be classified as semi-generative approaches based on heuristics and geometric rules in order to facilitate the assembly phase of the product [7–9]. Based on detailed product geometry and a part-to-part oriented evaluation, DFA analysis leads to a redesign of products [4]. On the other hand, research work on ASP has resulted in generating, through algorithms, exact and heuristic methods – which are presented through graphs and diagrams – and evaluating assembly sequences with decision criteria from detailed product geometry and the related assembly relational models [10,11].

In such a context, where product design and assembly sequence planning phases are normally undertaken separately and sequentially, which results in missing the true integration between both phases, AOD is a promising way to tackle current engineering practices focused on detailed part geometry [12]. Here, the assembly oriented practice of product development can be considered as a top-down approach by proactively considering the assembly related product design and their relationship issues in the early phases of the product development process [13,14]. This emerging trend highlights some challenges related to the recent shift in engineering design that promotes the relationships-based modelling and management paradigm [15]. Thus, engineering requirements consist of closer integration of product design model and lifecycle models, better traceability on various levels of abstraction of the product (i.e. functional, behavioural, structural, geometric, technological, etc.) and rational and consistent information management support with the concept of ‘‘relational design’’.

2.2. Assembly relational modelling

The study of various research works has provided many data models and ontologies dedicated to the representation of various engineering fields and product lifecycle stages. In general, a product model aims at eliciting data and information at various abstraction levels through its lifecycle. These models are not only focused on technical objects describing the product through its lifecycle but also gather the views of technical objects based on stakeholders' viewpoints involved in the product development process [17].

Among the existing models related to the AOD issue, it is possible to identify different kinds of models and formalisms such as generic, functional, business and multi-view. Only assembly relational models relevant with the scope of the paper have been reported here. First of all, Bourjault was the first to propose functional relation through a directed graph [18]. This representation and the related reasoning procedure were reused and improved later on by De Fazio and Whitney [19]. Homem de Mello and Sanderson presented an AND/OR graph as a decomposing graph of the assembly, in order to influence and facilitate the assembly sequences generation [20]. In parallel, further work provided matrix-based modelling models to define and analyse assembly relationships for ASP [21,22]. These research works can be considered as a basis on which many researchers and engineers have built their works and efforts over the last two decades.

Furthermore, the significant growth of semantic value of information and knowledge models during the last decade has highlighted new contributions towards assembly semantic formalisms. At the beginning of the 2000s, Zha and Du promoted a knowledge-based system using multi-agent system and Petri Net to support assembly design and ASP by considering a start from part relational information [3]. In a separate paper, Dong et al. described a knowledge-based ASP approach, in which the assembly was modelled as a connection-semantic-based assembly tree [10]. In addition, Kim et al. proposed a spatial relationships-based assembly design formalism describing assembly relations, and an assembly relation model, in which relations were represented in XML format [23]. This first attempt was only focused on the geometric aspect of the product and did not enable an efficient interpretation by computer-aided design (CAD) tools. Recently, Kim et al. have tried to demonstrate the feasibility of an ontological representation of assembly and associated constraints [24]. The same authors have proposed an ontology-based representation for assembly joints in collaborative product design by using mereotopological primitives and SWRL formalism [25]. Although this latter reported work is case study oriented, it can be echoed here with the scope of the paper.

More recently, Demoly et al. have described a novel product–process data management approach by introducing the management of product relationships at various abstraction levels and in separate manner [16]. They have introduced four kinds of product relationships – such as contact, precedence, kinematic, and technological – and the related associations in PLM (Product Lifecycle Management) systems, which have a role to play in the AOD issue. All these relationships have been represented through a multi-view model called MUVOA (Multiple Viewpoints Oriented Assembly) [17] which has been implemented in a PLM-based application.

2.3. Mereotopology and spatio-temporal relationships

This section introduces research work on a mathematical and philosophical theory in the field of formal ontology, which is intended to be the support of the proposed approach. Mereotopology can be considered as a theory derived from mereology which is the theory of part–whole relation [26]. Mereology enables the description of parthood relation which is a reflexive, antisymmetric and transitive primitive. An extension of this mathematical theory towards pointless topology is reported by the mereotopology, which provides a further first-order logic description of connections between entities such as spatial regions [27–29]. Indeed, instead of focusing on set theory, experience in product modelling and design has emphasised on the need to work with a region-based theory by considering the product as it is perceived in the real world [30].