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A formal ontology-based spatiotemporal mereotopology for integrated product design and assembly sequence planning

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ABSTRACT

This paper introduces the development of a formal ontology based on spatiotemporal mereotopology in the context of integrated assembly design and sequence planning. The main objective is to make assembly information accessible and exploitable by information management systems and computer-aided X tools in order to support product architects and designer's activities. Indeed product design information and knowledge as well as the related assembly sequence require a semantic and 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, a literature survey on formalisms in assembly-oriented design, mereotopological theories and spatiotemporal ontologies is presented so as to highlight the current research issue. Then, a mathematical description approach of product relationships based on mereotopology and temporal relationships is introduced. Built on this, an ontological development of the proposed theory using description logic rules is proposed. Finally, a mechanical assembly, as a case study, is introduced to illustrate the relevance of the proposed ontology.

1. Introduction

Nowadays, the product development process becomes more and more complex and knowledge intensive for delivering lifecycle friendly products (i.e. assembly friendly products, green products, services oriented products, etc.), which generates design mistakes and misunderstanding. This requires therefore additional supports and assistance, especially in the early design stages. In this context, information and knowledge inconsistency, such as generated and used during product design, is considered as a recurrent issue. To overcome this, the relationships between engineering objects have to be checked from a semantic and logical point of view [52]. As a consequence, a theory has already been proposed to cover this need [23]. Here the JANUS (Joined AwareNess and Understanding in assembly-oriented deSign with mereotopology) theory qualitatively describes product-process relationships based on spatiotemporal mereotopology. The stake is to link spatial and temporal objects in a formal and semantical manner. Indeed, designers need to be assisted by advanced knowledge management tools in order to make right decisions. In addition semantic web technology has been considered so as to formalize this theory and to represent information in a structured and understandable manner [45]. By using an ontology, it is possible to capture, represent and reuse knowledge in PLM systems and therefore ensure information and knowledge consistency in product design stage.

The paper is focused on the development of a spatiotemporal ontology in AOD (Assembly-Oriented Design). The objective is to provide a product design description by proactively considering its assembly sequence as early as possible in the product development. Such description enables information consistency checking with preliminary information through PLM systems by introducing specific rules. Built on this, further efforts are done so as to introduce DL (Description Logic) and SWRL (Semantic Web Rule Language) rules and then develop a specific reasoning layer.

Firstly, the paper presents, in Section 2, a literature review on formalisms in AOD, mereotopological theories and spatiotemporal ontologies. Section 3 briefly introduces the proposed mereotopological theory (JANUS) in the three dimensions (i.e. spatial, temporal and spatiotemporal). Then, Section 4 describes the proposed formal ontology with OWL (Ontology Web Language) language, which describes product-process relationships over space and time through semantics and logics. Moreover, rules are introduced within the ontology with DL and SWRL in order to check information consistency. Section 5 introduces a mechanical assembly to illustrate the relevance of the spatiotemporal ontology. In Section 6, the advantages and limits of the model are discussed. Finally, in Section 7, conclusions and future work are given.

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2. Literature review

2.1. Formalisms in assembly-oriented design

Over the last decade, numerous data models and ontologies have been built to represent various engineering fields and product lifecycle stages. Product model generally aims at describing data and information at different abstraction levels through its lifecycle [10]. These models also consider stakeholders viewpoints covering the project life.

In the AOD context, models can be generic, functional, business, multi-view and so on [9]. Some of them are presented below. Bourjault was the first to propose functional relation through a directed graph [5]. His methodology has been reused and improved by De Fazio and Whitney [7]. In addition, an AND/OR graph, whose purpose is to facilitate the assembly sequences generation, has been presented by Homem de Mello and Sanderson [26]. In parallel, research works have been carried out on matrix-based modeling models in order to define and analyze assembly relationships for ASP (Assembly Sequence Planning) [43].

Moreover, new contributions on knowledge models and semantics in assembly formalisms have been introduced. As such, Zha and Du have built 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 [55]. A knowledge-based ASP approach has also been promoted by Dong et al. Here the assembly is modeled as a connection-semantic-based assembly tree [13]. Furthermore, 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 (Extensible Markup Language) format [30]. This approach was not interpretable by Computer-Aided Design (CAD) tools, but was only focused on the geometric aspect of the product. Later, they have presented an ontology-based representation for assembly joints in collaborative product design by using mereotopological primitives and SWRL formalism [31].

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 [11]. Four kinds of product relationships (i.e. contact, precedence, kinematic pair, and technological pair) and the related associations in PLM systems have been presented. All these relationships have been represented through a multi-view model called MUVOA (MUltiple Viewpoints Oriented Assembly) [10] which has been implemented in a PLM-based application.

2.2. Mereotopological theories

Lesniewski initiated efforts in a mereology-based theory with theorems and axioms [36]. His purpose was to develop the parthood relation in a formal manner [9], which uses the *part of* primitive [14], denoted ***P*** and represents the part-whole relationship. But limits and basic problems of such theory have been highlighted [41,42,49]. As an automotive example, the speedometer is *part of* the dashboard, the dashboard is *part of* the car and the car is *part of* the garage. This seems to be logical sentences, but in no case the speedometer is *part of* the garage. Here the problem is that parthood relation is transitive (i.e. parthood means only one thing at once) in the first two statements and intransitive (i.e. parthood means something else) in the last one [42]. To overcome this paradox, the notion of topology has been added and considered together with mereology so as to initiate mereotopology. Two fundamental predicates are formalized in this theory: parthood (i.e. one entity is *part of* another) and connection (i.e. an entity is *connected to* another, denoted ***C***) [41]. The current challenge of the mereotopology-based theory in engineering design is to consider the product as it is perceived in the real world [9]. In other words, mereotopology aims at describing relationships between parts with a strong "engineering sense". Here, the engineering sense requires a more accurate and more structured prospect [41]. So, such theory enables the description of the engineering sense actually required in AOD. A proposed classification of the existing theories in product design is presented in Table 1. It seems that few contributions are focused on mereotopological theories in the domain of engineering design, where a lack of spatiotemporal description can be identified.

2.3. Spatiotemporal ontology models

Semantic web has been introduced in the early 2000s in the field of computer science and internet [45]. It is based on ontologies, which formally and explicitly classify and describe concepts within a specific domain of knowledge [2] with axioms, definitions and theorems [4]. In addition, knowledge can be stored and exchanged over a world wide network with ontologies [21]. Having many advantages, ontology has been applied to other domains such as design and manufacturing [56].

Moreover a common vocabulary between all stakeholders is provided by ontology [35]. As such, information is formalized and machine-interpretable. Information consistency is checked with the logics and semantics included in the ontology [1]. The

Table 1
Mereotopological theories and their related primitives in assembly design.

Author	Dimension			
	Spatial		Temporal	Spatiotemporal
	First primitive	Developed primitive		
Demoly et al. [9]	***P***	***O; IP; D; Point; X; St; B; T; IB***	<	O_t; ⋇; $\subseteq t$
Kim et al. [31]	***P; IP***	***O; D; Point; X; St; B; T***		
Salustri [41]	***P; C***	***PP; O; EC; TPP; NTPP; SC; E***		

Note: < (Precedence), $\subseteq$ **t** (temporal inclusion), ⋇ (temporal connection), **B** (Before), **E** (Enclosure), **IB** (Interior Boundary), **NTPP** (Non Tangential Proper Part), **Ot** (temporal Overlap), **SC** (Self-Connection), **T** (tangent), **TPP** (Tangential Proper Part).

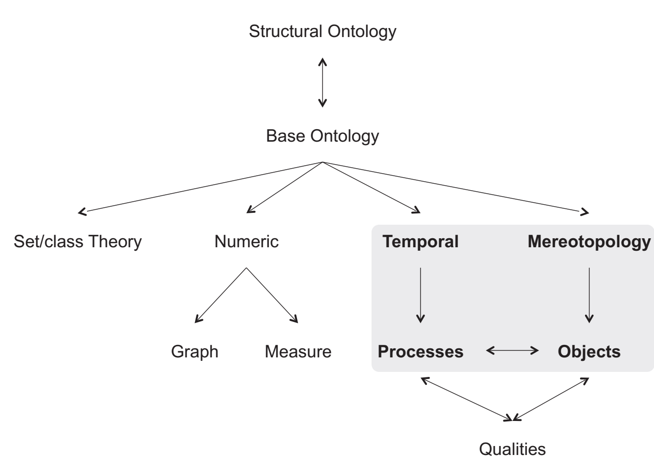

Fig. 1. Hierarchy of the SUMO ontology.