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Formal ontology and CAD integration with macro parametric approach

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ABSTRACT
This paper discusses an ontological integration framework in the context of mereotopological formal ontology and CAD systems. Based on a comprehensive literature review of current design knowledge management and formal ontology research works, the authors propose the integration framework that can incorporate design knowledge with CAD systems. The primary role of mereotopology in this research work is the formal representation of design knowledge for the 3D solid assembly models. Most of the existing research works about design ontology present an abstract form and often require significant additional efforts to be integrated into CAD systems. Thus, this work introduces a formal ontology for CAD (OCAD) and macro-parametric approach as a practical way to integrate design knowledge with CAD systems. For the implementation, Protégé, SPARQL, and commercial CAD system are employed. We also propose the enhancement of the developed framework for the future use to aid dynamic modeling.

KEYWORDS
Formal ontology; CAD; mereotopology; macro parametric approach; design knowledge

1. Introduction

The quantity of information is growing rapidly in today's world. This is often termed as information deluge or information explosion [2]. It is important to develop systems of exchanging and processing information that can be automatically interpreted by the computers. The concept of ontology, which was introduced in artificial intelligence [14], encompasses the domain of knowledge representation and management, also it facilitates a shared conceptualization as well as a structured way to manage the information. Hence, it makes the knowledge accessible as well as interpretable. Representing knowledge in a defined ontological format is important to utilize those ontologies for practical or industrial uses. However, the process of representing knowledge is often case specific and requires more formal approaches. Some researchers [8, 19, 20, 21] use a mereotopological formal theory to build ontology-based knowledge models. The mereotopological theory deals with the behavior of spatial regions and inter-relationships among those regions. This theory is based on mereology and topology. Mereological theory is concerned about the parthood relationships among the objects, which was introduced by Leśniewski [23]. Mereology deals with the part-to-part or part-whole relationships, hence there is another theory to work with the notion of connectedness [28, 30]. This theory is known as topology. To express entities that exist in other spaces besides the usual physical one; region-based mereotopological theories were introduced [9, 22].

In a recent past, Kim *et al.* [20, 21] have presented a mereotopological ontology that can provide the assembly information of different mating parts of a mechanical system. However, the remaining shortcoming of mereotopological ontologies is that there are few systematic ways to integrate mechanical assemblies in CAD systems and the ontological design models. In this research work, a systematic way is proposed to integrate mereotopological ontology with the traditional CAD systems. In Section 2, a literature review explains the contemporary research efforts to build various integrated platform, in Section 3 we discuss how mereotopological primitives are represented with simple CAD models. Section 4 represents the integration framework for ontological design model and CAD systems. Lastly, this paper concludes by showing future research directions.

2. Literature review

This literature review section is divided into three subsections. In the first subsection, the contributions of formal ontology to bridge the gap between different systems are explained. Second, contemporary research efforts of system integration are shown and lastly various aspects of the macro-parametric approach are described.

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2.1. Formal ontology and systems integration

In science and engineering, ontology refers to the formal representation to clearly specify the knowledge domain and relationships among those domains. Ontology is typically used to develop the knowledge base and that knowledge can be utilized to eliminate the gap between heterogeneous systems.

Garcia [10, 11] develops an ontology-based framework to enable data interoperability between CAD systems. Chaparala *et al.* [5] present a framework to interoperate product design data in CAD systems using ontology. In this research effort, ontology is converted into STEP format to enable the interoperations. By Karimi and Akinci [17], CAD and geographic information system (GIS) data interoperation is represented; where semantic web service is utilized. An ontology-based CAD to CAE integrated framework is represented by Zhu *et al.* [33]. Ahmed and Han [1] present an ontological framework to integrate CAD to CAM systems. Geometric product information is typically provided by the CAD systems; hence to maximize the advantage of using CAD systems in an industrial environment, an ontological framework is developed (Perzylo *et al.* [27]). In their research, a link is established using the ontology to minimize the gap between CAD data and the industrial robots.

In this paper, formal ontology is extended to represent the knowledge behind a designer system and the knowledge is based on mereotopology. Later, this knowledge is utilized through the proposed framework (described in Section 4) to be used in designer systems (CAD).

2.2. Contemporary research efforts on system integration

Contemporary research efforts on various integrated systems (e.g., CAD to CAD, CAD to CAE and between other systems) are highlighted in this section.

An industrial product's multiple facets are handled by Product Lifecycle Management (PLM) systems [3]. In PLM, system integration is critical to enable a collaborative design environment. Design collaboration is an issue at every stage of a product's life cycle, starting from the conceptual design to the product launch. Various research activities are conducted to enhance the collaborative environment by enabling different system integration. To integrate the CAx systems, some research efforts present integrated frameworks between CAD to CAE systems. Gujrathi and Ma [15] develop common data model (CDM) to integrate CAD and CAE systems. The intermediate CDM is used as an integrator between CAD and CAE systems, which contains various parametric and analysis information. Hence, CDM contains the necessary design and analysis information between both systems. Cao *et al.* [4] show a research effort to develop common geometric module (CGM) between the CAD and CAE systems to capture spatial and some variable mesh (temporal) information. Prime focus of this research work is to integrate CAD to CAE systems. Integration is done by three ways (neutral formats like STEP, STL, IGES; CAD kernels like ACIS, ParaSolid and using private plug-ins). The aim of this research is to integrate CAD to CAE systems, utilizing all of the three ways. A common geometric module is built to contain all of the geometric information to interact with the CAE systems. CGM is mainly focused on the parametric information (e.g., length, width etc.). CGM does not use design history for model generation, so there is the possibility of losing design intents and it may produce a frozen or dumb model according to Mun *et al.* [25]. Yan *et al.* [31] develop a bridge platform to connect between CAD to CAE systems. This research is done for hydropower industrial design analysis. Bridge platform is introduced between design and engineering to achieve seamless data transfer from CAD to CAE systems; however, the bridge platform contains only the parametric information. Yi and Hua [32] develop a web-based platform to interact between CAD and CAE systems. As an intermediate medium or neutral file, XML-SOAP (Simple Object Access Protocol) and UDDI (Universal Description Discovery and Integration) are built to interact between CAD to CAE systems. This intermediate XML-based platform is used to capture the parametric (spatial) CAD information.

2.3. Macro-parametric approach

Macro-parametric approach (MPA) is typically used to resolve the interoperability issues between CAx systems. Interoperability between CAx systems is a critical issue [24], where design collaboration is needed for product design and development. A study of National Institute of Standards (NIST) by Markson [24] estimates that each year automotive industries bear one billion US dollar financial damages because of mismatch in product data among heterogeneous systems. To deal with this interoperation issue, various research efforts are made. For example, STEP (AP 203) [12], IGES (ANSI standard) [13], VDAFS (DIN standard) [26] and MPA are some approaches to aid the interoperability issue. Most of these approaches are not concerned about preserving the designer's design intent, as a result, the interoperation often produces un-editable frozen models; however, MPA is entirely dependent on the design history of the designer and that design history preserves the design intents. MPA is first proposed by Mun *et al.* [25] to interoperate part models among CAD systems by preserving the designer's design history (intent) (Choi *et al.* [6]), which is prone to loss at every stages of a product's life cycle. MPA works with the preserved design history, which is initiated by the designer. Design history is preserved in the macro file of the designer systems. MPA works with those macro files among different designer systems. A schema mapping is required between the targeted systems to carry out the design information from one system to another. Because of preserving design history, MPA can generate editable models to the targeted systems. Although MPA is developed to work with CAD to CAD data interoperations; however, later this work was enhanced to interoperate between CAD to CAE [18] and CAD to CAM [1] systems.

The primary role of MPA is still the same in this research work, which is to visualize the solid models with design intent preservation. Usually, MPA is used where there are interoperability issues between heterogeneous CAx systems; however, in this research work, MPA is employed to interact between ontology web language (OWL) to CAD system.

3. Mereotopological primitives and formalism

This section is divided into two subsections. The first subsection shows how mereotopological primitives can be represented in terms of solid modeling. The second section presents a mereotopological formalism and a simple case.

3.1. Mereotopological primitives and solid modeling

This section starts with basic definitions of mereotopological primitives as described in Smith's mereotopology [30]. Each primitive is written with a bold case between two entities as follows, $a\boldsymbol{R}b$, where $\boldsymbol{R}$ indicates relationships between the variables (a, b, c, etc.), which are ranged over entities [8]. Tab. 1 presents operators and symbols usually used to describe the various mereotopological relationships.

The mereological theory expresses the parthood relationship, where $x\boldsymbol{P}y$ means x is part of y as shown in Tab. 1. Based on this primitive, other primitives can be further derived. The first derived mereological notion is that x overlaps$y$, denoted as $x\boldsymbol{O}y$ when z is any part of$x$ and$y$. The second primitive is that x is discrete from$y$, and is written as $x\boldsymbol{D}y$, this primitive means that x does not overlap$y$, $x\boldsymbol{T}y$ indicates that x is tangent to$y$. Tab. 2 shows the mereotopological primitives and their corresponding definitions.

The term topology indicates the concept of connectedness in a product or product model, and it also contributes to developing mereotopological primitives [8]. A primitive derived from $\boldsymbol{P}$ is that $x\boldsymbol{IP}y$ and means that x is an interior part of y. Another one is that x crosses y, and written as $x\boldsymbol{X}y$. This primitive means that x is not a part of y also discrete from y. It also means that x overlaps both y and its complement. More detail description of mereotopological primitives can be found in Smith's analysis [30].

In this section, a fundamental mapping between the mereotopological primitives and CAD solid models is described. In Section 4, an integration framework for the ontological design model and CAD systems is introduced to capture mereotopological primitives and transfer this information to CAD systems. As shown in Tab. 3, a cylinder can be denoted as x and a box as y. The relation $x\boldsymbol{P}y$ (x is a part of y) implies both x (cylinder) and y (box) shares z as a common part of them (see the second column in Tab. 3). Similarly, we find $x\boldsymbol{IP}y$, which indicates that x (cylinder) is an interior part of y (box) and x is not tangent to y (the third column in Tab. 3). Also, x (cylinder) overlaps y (box) denotes $x\boldsymbol{O}y$ and they have a common region z. Similarly, $x\boldsymbol{D}y$, $x\boldsymbol{X}y$, and $x\boldsymbol{T}y$ are represented as shown in Tab. 3. These mereotopological primitives can be represented in the ontological design model and can be visualized in the CAD systems via the proposed integration framework.

To visualize a mereotopological model in the CAD system, three tasks are required; the type (e.g., box, cylinder, pyramid, etc.) of the solid shapes, CAD operations (cut, extrusion, protrusion, etc.) and the coordinate of each solid mating discrete shapes. These three pieces of information are incorporated in the

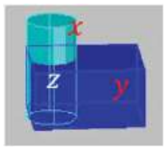
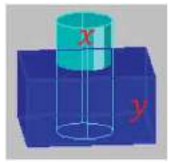
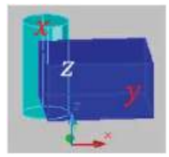
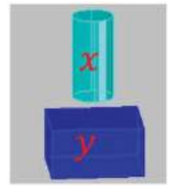
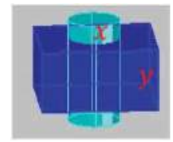
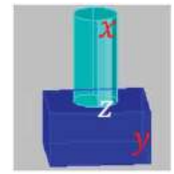
Table 1. Fundamental mereotopological operators [8]

Symbol	Name	Symbol	Name
$\wedge$	Logical conjunction	$=$	Equality
$\vee$	Logical disjunction	$\equiv$	Equivalence
$:=$	Definition	$\forall$	Universal quantifier
$\rightarrow$	Logical implication	$\neq$	Difference
$\exists$	Existential quantifier	$\emptyset$	Empty region
$\neg$	Logical negation	$\boldsymbol{\Lambda}$	Sum of logical conjunction

Table 2. Fundamental mereotopological primitives' definition [8].

Primitive description	Definition
$xPy := \forall z(zOx \rightarrow zPy)$.	x is a part of y
$xOy := \exists z(zPx \wedge zPy)$.	x overlaps y
$xDy := \neg\, xOy$.	x is discrete from y
$Pt(x) := y(yPx \rightarrow y = x)$.	x is a point
$xXy := \neg xPy \wedge \neg xDy$.	x crosses y
$xSty := \forall z\ (xIPz \rightarrow zXy)$.	x straddles y
$xBy := \forall z\ (xPx \rightarrow zSty)$.	x is boundary of y
$xTy := \exists z(zPx \wedge zBy)$.	x is tangent of y

Table 3. Mereotopological primitives and CAD solid models.

Primitives	*x is Part of y*	*x is Interior Part of y*	*x Overlaps y*	*x is Discrete from y*	*x Crosses y*	*x Tangent y*
Description	$xPy := z(zOx \rightarrow zPy)$	$xIPy := xPy \wedge \neg xTy$	$xOy := \exists z(zPx \wedge zPy)$	$xDy := \neg xOy$	$xXy := \neg xPy \wedge \neg xDy$	$xTy := \exists z(zPx \wedge zBy)$
Associated parameter for CAD macro	Coordinate and dimension of *x* & *y*	Coordinate and dimension of *x* & *y*	Coordinate and dimension of *x* & *y*	Coordinate and dimension of *x* & *y*	Coordinate and dimension of *x* & *y*	Coordinate and dimension of *x* & *y*
Visualization in CAD						

macro file of the CAD systems, which is illustrated in Section 4.

3.2. Formalism for solid modeling

Mereotopological formalism can represent solid modeling. In this section, it is shown how mereotopology can represent the solid modeling with an example of a hole in a box case.

In Fig. 1A, it shows that many tangent rectangles can generate a box and this relation can be represented as follows.

$$\bigwedge_{i=1}^{i=n} l_i T l_{i+1} := B \tag{1}$$

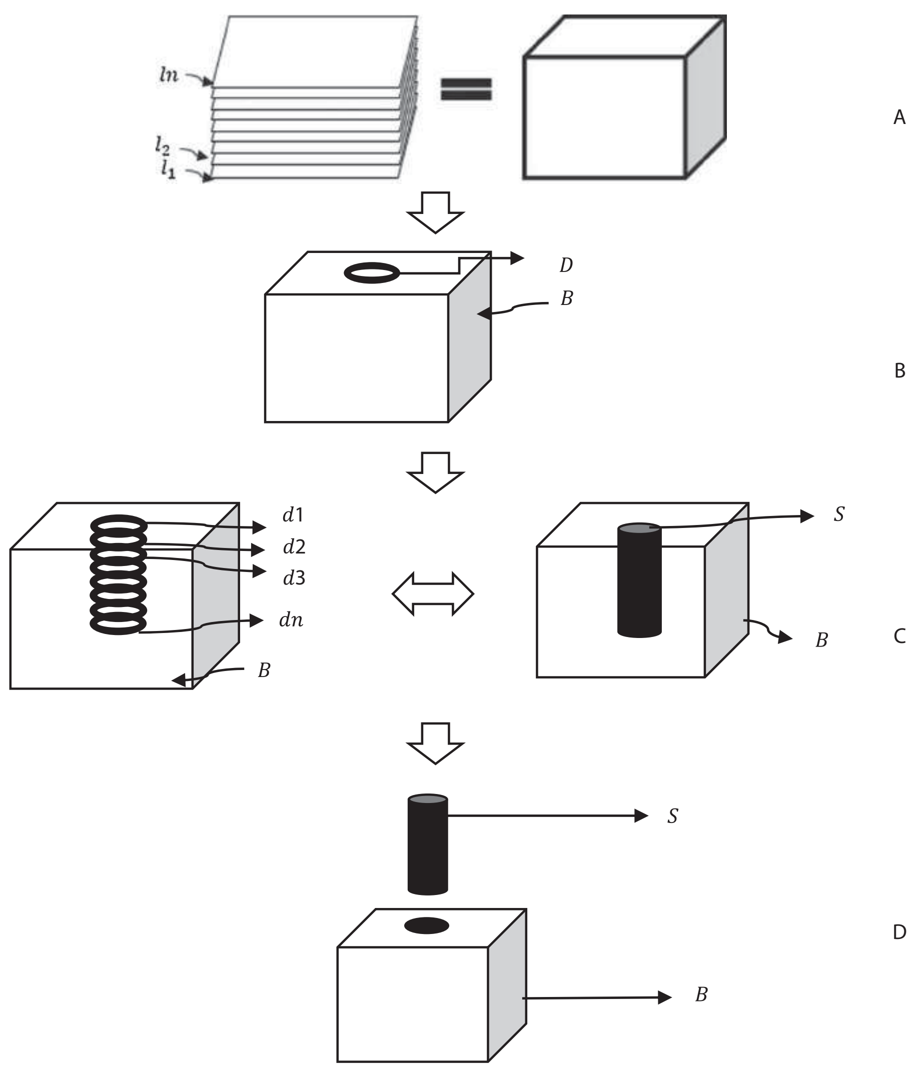


Figure 1. Mereotopological formalism to represent a hole in a box.

Aa B is now representing the box. Figs. 1B and 1C show an internal part (a disc) of a box. Piles of tangent discs (di) can create a cylinder. The disc is an internal part of the box and it is represented as follows.

$$DIPB \;:=\; DPB \;\wedge\; DTB \tag{2}$$

Tangent discs can form a cylinder (S) and that cylinder formation can be represented by mereotopological notations.

$$\overset{i=n}{\underset{i=1}{\Lambda}} d_i T d_{i+1} := S \tag{3}$$

In order to create a cylindrical hole in a box, a cylindrical shape needs to be removed from the box. In this case, the box is represented as B and cylinder is represented as S. Hence, S needs to be removed from B to create the hole and it is represented as follows.

$$SDB\Lambda\neg SPB\Lambda\neg SOB \tag{4}$$

Hence, mereotopology can be utilized to mathematically represent solid modeling for the designer (CAD) systems. Based on this representation, the subsequent section develops a mereotopological ontology for the CAD systems and this ontology is later integrated to the CAD system by capturing knowledge from the ontology and using a macro parametric approach (MPA).

4. Integration framework of ontological design model and CAD system

In this section, a framework to integrate the ontological design model and the CAD systems are described. The whole process can be divided into five different steps. First, the development of the ontology for CAD systems is completed. Second, a knowledge hub is built to contain the ontological design model and semantic query language [8, 9] is used to extract the information from the ontological design model. After this step, macro files for the specific CAD system is used to transfer the information from the knowledge hub to the CAD system. These macro files do not contain design parameters (e.g., dimensions, length, width, etc.). Thus, in the next step, design parameters from the ontological design model are added in the macro files and finally, macro files can be visualized as a solid model in the CAD interface. Macro file is also known as 'journal file'. Different commercial CAD systems have their own macro/journal file system. Fig. 2 illustrates this process.

4.1. Schema mapping

Schema is the internal structure of a database, which acts as a blueprint of such database systems. Schema mapping refers to specifying the description of data transfer among heterogeneous schemas. Schema mapping is necessary when an interoperation or data integration is needed among different systems.

In this research work, two heterogeneous systems are mapped to enable seamless data transfer. OWL data structure is mapped to the targeted data structure of macro-based CAD modeling system. Simple protocol and RDF (Resource description framework) query language [29] (SPARQL) is used as a bridge to map between the two systems. Fig. 3 illustrates the schema mapping scenario between OWL to CAD macros.

4.2. Knowledge repository development

In this research work, a knowledge repository is developed. A knowledge repository is a system that can

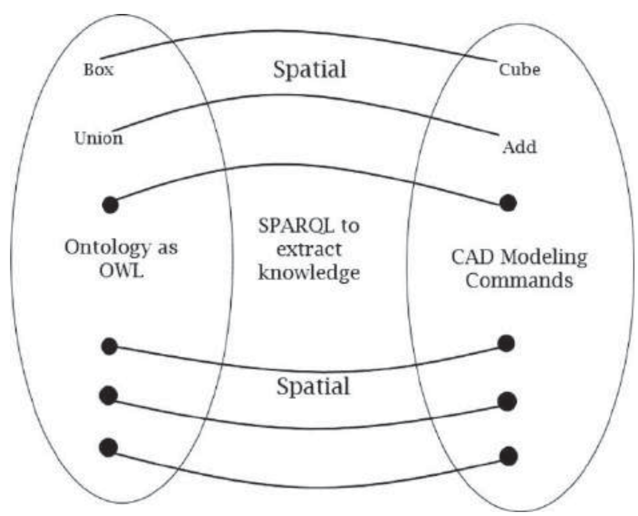


Figure 3. Schema mapping for the integrated platform.

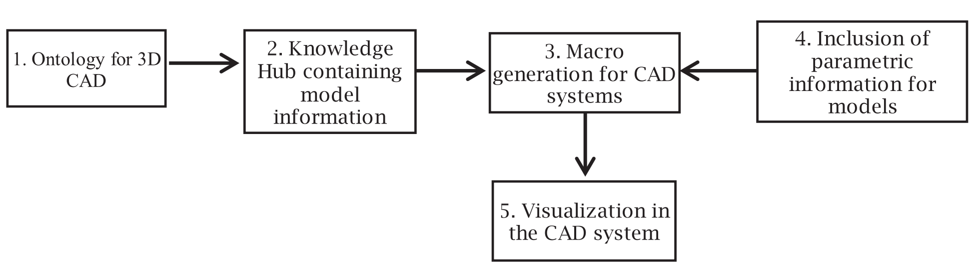


Figure 2. Steps to transfer the ontological design model information to the CAD system.

capture, coordinate, and prepare knowledge for a future use. In this work, knowledge repository is built for the CAD systems. Knowledge is captured from the ontology.

Fig. 4 shows how knowledge is captured and stored for a future use. In this research work, knowledge is captured from the ontology. To perform this task, a knowledge query server is prepared first [16]. After that, CAD ontology is integrated to the query server and then necessary knowledge is being captured by making the query. Lastly, knowledge is preserved for the next step.

Previously, there were some research efforts for ontological representation of 2D CAD systems [7]. In this work, we extend their approach to be applicable for 3D shapes by the OCAD ontology (e.g., cylinder, box, pyramid, etc.). It facilitates the assembly models to be visualized in the CAD system. A concept map can express the thoughts behind a knowledge, as well as the coherence of thoughts can be visualized using a concept map. From Fig. 5, we observe that the OCAD ontology has two different sections; one is for 2D and the other for 3D shapes. In this research effort, we focus on 3D solid modeling. The ontology also contains all the necessary CAD operations, which includes constructive solid geometry (CSG) primitives (i.e., difference, intersection, union) and other operations, such as cut, trim, move, revolve, extrusion, mirror, move, protrusion, etc. The portion of the OCAD ontology can be visualized in Fig. 6.

The knowledge base is represented by the OCAD ontology. Indeed, knowledge is needed to be captured from the knowledge base for future use. In this case, the extracted knowledge is mapped to the designated CAD system, macro files are used to represent the solid geometries [25] for the targeted CAD system. Since this macro file does not contain the parametric information, the following step is extending the macro file with parametric information from the ontological design model. Most of the CAD systems have their own macro file systems.

Only extracting the knowledge is not enough to represent a model for the designer systems. At the same time, the organization of knowledge is important to represent

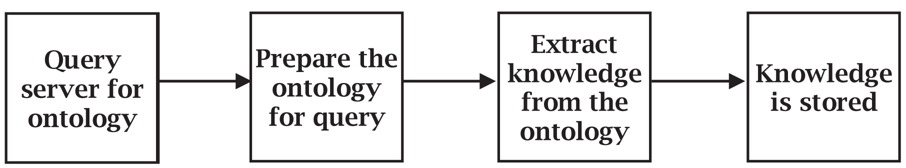


Figure 4. Activity in knowledge repository.

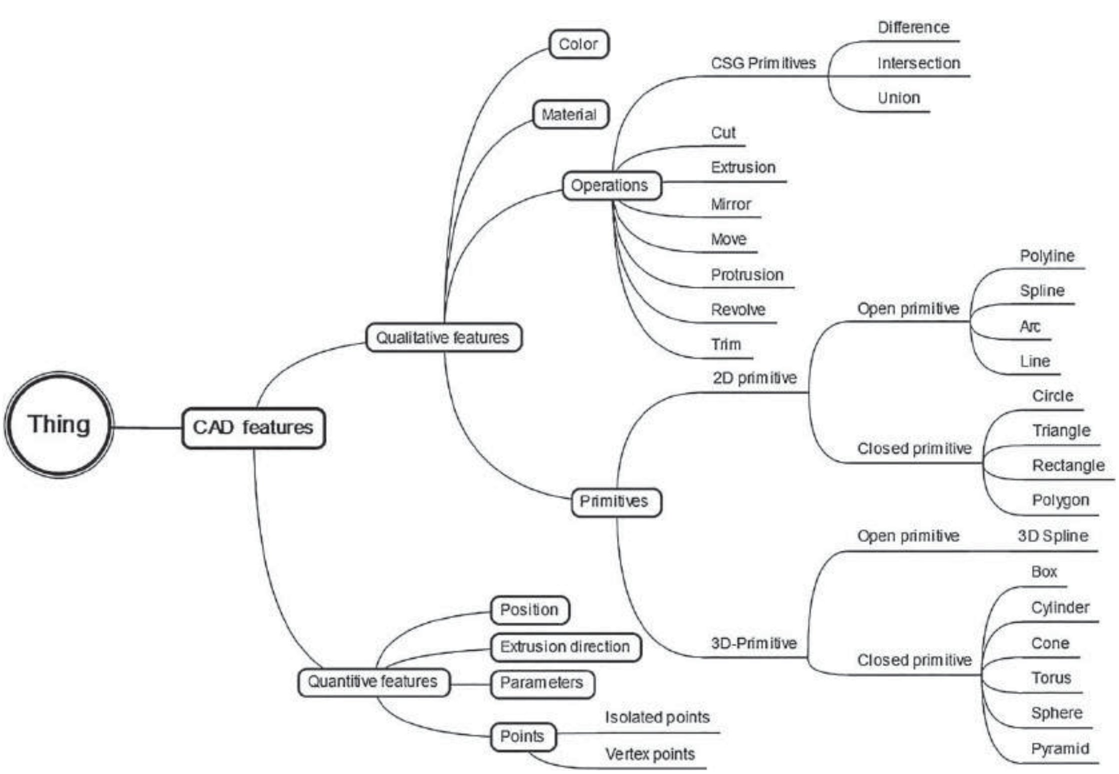


Figure 5. Concept map for the OCAD ontology.

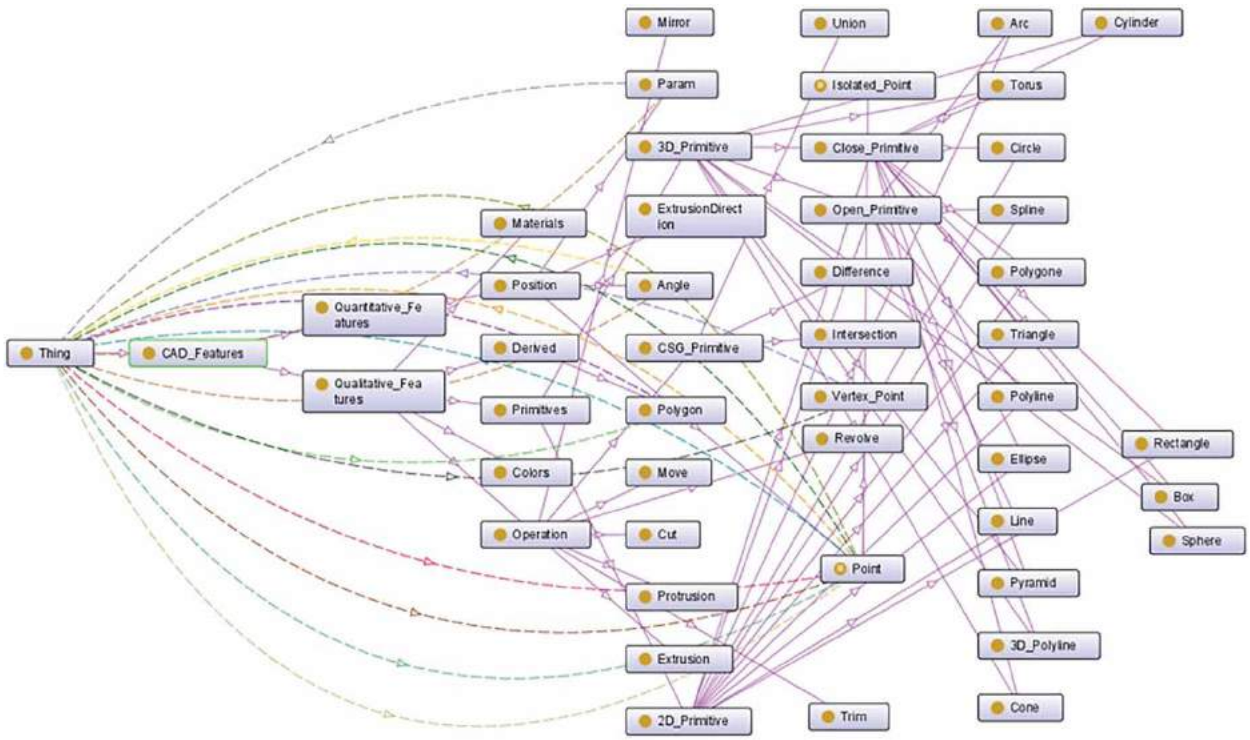


Figure 6. OCAD ontology for the designer systems.

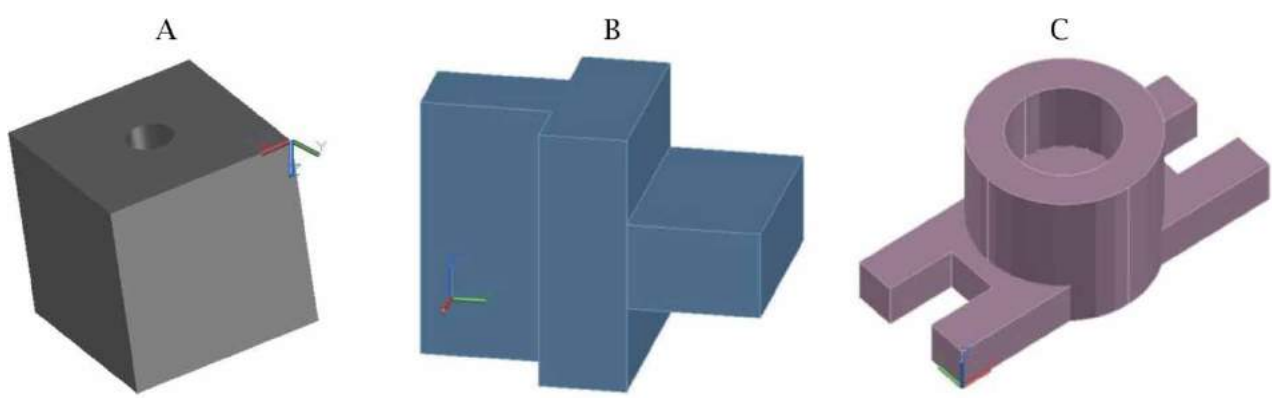


Figure 7. Output from the integrated platform: (a) simple box with a hole; (b) a double T block; (c) H-block with hollow cylinder.

the solid geometries in the user interface. Knowledge needs to be arranged in a pre-defined pattern (for the respective macro system) to be visualized by the CAD systems, hence schema mapping is useful. Fig. 7 shows the output from the integrated platform. To represent these shapes, knowledge is extracted from the ontology and then transferred to the macro file for the next step of visualization in the CAD interface. The extracted knowledge (from the ontology) includes various shape primitives (box, cylinder, etc.), CAD operational commands (extrusion, revolve, protrusion, etc.) and quantitative features like position of the shape, direction for extrusion, etc. All these extracted information are arranged in the macro file and thus solid geometries are visualized.

5. Conclusions and future direction

This research work shows a result from an effort to integrate mereotopological formal ontology and commercial CAD systems. In this paper, we discussed the concept to transfer information about basic mereotopological primitives to CAD systems by using the macro-parametric approach. The proposed framework is tested for three simple models. Complex solid geometries are not tested using this proposed framework and in future this work can be extended for complex solid models. The structure of macro file systems varies from CAD to CAD and for this research work, only one CAD system was utilized to test the proposed framework. In future, heterogeneous commercial CAD systems will be used to extend this research effort.

In this paper, only spatial perspective of mereotopology is highlighted; however, mereotopology has another facet to represent the temporal entities (time) and that branch of research activity is termed as 'spatiotemporal mereotopology'. Hence, this research is a preliminary implementation to realize a 'spatiotemporal' CAD system. Traditional CAD system can generate static models; however, often product models have dynamic (temporal) behaviors to be captured in the CAD models. This dynamic behavior is often caused by production process and functional requirements. In the future study, we will extend more complex assembly models and multi-stages of spatiotemporal mereotopological relationships. Also, ontological design model generation from CAD models will be addressed in the future work.

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