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ONTOLOGY-BASED DESIGN KNOWLEDGE MODELING FOR PRODUCT RETRIEVAL

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1 Introduction

Nowadays, computer-aided tools have enabled the creation of electronic design documents on an unprecedented scale, while determining and finding what can be reused for a new design is like searching for a "needle in a haystack." For example, as reported by Marsh [1], there are approximately 40,000 documents produced in the design of a single engine in an aerospace company. The availability of such extensive knowledge resources is creating new challenges as well as opportunities for research on how to retrieve and reuse the knowledge from existing designs.

There are three major considerations regarding how to reuse design knowledge: representation, retrieval, and adaptation (analysis and synthesis). This paper focuses on the first two issues. We classify the current design representation methodologies into three major areas: function modeling and function-based design [2-13], shape/geometry-based engineering information search methods [14, 15], and attribute-based retrieval [16]. The last one can be further classified into case-based retrieval [17, 18], online product catalogs [19-21], and Product Data Management (PDM) and Product Lifecycle Management (PLM) systems [22, 23].

Despite the progress made, none of these approaches satisfies the realm where design engineers need to reuse previous design knowledge at different levels of granularities such as assemblies, components, features, and geometry elements and from different perspectives such as structures, functions, behaviors, and manufacturing requirements [24, 25]. We need a framework that can provide the formalism to guide the modeling process of the design knowledge as well as the primitive concepts to describe the design knowledge. Conventional research has failed to propose such a framework and none of it considers the multi-granularity and the multi-perspective representations of the design knowledge, especially a well-defined transformation schema among functions, behaviors, and structures [26]. Therefore, the objective of achieving the unified knowledge-based design-by-reuse environment has not been accomplished.

In this paper, we propose an approach to tackle the problem. The approach involves: 1) exploring a systematic and intuitive way of design knowledge representation by using ontologies; 2) extracting the design knowledge which has been embedded implicitly and incrementally in the 3D CAD models during the design process; 3) developing an ontology-based personalized retrieval system to assist engineers in finding suitable previous designs; and 4) addressing the transformation between user-specific semantics and system semantic representations.

2 Background

2.1 Classification of design knowledge

Mechanical design, either adaptive or inventive, can be considered an information transformation process driven by the application of design knowledge [27-29]. What is design knowledge? One of the inherent difficulties in classifying design knowledge is the multiple ways it can be done, even by assuming that the 3D CAD models are the only instrument of design knowledge. A single CAD model can represent many things because the information it contains can be mapped to concepts at different levels of abstraction. The distinction and association between these abstract and more concrete descriptions constitute an important step towards organizing the design knowledge.

Historically, knowledge, information and data have been treated as synonyms [30] or relative concepts [31]. However, in the more recent literature about knowledge management and engineering design, attempts have been made to distinguish them and therefore allocate them accurately [27, 32]. In our research, we define design knowledge from the reuse perspective. It refers to the implicit contents which are embedded in the designs as well as the explicit contents which are extracted from the designs. Design engineers use these contents to understand prior designs. Design knowledge includes representations at different levels of abstraction: data, information, and knowledge. Data is the syntactic unit of the information, either numeric or symbolic; information is the structured representation of the data, such as relational tables for text data and solid models for geometry data; and knowledge is the explicit generalization from the information model. Knowledge includes both domain-specific facts, such as rules of design for manufacturing, and processes such as physics, mathematics, and mechanics. The processes are used to assist the inference at the semantic level within the information models.

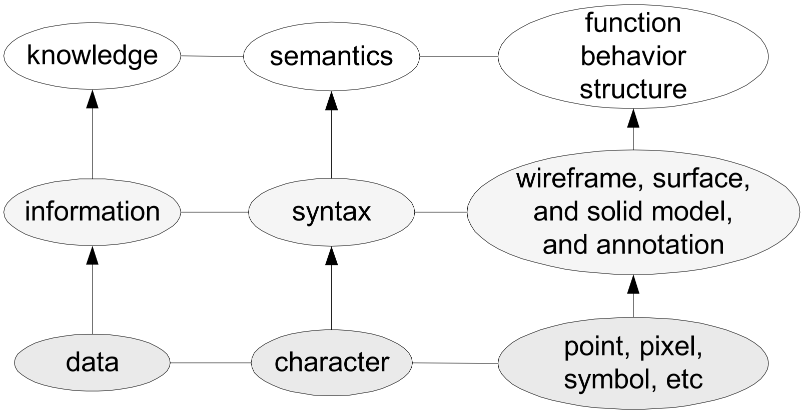

Figure 1. Classification schema of design knowledge

It is important to interpret design knowledge from the cognitive perspective since design is the confluence of technical processes, social processes, and cognitive processes [33]. In a similar way to which data is the basic unit of information representation, character refers to the basic visual and verbal elements, e.g. pixels, 3D points, and words; syntax refers to the way characters are arranged without considering the meaning of such arrangement; and semantics deals with the meaning of these elements and the meaning of their arrangements. Figure 1 shows the corresponding classifications of design knowledge from the perspective of information management and cognition.

2.2 Importance of design knowledge reuse

Why is design knowledge reuse important? In mechanical design, the same part and physical behavior can be found in different products. Therefore it is straightforward and pragmatic to reuse an existing design in a new product. Also, the physical environment such as engineering databases and computer networks makes reuse in design possible and desirable within teams either collocated or distributed. Furthermore, reusing a good existing design reduces efforts as well as risks at the design stage and downstream stages because proven products preserve validated design knowledge. Also, not using knowledge that has been found unworkable reduces the possibility of making similar errors. Design by reuse can save up to 75% of non-recurring costs because most of them are committed by the end of the design process [33]. Reuse can reduce lead time by taking “short cuts” and eliminating many downstream activities as well as iterations. By reducing part proliferation, design knowledge reuse lowers product variability and improves inventory efficiency. It leverages procurement by referencing the cost of the previous designs.

Furthermore, empirical studies conducted in [34-36] show the importance of design knowledge such as functions, behaviors, and structures in understanding existing designs.

Despite the benefits, industries find that design knowledge reuse has only met limited success in practice. Design engineers always find it hard to locate previous designs for their needs [37]. The reasons for this are that there is no mechanism for engineers to be aware of the contents or knowledge embedded in the previous designs and retrieve them using their own vocabulary; and the design knowledge underlying the physical design structure is not adequately represented and indexed. There is an absence of a systematic framework to integrate the design knowledge being generated from different product information facets, such as associating the functional semantics with the 3D structures.

3 Definitions

To allow the reader to follow the remainder of the paper, several fundamental terms are defined formally here.

Assembly: The attachment of a machine or mechanism among its components to achieve certain functions.

Sub-assembly: A mechanically linked group of components pertaining to some specific sub-functions of the assembly.

Component: An individual geometric entity or a combination of features to achieve some specific functions. Examples of components are pins, shafts and their subgroups.

Part: An assembly, a sub-assembly, or a component.

Feature: A predefined representation and reasoning unit of design in which function and shape are integrated. The feature concept used in this paper is in terms of geometry as well as functionality. Examples of feature concept are holes and slots.

Structure or form: The shape of the parts and mating relations between parts, or the geometry and topology of features, of one component, or between two components.

Behavior: The response of the parts to the input from other parts or from the environment. In this paper, we focus on the intended behavior. Behavior can be described either qualitatively such as clockwise rotation, or quantitatively, such as the attributes and their values which describe the rotation.

Function: The abstraction of the behavior. This is how humans perceive the purpose of the part or the feature and is represented qualitatively as a transitive verb (and objects). Unlike electronic design or some other specific design domains such as modular design, in general mechanical design, function sharing and function redundancy must be taken into account.

Meta-Knowledge: "Knowledge about knowledge." This refers to the elemental concepts and relationships of the ontology model in this paper.

4 Overview

Mechanical design is the process of materializing the design information into a physical prototype driven by the design knowledge. The 3D CAD model is one of the prevalent data formats and information models. It implicitly represents the design knowledge involved during the design process, such as requirements, specifications, functions, behaviors, and structures. For design knowledge retrieval and reuse, the extraction of such knowledge from existing 3D CAD models is necessary.

Our knowledge representation model is represented by function-behavior-structure ontology (FBSO). The model represents the three fundamental aspects of the design knowledge and infers how the functions and behaviors are achieved based on geometry reasoning. We derive the design knowledge about the function and the behavior from the 3D CAD models. It directly answers many questions about the design intent and sets the stage for further analysis as well as design by reuse.

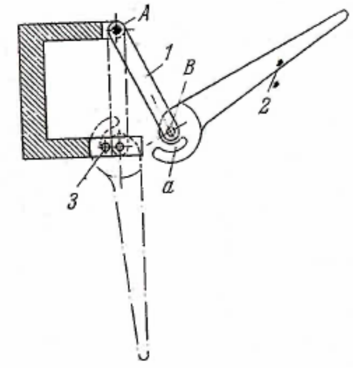

Figure 2. Locking mechanism from [40]

We seek to develop concise and complete descriptions of the design knowledge. These descriptions should be both qualitative and quantitative. Qualitative descriptions characterize the design functions and working behaviors of mechanical parts concisely and abstractly [38, 39]. They allow design engineers to design and modify complex mechanisms before delving into details. On the other hand, quantitative descriptions provide the details for tasks which qualitative descriptions lack. The complete description combines both methods to avoid the deficiencies of using only one method. It allows the design engineer to understand, evaluate, and reuse previous designs under various conditions. Figure 2 shows an example of the complete description of a locking mechanism. The mechanism is to lock the covering plate.

Lever *2* and plate *1* rotate counter-clockwise to lock and clockwise to unlock. The diameter of pin *3* should be equal to the width of the curvilinear slot *a* with the sliding fit tolerance.

Extracting design knowledge from 3D CAD models requires recognizing the shape of each part, examining interactions between parts, and constructing the knowledge base to support the reasoning process. Meta-knowledge is also needed to fulfill the inference. This is a nontrivial task even for a simple design with only a few components. Design engineers often derive the function and behavior of a complex system using three steps. First, decompose it into subassemblies, components, or features. Then derive the function and behavior of the targets at the lowest. Finally, compose the results.

The FBSO model is not only used to assist the meta-knowledge acquisition and the reasoning process, but also provides the contents to annotate and index the parts. We developed an automatic structure analysis algorithm which analyzes the 3D CAD model and generates meta-data about its structure. These meta-data are then transformed into the corresponding concepts and relationships in the ontology model. An ontology-based retrieval algorithm is developed to support the design knowledge retrieval.

At the analysis stage, the inputs are the project folder including a 3D CAD assembly file and all its component files; the outputs are the design knowledge extracted from these files, which are the descriptions of their functions, behaviors, and structures. At the retrieval stage, the input query is the keyword description about the function, behavior, or structure of the part in plain text; the outputs are previous designs ranked by their relevance to the query.

The FBSO model integrates several correlated ontologies such as the function concept ontology, behavior concept ontology, and structure concept ontology. The contents of these ontologies are generalized from engineering encyclopedias, mechanical design handbooks, standards, patents ([40-42], STEP API 224, www.uspto.gov), etc. Some pragmatic issues are also considered. For example, we allow design engineers to create and edit the contents of these ontologies.

5 Ontology modeling

Ontology is an abstraction of the domain. It can be seen as a realization as well as a practical argument for knowledge-based processing [43]. The ontology model defines a set of representational terms which we call concepts, the attributes/constraints of each concept, and the relations among concepts. It can explicitly conceptualize the target domain as well as model the background knowledge of the domain knowledge base. The ontology represents the domain at both the syntactic and semantic levels and integrates different inference mechanisms within one structure through relationships. It acts as the data structure and the representation model to systemize the "ill-structured" design knowledge.

Figure 3 shows the layered FBSO model for design knowledge representation. The ontology models at each layer are distinguished by different levels of generality [44]. The concepts in a certain layer are described in terms of the concepts in the lower layer. At the generic layer, the spatial geometry ontology defines the fundamental concepts and relationships of the spatial geometry such as the terms of plane, axis, horizontal, and vertical. The physics ontology describes the physical principles of the domain such as the principles of motion, force, and material.

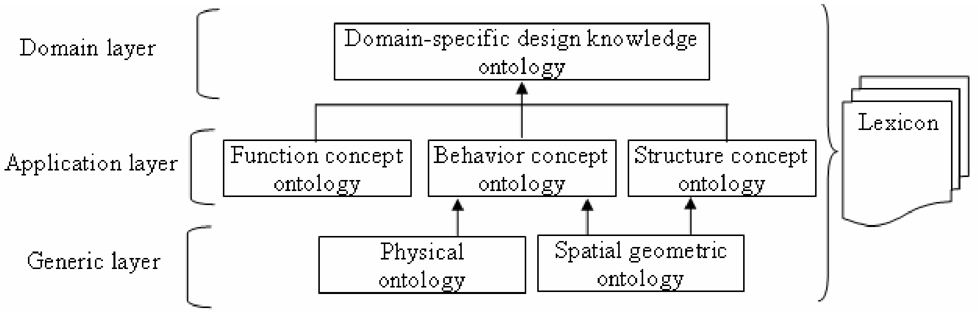

Figure 3. The layered FBSO model

The application layer includes the function concept ontology, behavior concept ontology, and structure concept ontology. The function concept ontology specifies the functional concepts which represent the purpose of the structural concepts and the hierarchical relationships among the functional concepts, while the behavior concept ontology describes the fundamental concepts about behaviors and behavior attributes, and the relationships among these concepts as well. The behavior includes motion behaviors, material behaviors, etc. The structure concept ontology includes feature ontology, mating relation ontology, and component ontology. Leaf entries in the structure concept ontology are pre-annotated by using the concepts from the function ontology and the behavior ontology.

One focus of this paper is the model and the automatic generation process of the domain-specific design knowledge ontology at the top layer. The concepts and the relationships formulate the domain-specific design knowledge extracted from the CAD models. It demonstrates the different aspects of the design knowledge by using the function, behavior, and structure concepts, as well as the relationships between these concepts.

Each ontology is represented as a directed graph structure with a root, each node represents a concept, and each arc represents a specific relationship. In general, each concept in the ontology at the application layer as well as of the domain-specific design knowledge ontology contains a unique reference/pointer, which refers to its comprised term(s) in the lexicon. These concepts/terms are to be matched with the keywords in the user's query during retrieval. Query processing is discussed in the next section.

5.1 Relationships

Concept nodes are connected by relationships/arcs. There are eight kinds of relationships in our ontology: specialization (is_a), part-whole (is_part_of), achievement (has_function_of), spatial relation (are_assembled_by and are_positioned_by), characteristic (is_attribute_of and is_constraint_of), and instance (is_value_of). All these correspond to key primitives in typical ontological semantic models for mechanical designs.

Is_a: It also can be phrased as is_a_kind_of or is_a_way_of. This relationship represents concept specialization. A concept represented by C_j is said to be a specialization of the concept C_i if and only if C_j is a kind of C_i. For example, the concept "prismatic joint" is_a_kind_of concept "kinematic joint" and "axial alignment" is_a_way_of "alignment." In other words, "alignment" is the generalization of "axial alignment."

Is_part_of: A concept represented by C_j is_part_of a concept represented by C_i if and only if C_i has C_j as a part, or C_j is a part of C_i. For example, "cylindrical joint" is_part_of "revolute joint."

Has_function_of: Each structural concept may correspond to several functional concepts and vice versa. This relationship refers to the connection between a function concept and a structural concept.

Are_assembled_by: Two or more structure concepts such as features and components can be assembled together through a mating relation concept such as a kinematic joint concept or a rigid attachment concept.

Are_positioned_by: The specific relative position between two feature concepts can be represented by a mating relation concept such as a relevance condition concept between them given that they do not physically touch each other.

Is_attribute_of: In general, each structural concept such as a component and a feature has several metric attributes governing its geometry. For example, “length” is_attribute_of “pin,” and “radius” is_attribute_of “cylindrical surface.”

Is_constraint_of: A constraint concept specifies the type (numeric/symbolic) and range for the value of an attribute concept. The relationship between the constraint concept and the attribute concept is defined as is_constraint_of.

Is_value_of: The value concept can be recognized as an instance of an attribute concept.

6 Meta-knowledge acquisition

Functional concept ontology

The function concept ontology provides the vocabulary for the functional description of the concepts in the structure concept ontology as well as the relations among the functional concepts. Our vocabulary of functional concepts is based upon several previous efforts in this area such as Functional Basis [3], NIST design repository [45], TRIZ [46], and Failure-Experience Matrix [12]. However, our approach is different from theirs. We systemize the semantic relations between the functional verbs rather than group the verbs at different levels or organize them as a flat list. Although the functional representation of “transitive verb (and objects)” is domain-specific, the definition of each function concept is general, and so is the approach of specifying how the function is achieved by the structural element. Each function concept is a transitive verb with the semantic relationships defined with other verbs. Examples of these relationships are superordinate and subordinate. The function concept ontology is developed by tailoring the general linguistic ontology such as WordNet [47]. Each functional concept is a verb with its synonyms and inflections. The functional concepts are grounded in the structure concept ontology and behavior concept ontology, such that the functional concepts are defined operationally. “Operationally” means the definition enables automatic computation and human understanding.

Behavior concept ontology

The behavior ontology is organized with an is_a relationship to define the inclusion and the inheritance between different levels. Each behavior concept has attributes. Figure 4 shows part of the behavior ontology, i.e. the motion behaviors. There are two primary motions: singular motions which refer to the motion of a component, and pair-wise motions which represent the motion of a pair of components. Examples of the singular motions are translation

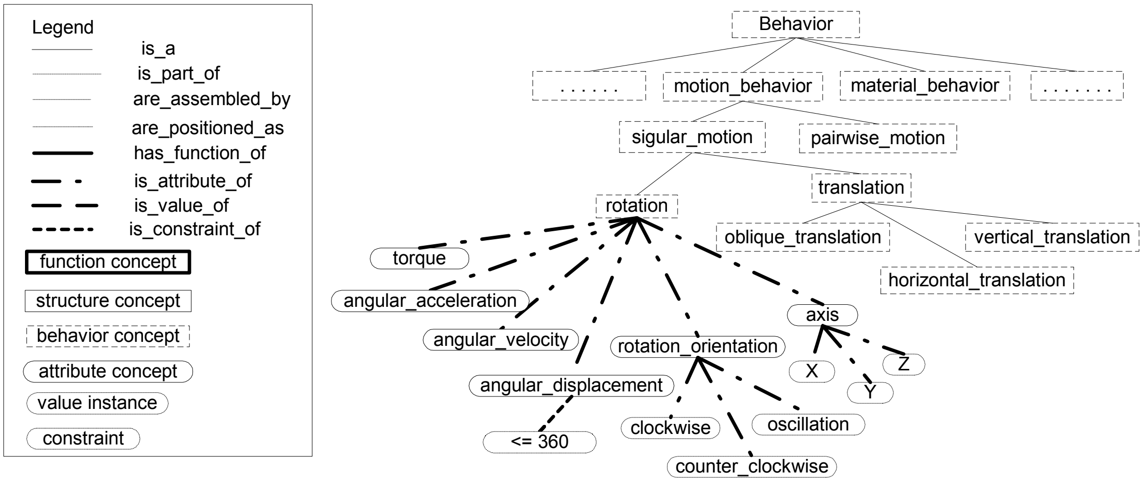

Figure 4. Behavior concept ontology (motion behavior)

and rotation. Examples of the pair-wise motions are co-planar pair motions and orthogonal pair motions. The concepts about the motion behavior are associated with the corresponding concepts in the function concept ontology, such as rotation → rotate.

Feature ontology

Two major issues in extracting functional knowledge from the 3D CAD models are identifying the features on a part and the inter-relationships between two mating parts [48]. The feature ontology is a hierarchical organization of generic shapes defined from the functional point of view, i.e. each feature is associated with its potential functions, as well as the geometry definitions. The geometry definitions are expressed as a set of rules and facts [49]. For example, a linear slot may have the function of guiding. Its geometry definitions are that it has adjacent top and side faces; all faces are parallel to a common axis as well as sequentially adjacent to one another; and all faces are simultaneously adjacent to the end face. The feature ontology is by no means exhaustive, but is nonetheless able to cover most of the features in many designs. Also, because we allow the users to define the feature ontology by themselves, we assume that the completeness is not a problem.

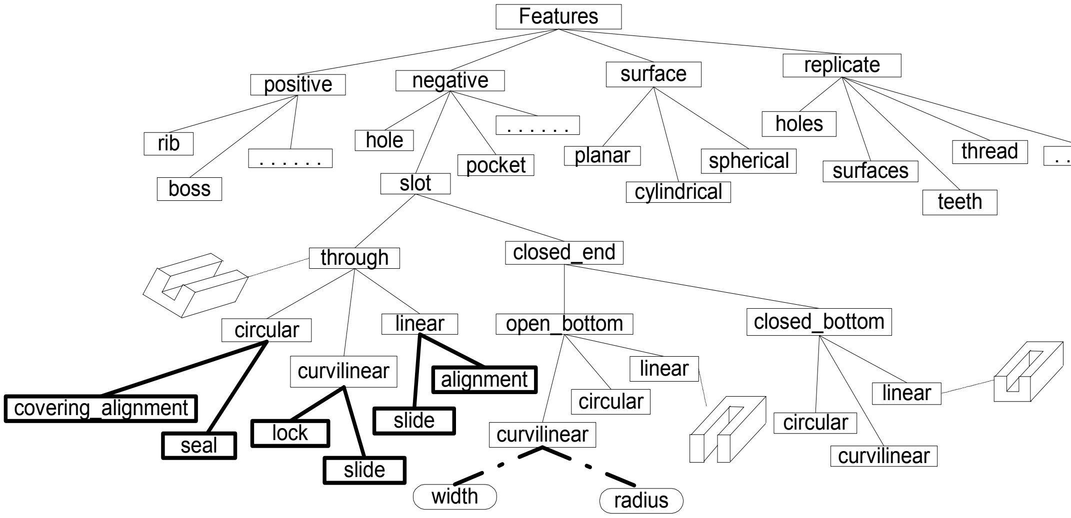

Figure 5. Example of feature ontology

Four primary feature types are defined in this paper: positive, negative, surface (curvilinear and planar), and replicate (pattern of features). The first two primary features are also defined as "feature entity." A surface feature is introduced because surface may have specific functions, e.g., the planar surface of a vise has the function of hold. Figure 5 shows the example of the feature ontology with geometric illustrations for some feature concepts.

Component ontology

The component ontology is structured in a similar way to the product catalog used in many companies. It classifies the most important names, each of which implies a particular functionality and presents finite kinds of generic shapes. More specifically, these shapes are governed by some attributes. Examples of these components are shafts, pins, keys and their subgroups. It is by no means exhaustive, but it covers most of the components found in mechanical designs. One of the differences between our component ontology and other product catalogs is that all the component instances are recognized and classified automatically instead of manually with respect to the pre-defined classification schema [50].

Mating relation ontology

A mechanical assembly can be viewed as a collection of components with a set of spatial mating relations between the components [51]. This is a fundamental view at the detailed geometric level since the mating relations specify the relative spatial relations, constraints, and fits between surfaces rather than components or feature entities. Each concept in the mating relation ontology is also defined functionally and geometrically. The mating relations include rigid attachments, kinematic joints, and reference conditions.

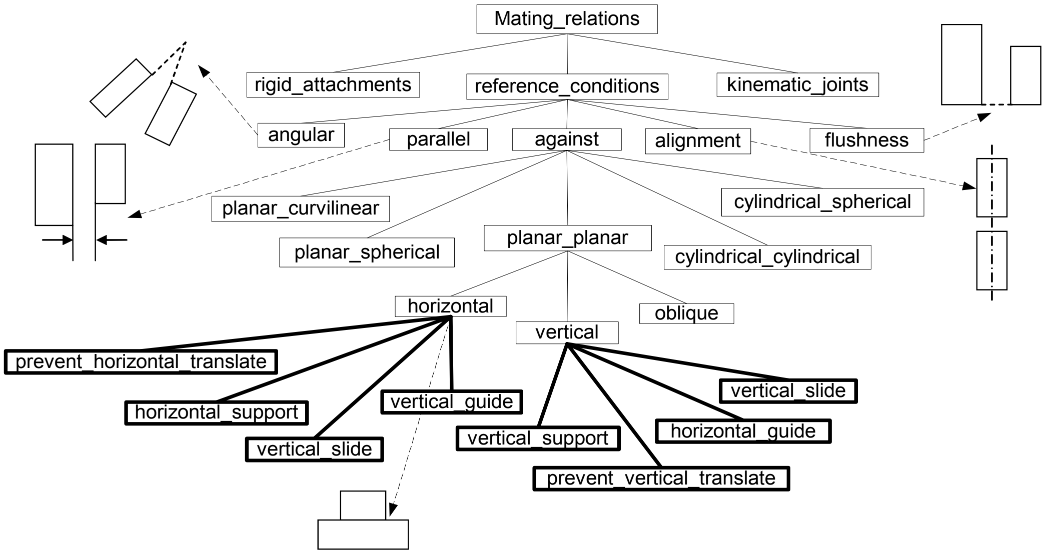

Figure 6. Mating relation ontology

Rigid attachment permits no relative motion between two mating surfaces. It is either permanent or detachable. Permanent attachment includes welding, riveting, soldering, brazing, inference fit, etc. Detachable attachment includes fasteners, transitional and clearance fits, etc. We do not consider the relationship between functions and tolerances in the current research.

Kinematic joints represent physical constraints of one component or feature entity on another. They are grouped into "low pair," such as revolute joints, prismatic joints, screw joints, cylindrical joints, and spherical joints [42], or "high pair." In our research, the kinematic joints only include "low pairs." The "high pairs" are classified as "against" type of reference conditions.

Reference conditions involve the relative orientations between two or more surfaces which imply some functional meanings. For example, two planar surfaces against each other could mean one supports the other. Figure 6 shows a portion of the mating relation ontology with geometric illustrations for the examples of some reference conditions.

Design knowledge ontology

The input 3D CAD model is recognized based on what features and components it has, and the mating relations between the features of two parts. The instances of their correspondent structure concepts in the structure concept ontology are generated, and so are the instances of the associated function and behavior concepts. The relationships are identified between these concepts such as "are_assembled_by." If the component concepts or feature concepts have pre-defined geometric value concepts, these dimensions are also extracted.

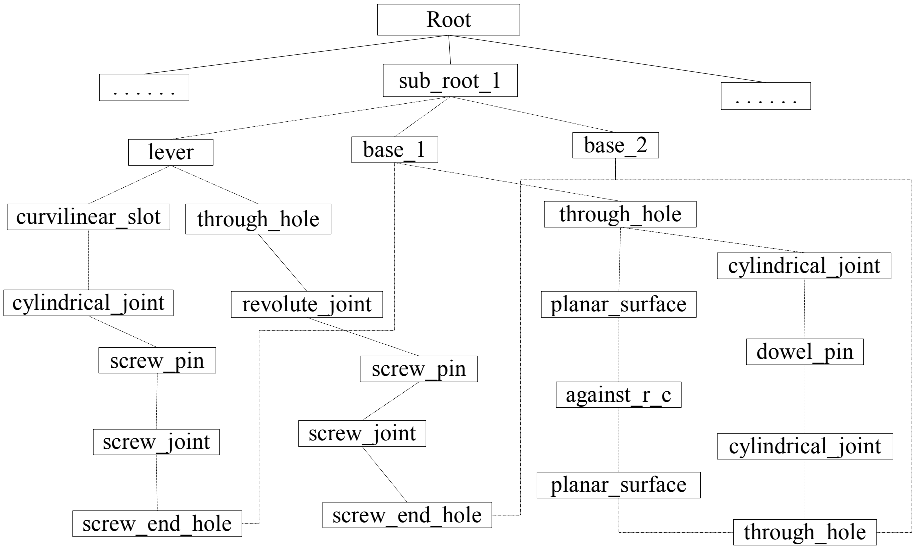

Figure 7. Design knowledge ontology (structural aspect)

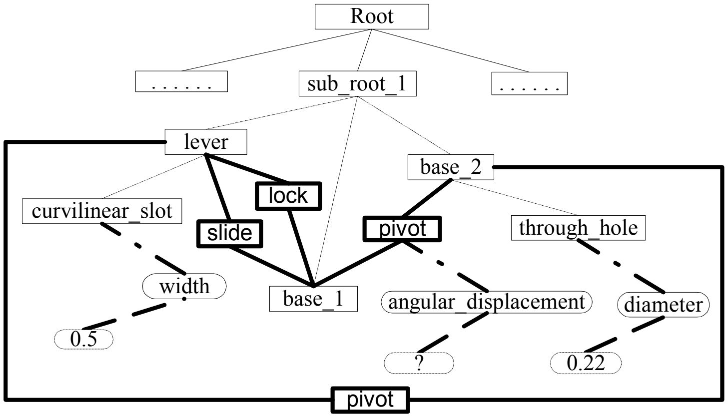

Figure 8. Design knowledge ontology (functional and behavioral aspects)

The design knowledge ontology is used to annotate and index the 3D CAD models based on the meta-knowledge extracted from these models. As mentioned before, the extracted design knowledge, i.e., concepts and relationships, is represented in a directed graph structure with a root node. Each graph is used to automatically extend the root node concept of the design knowledge ontology, which is either a generalized concept of all the products a company produces, or a concept of an assembly. For example, car is a generalized concept of all models of cars of an automotive company. A reference to the project folder or the assembly file is assigned to the "dummy" root node of the generated graph (e.g., "subroot_1 in Figure 7). Each structure concept also has a reference to the component file to which it belongs. The design knowledge ontology which describes the locking mechanism of Figure 2 is shown in Figure 7 and Figure 8, respectively, for ease of illustration. Figure 7 shows the structural aspect and Figure 8 shows the functional and behavioral aspects of the extracted design knowledge.

7 Query processing

7.1 Concept disambiguation

The user's query is a list of keywords representing the query intents. The ontology provides concepts as index keys that are matched by the keywords: tokens are generated from the query; these tokens are matched with concepts in the ontology through the terms and their synonyms in the lexicon. Each term has a list of synonyms. The term is a synonym of itself.

False matches, which cause loss of precision and recall, result from associating a single keyword with more than one concept in the ontology model [52]. For example, "alignment_reference_condition", "axial_alignment", and "radial_alignment" share the common term of "alignment." For retrieval purposes, we need a metric that can resolve which concept is intended from the keywords.

Our *scoring region* metric which is adapted from the algorithm in [52] is to measure the relevance of the concepts to the user's query. The metric is based on an observation from linguistics: the way to disambiguate the meanings of a word in the sentence is by referring to its contexts such as the adjacent words, sentences, or paragraphs. Each scoring region refers to all the sub-concepts and the relationships under the same parent concept. The metric includes two separate measurements: number of hits (NOHs) and concept distance (CD). NOHs measures the number of unique matches between the keywords and the concepts in a region. The region with more matches has higher NOHs. To calculate the CD, we give positive weight to each relationship in the ontology model. Suppose two keywords used in the query are "alignment" and "translate," and further assume that there are only two concepts in each region which include these two keywords, respectively. The CD of each region is then calculated by traversing the graph from one concept to the other and adding the weight of each traversed arc. In general, the retrieved results are first ranked by NOHs, and then the CD is used to order the results which have the same NOHs. The region with the maximum NOHs and minimum CD represents the most relevant design.

7.2 Personalized retrieval

As the number of CAD models grows, it becomes more difficult for engineers to retrieve the parts which reflect what they want. We build a user taxonomy by tracking behaviors during retrieval and browsing. It is also important for a text-based retrieval system to establish the relationships between the system taxonomy and the user taxonomy. The personalized retrieval algorithm first collects the user's selections, i.e. 3D CAD models, and the corresponding concepts in the design knowledge ontology model. Then it adds the concept to the list of that keyword. This procedure forms the user profile, illustrated in Figure 9 as a dynamic table. The second column of the table records all the different keywords used by a specific user. The third column lists the selected concepts. The references to the associated CAD models are listed in the fourth column. During each retrieval, if the keyword from the user's query is in the user profile, all the CAD models referenced by the concepts of that keyword will be displayed, followed by the results further processed with the disambiguation algorithm. The user profile is updated whenever there are new concepts selected for an existing keyword.

	User keywords	Concepts in the FBSO model			CAD model instances			
1	Alignment	Horizontal_positioning	Vertical_support	Axial_positioning	Label 101	Label 32	Label 21	… …
2	Connection	Fastner_attachment	Welding_attachment	……	Label 33	Label 01	Label 10	… …
3	……	……	……	……	…	…	…	… …

Figure 9. User profile

8 Conclusion

A successful conceptualization of an ontological modeling schema for design knowledge extraction and reuse is reported in this paper. The needs for design knowledge reuse by industry as well as the problems faced by academia are identified. We propose a unified ontological theory which explicates the functional, behavioral, and structural design knowledge from existing designs. The primary elements underlying the ontology framework are described. Our approach systematizes the design knowledge based upon the automatic geometric reasoning of 3D CAD models. We propose definitions for the meta-knowledge of the ontology model. The definitions are indispensable to design knowledge acquisition. Ontology-based knowledge retrieval is discussed and our method enables the transformation between the user-specific semantics and the semantics of the system representation.

We believe that ontology representation is the crux of knowledge systematization by providing the theory of the content and the mechanism of inference. It structures the domain knowledge based upon different perspectives. An ontology model provides guidelines for capturing the target domain and indices for knowledge retrieval. The research can be regarded as a promising start in this area.

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