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A Design Method with Knowledge Modeling for Complex Product Based on Ontology

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ABSTRACT

Innovation design for complex products is a difficult issue in the military manufacturing industry. Ontology may provide a feasible way to rebuild the design process for complex products via sharing and reusing of design knowledge. In this paper, a design method used in the innovation design process of the complex products with knowledge modeling is proposed. Knowledge modeling is realized through ontology construction by combining the cycling evolutional theory of constructing ontology and OWL (Ontology Web Language)-based knowledge representation. As a case study, the satellite is selected as one of the complex products. The application domain of the satellite ontology is analyzed. According to the analysis result, the knowledge structure of satellite ontology is put forward based on OWL. The application of satellite product design shows that the method can effectively organize and reuse the knowledge resources in the innovation design of complex product and help companies to create more competitive products based on the existing knowledge and experience.

Keywords: Complex Product; Satellite; Ontology; OWL; Knowledge Modeling; Innovation Design

1. Introduction

Improving the capability of fast design and development innovation of complex products is important to raise the level of technology and competition in the military industry. Currently, knowledge-based design has become a new means for the leading companies to improve the products innovation design capability. Ford Motor Company, Chrysler Company and many other leading companies which adopt the knowledge-based fast design method have shortened their product development cycle by 30% - 60%. The Boeing Company has built up their knowledge management system based on PDM, which managed the experienced cases using for the design of new products. Boeing 777 developed by utilizing the knowledge management system created a recode of most successful and non-mistake development in the history of Boeing Company.

Compared to the advanced countries, the product design based on knowledge is in the developing stage in China. There exist some theories, methods and practical problems that shall be studied and resolved for the innovation design of complex products, such as the knowledge organization and reuse, innovation technology and method for the product innovation design. Therefore, in this paper, a study is made to combine the Ontology evolution cycle of the construction technology and the knowledge expression way based on OWL. Also, an ontology construction method which drives the multi-field knowledge integrated innovation is proposed for the complex products design. As a validation, the knowledge structure of satellite ontology is put forward and used for the product design.

The paper is organized as follows. Section 2 describes the product innovation design process and structure of design knowledge. Section 3 details about definition and modeling method of ontology. Section 4 provides knowledge modeling of innovation design for satellite products. Section 5 concludes the work.

2. Innovation Design Process Based on Knowledge

2.1. Product Innovation Design Flow of Self-Organizing

The development of new products is always transferred from the existing ones. The products characteristics are presented by a serial of characteristic parameters of the component units of expression, by a number of generational rules to combine and exchange via recombinants, which make the product be newly created quickly. The establishment of generating self-organizing rules is critical in the process. In the process of product concept design, it is described as: inputting the demand parameters, matching component unit automatically, generating product prototype according to the matched generated self-organizing rules to recombine the component product units using the Ontology Library, evaluating and selecting the prototype by using the Evaluation Library. Until satisfying the demand the process of recombining, evaluating and selecting is repeated to create a new product. The design method can be illustrated in **Figure 1**.

In the process of product self-organization evolution of innovative design, it is important to build Ontology Library that can support product to generate self-organizing rules with reasoning calculation and evaluation. The design ontology contains all kinds of knowledge, such as principle function, component information, the associated constraint relation among them, and the innovation product cases.

2.2. Demands and Structure of Design Knowledge

During the whole life cycle of complex product, the product design is the important stage which decides the most of the performance and cost. The process of product innovation and design is carried out by using the acquired knowledge, according to the user requirement, based on the analysis and decomposition of product functionality. Designing, creating and compositing product function principle make the matched product structure.

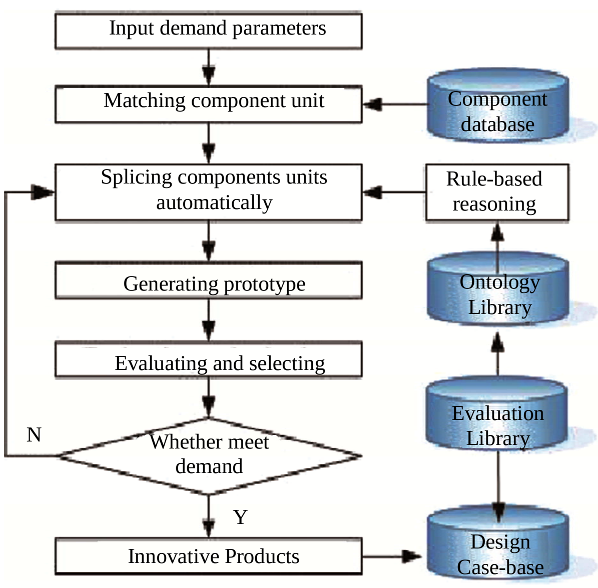

Figure 1. Self-organizing innovation design flow.

The process of complex product design contains many kinds of knowledge source, such as dominant and recessive knowledge. According to the condition of design assignment, the designer usually needs to find all kinds of acquired materials and the matched information given by vendors, and do the selected design of matching pieces. The existence of all those materials and information may be kept in the files, personal computer, all kinds of paper, and electronic copy or drawing paper. All those usually are dominant knowledge, but large of tacit Knowledge also exists in database and the mind of designer, such as the design experience and good practice of experts, and the tacit relations among the acquired explicit knowledge.

The knowledge resources of complex product design can be summarized as: design specification, design wizard, design manuals, computer programs, product model, design experience, case, outsourcing pieces of knowledge, as well as user demands, etc. Except design experiences, all the others are explicit knowledge. The historical data of products exist in company's PDM; the design experience usually exists in the personal note and memory of designers which is tacit Knowledge. The demand of designer is to store and fetch the acquired explicit knowledge easily, at the same time explore tacit knowledge and transfer it into explicit knowledge, by using some knowledge manage tools and methods, to find out the correct knowledge resources, and reuse it by appropriate form to support the design work. Therefore, the knowledge ontology top-level structure of complex product innovation design process is shown in **Figure 2**.

3. Definition and Modeling Method of Ontology

3.1. Definition of Design Knowledge Ontology

Ontology is a formal specification of a shared conceptualization. Shared conceptualizations include conceptual frameworks for modeling domain knowledge, content-specific protocols for communication among inter-operating agents, and agreements about the representation of particular domain theories. In the knowledge sharing context, ontologies are specified in the form of definitions of representational vocabulary.

Expanding the design ontology to eight-tuple [1]: $O := \left\langle C, P^C, \leq_C, R, P^R, \leq_R, \sigma, A \right\rangle$.

In the formula, ① C is a concept set. ② P^C is the set which contains many concept sets. ③ $\leq_C$ is a partial order based on C. ④ R is a relationship set, R: $C_1 \times C_2 \times \cdots \times C_n$, and $C \cap R = \Phi$. ⑤ P^R is the set which contains many relationship sets. ⑥ Function $\sigma: R \to C^+$ known as the signature. ⑦ $\leq_R$ is a partial order based on R, when $r_1 \leq_R r_2$, $i: 1 \leq i \leq |\sigma(r_i)|$ have $|\sigma(r_i)| = |\sigma(r_2)|$, and $\pi_i(\sigma(r_1)) \leq_c \pi_i(\sigma(r_2))$. ⑧ Assuming L is a logic lan- guage, L Axiom System A of ontology O is a dual: in $A := (AI, \alpha)$, AI is the set of Axiom identifier, $\alpha: AI \to L$ is a mapping, the elements in $A := (AI)$ known as an axiom.

3.2. The Ontology Construction Method of Cycle Evolution

Referring to Uschold&King [2], TOVE [3], METHONTOLOGY [4] and many other ontology construction methods, an applicable and feasible method for ontology construction is found out through our self-experience during building ontology, which is called cycle evolution for knowledge engineering method. The processes are shown as follows in **Figure 3**.

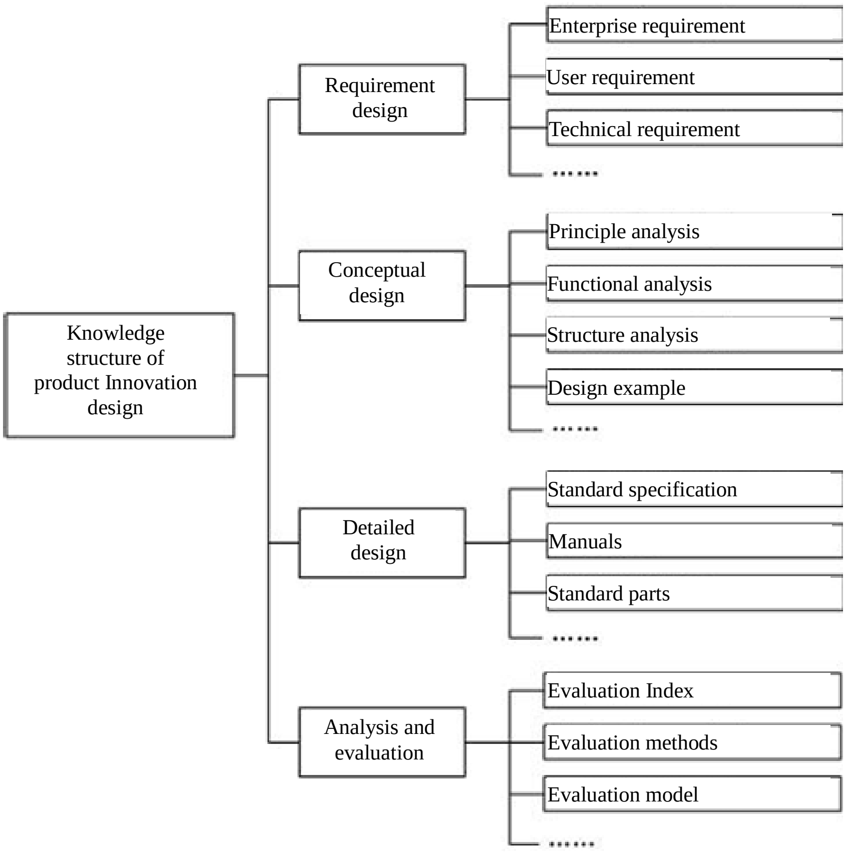

Figure 2. Structure of design knowledge.

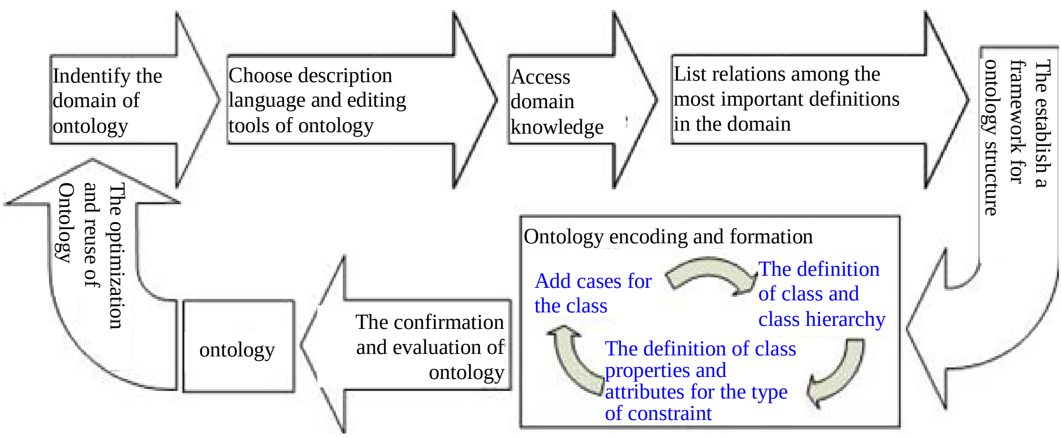

Figure 3. Ontology construction flow.

Step 1. Identify the domain of ontology

The first step to construct ontology is to decide ontology application needs, including information typies contained by ontology and users & defenders of ontology, etc. According to the application needs, identify the domain of ontology construction.

Step 2. Choose description language and editing tools of ontology

According to practice, choose the proper description language and editing tools, which can speed up the process of constructing ontology, and promote the late ontology reuse, integration and knowledge sharing among various systems. At the same time, make the research of the advantages and disadvantages of chosen tools of language, and the characteristics expressed during constructing ontology.

Step 3. Access Domain knowledge

Accessing the domain knowledge is the base and premise for ontology construction. By collecting filed information, we can know the present filed knowledge situation fully, to lay a foundation for the ontology construction. To attain field information we need to combine two methods: one is of reuse and transformation of the existing ontology, the other is to attain by using the related methods and ways, such as organizing the filed expert's construction or by using the knowledge acquisition tools to extract related fields classification system and knowledge from subject databases and network resources.

Step 4. List relations among the most important definitions in the domain

After totally knowing of filed knowledge, refine the most important definitions in the filed, and set out to state or explain it. The set out definition, after the confirmation of filed experts to become the core concept of sets for the filed ontology which will be constructed later. Meanwhile, the preparation of "set of terms" is to describe the process of choice of terminology, the final list of selected terms and their natural language description.

Step 5. Establish a framework for ontology structure

According to certain logical rules and relevance, divide a large number of domain concepts, and form different areas of work. In addition, estimate the importance of each concept, select key terms, express the knowledge in the field as accurate and concise as possible, and ultimately establish a domain ontology framework.

Step 6. Ontology encoding and formation

Ontology encoding and formation consist of three steps: the definition of class and class hierarchy, the definition of class properties and attributes for the type of constraint and added examples. The definition of class and class hierarchy is an important step in the ontology construction. There are three kinds of building methods: top-down method, bottom-up method and synthesis method. Choose terminology which describes independent existence object to be the categories in ontology, and can also refer to the previous established framework in last step to establish Class Hierarchy. And then describe the internal structures among concepts, once decide the object and the matched described attributes, in addition, we need to add constraints for some attributes. In this process, it can refer to relationship among descriptors and descriptors word limit in the field of thesauri, the meaning of the notes, and the relationship between words, such as in the field of type to add attributes and attribute constraints. Finally, add examples for categories, by describing the concept of the individual fields, their attributes and assignment constraints, we can gradually establish a knowledge base in this field. In this step if finding out the added examples which can be defined into categories, we need to re-started classes and class hierarchy of the establishment, until there is no conflict between examples and types. Enter the next step.

Step 7. The confirmation and evaluation of ontology

According to the clarity, consistency, scalability, completeness criteria and many other ontology construction guidelines, combine the views of experts in the field to confirm and evaluate the ontology prototype.

Step 8. The optimization and reuse of ontology

After confirmation and evaluation the core ontology is made as the final point of the initial constructions and the first point of ontology evolution, the knowledge engineering method with the cycle of evolution can be used to build core ontology and expand in the use process. Ontology evolution in many different ways can form a new body supported by computer systems. Furthermore, it can be defined new concepts and new relationships manually by experts in the field, or through machine learning and knowledge discovering and many other methods to discover new knowledge.

In summary, the method uses general knowledge engineering theory to build ontology. Also, it can be extended and improved through the cycle of evolution method.

4. Knowledge Modeling of Innovation Design for Satellite Product

4.1. Ontology-Driven Innovation Design Process of Satellite Product

As a typical complex Product system, satellite products complexity and the variability of the various factors in developing process determine the satellite design which is such a process that needs to go through the design phase of a number of progressive refinements and iterative approximation of the design process repeatedly. The main design has analysis, optimization and other several steps. With the design analysis process, we can obtain the formation of subsystems design to make the overall program tree, an assessment and optimization. By optimizing the process, we can optimize the specific parameter to the overall design program.

In a satellite design flow [5], the ontology-driven creative design role is mainly embodied in the applications of satellite design, analysis and optimization process, specifically manifested in all kinds of Satellite overall program feasibility stage study by Knowledge of various ontologies [6] and the support of the innovative design in optimize the design phase. As shown in **Figure 4**, an ontology-driven innovation design process flow of the satellite is illuminated. By using the ontology construction method of complex product mentioned above, we

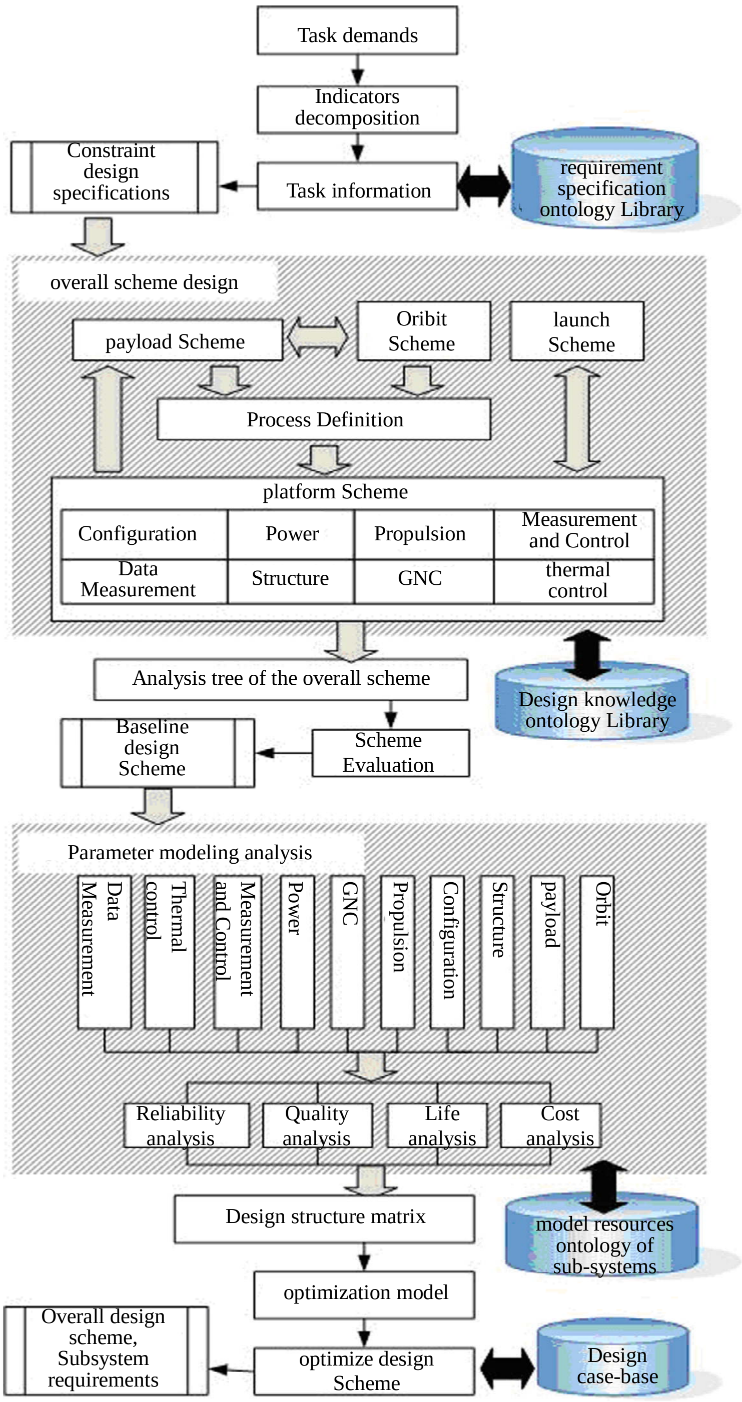

Figure 4. Ontology-driven innovation design process of satellite product.

can separately establish satellite requirement specification ontology, design knowledge ontology, resources ontology of sub-systems complexity changing model and the corresponding ontology library. In the process, the satellite requirement specification ontology library is established to support the analysis of design task requirements and setting the design specifications. In addition, the satellite design knowledge ontology library in the process is established to support the general design including payload, obit, platform, structure and so on. The ontology libraries established in the different stage in the innovation design process can provide the support functions of analysis, process, optimization and innovation.

4.2. The Examples of Knowledge Representation for Satellite Product Design Ontology

Data flow relations among the subsystem design models decide the knowledge flow relations of the satellite design process. The sequence of the relations among subsystems design missions may be serial, parallel. The complex-coupled feedback also may exist. As shown in **Figure 5**, a simple series/parallel data flow coupling relations consists of satellite design disciplines module, which has two data streams at the source of thermal control, power supply design. The plan reflected in the structure of subject knowledge is difficult to express if by a simple cross-classification system or thesaurus structure, but can be expressed by ontology technology.

The ontology top-level categories are combined shown in **Figure 2** and **Figure 5** which show the relations among satellite subject knowledge. Selecting relations among the concept of entities, the concept of attributes and concepts in conceptual design links illustrates the satellite product knowledge ontology expression through the implication concept, attribute associated mutual constraints, the definition of ontology axioms and many other building ways to form a satellite product design ontology model which has clear semantic relations.

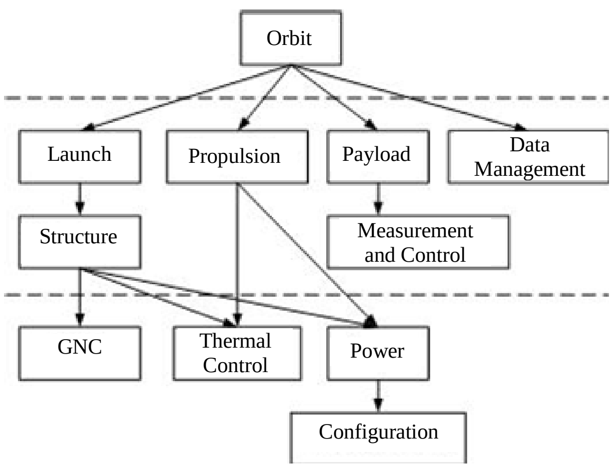

Figure 5. Relation of systems in the satellite design process.

OWL which is the latest specification by the W3C as a semantic network ontology language [7] can be used to clearly express a glossary of terms, as well as the relationship among these terms. The terms and their relationship are referred to as ontology. OWL has more mechanism to express the semantics, which overtake XML and RDF can only express content in machine-readable documents online. Therefore, this paper uses OWL language to describe design ontology model of satellite Product. Interception of the ontology fragment is described as follows:

```
<owl:class rdf:ID=“satellite”>
<owl:Restriction>
<owl:onProperty rdf:resource=“#type”/>
<owl:cardinality>1</owl:cardinality>
</owl: Restriction>
<owl:Restriction>
<owl:onProperty rdf:resource=“name”/>
<owl:mincardinality>1</owl:mincardinality>
</owl:Restriction>
</owl:class>
<owl:class rdf:ID=“Propulsion”>
<rdfs:subclass of rdf:resource=“#satellite”/>
</owl:class>
<owl:Object Property rdf:ID=“Propulsion Types”>
<rdfs:domain rdf:resource=“#Propulsion”/>
<rdfs:range rdf:resource=“#Orbit Scheme”/>
<owl:Object Property>
```

Semantic interpretation is one satellite product that only has one type, and at least has one name. Propulsion is a knowledge class of certain satellite product type inheriting product attributes knowledge, and also has the relations attributes of Propulsion Types. At the same time, making limits to Propulsion Types, such kind of knowledge only belongs to Propulsion knowledge field. Its value changes depend on the choice of the track program.

In the above semantic description, it is applied class axioms “subclass of”, relations attribute “Object Property”, axiom attributes “domain” and “range” and many other ontology concepts. Class axioms describe the inherit relations between two classes. The relation attribute describes a certain attribute or the relations between two types. The attribute axiom expresses the application and the values of the field basis and scope of attributes.

As the example process described above, it is to build the design knowledge ontology of satellite product, including the orbit, launch, propulsion, payload, data management, structure, measurement and control, GNC, thermal control, power and configuration and many other subject knowledge domain ontology. **Figure 6** is an example of display figure to show the related knowledge

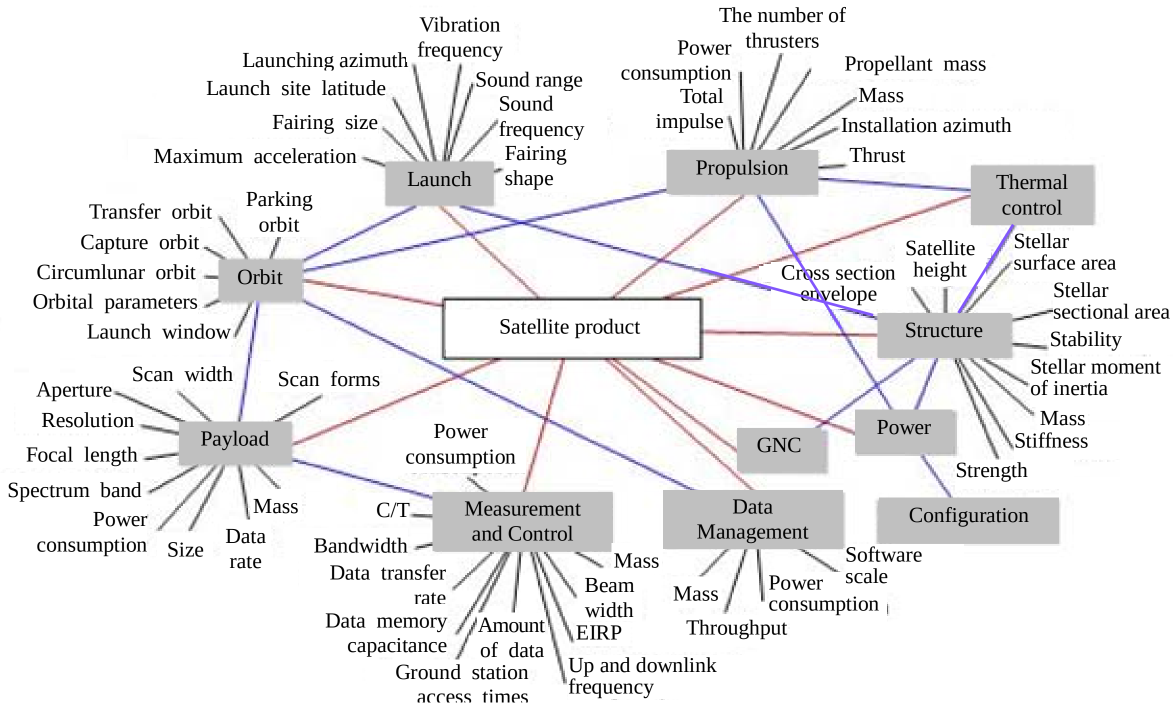

Figure 6. Knowledge structure of satellite ontology.

which has satellite product as the key type after founding ontology. The red line represents the inheritance and ownership relations, while the blue line expresses the link between the two types of relations.

5. Conclusion

In this paper the features of knowledge-intensive complex products are analyzed, and a theoretical study for the realization of knowledge ontology-driven complex product is made to provide some development concepts and practical experiences. Application examples of satellite product show the effectiveness and interoperability of knowledge ontology evolution cycle building method and OWL-based knowledge expression method in the application of complex product flow design. This method can effectively organize and reuse the knowledge resources in the product design process, and open out the implied relations among various kinds of knowledge, help companies to create more competitive products based on the existing knowledge. To realize the specific software framework, a further and in-depth study is still needed.

6. Acknowledgements

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