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Assembly planning based on semantic modeling approach

Wang Hui [a,*], Xiang Dong [a], Duan Guanghong [a], Zhang Linxuan [b]

[a] Department of Precision Instruments and Mechanology, Tsinghua University, Beijing 100084, PR China
[b] Department of Automation, Tsinghua University, Beijing 100084, PR China

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Abstract

There are still some challenges for the research of assembly planning. One of the reasons is the weakness in effective description of assembly knowledge and information.

An assembly semantic modeling approach is presented. Product (assembly) information is described by a three-level semantic abstraction (Concept/Function Level, Structure Level and Part/Feature Level). Semantic object is an abstract description of special product information, in particularly, for assembly relevant information in this proposed study. And by a multi-mapping mechanism supported by Semantic Interpreter and Semantic Dictionary, these objects could retrieve relevant technologic information, e.g. assembly design intention, basic function, assembly hierarchical structure, assembly relations and assembly knowledge, etc., from resource bank.

Based on this approach, an interactive assembly planning system is developed. Product semantic information model could offer much useful information for designer to finish the assembly (process) design and make determination in that process. Therefore, complex and low efficient computation in the design (or planning) process could be avoided.
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Keywords: Assembly planning; Semantic modeling; Abstraction

1. Introduction

Since the 1980s, much progress has been made to generate feasible assembly sequences even for complex assemblies [1–7]. However, there still exist difficulties in automatic generating good assembly sequences.

Such as, assembly work has a close relation with engineer's knowledge and product's design information, but due to the technologic status quo of product information modeling, product design and artificial intelligence, much information relevant to assembly design could not be described (modeled) and stored in product model, and obviously, could not be transferred from one design stage to another. Therefore, there are some difficulties, due to the lack of supporting information in product model (in fact, much important information could not be transferred from design stage to manufacture stage), in searching for good assembly sequences in a large search space and proper planning for assembling process with CAD tools, and so on. Meanwhile, alternatively, manual operating methods also have limitations. For instance, presentation of feasible assembly sequences to production engineers for a manual selection of good assembly sequences is not practical, because a large number of unfamiliar assembly sequences simply confuse and overwhelm production engineers [8].

Since there is a long way to realize the automatic generation of assembly sequences, assembly planning still relies on production engineers. Over the past several years, driven by strong demand of industrial applications, solutions of supporting interactive assembly planning systems other than the automatic generation of assembly sequences have been developed [9–11].

Generally, assembly sequence planning consists of two major activities: assembly modeling and assembly sequence generation. The efficiency of an assembly planning depends heavily on the way by which the assembly information is modeled. Thus, the importance of developing a good assembly modeling method as a primary step cannot be overlooked.

In this study, an assembly modeling method is proposed for its potential in integrating with assembly-related product

* Corresponding author. Tel.: +86 10 62773517; fax: +86 10 62773517.
E-mail addresses: wanghuisx@gmail.com, wang-hui03@mails.tsinghua.edu.cn (W. Hui).

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information and its capability to assist the generation of an assembly (process) solution effectively.

Assembly information modeling is the base of the research on design for assembly, which supplies the main information resource for product's assembly design. Therefore, in recent years, it is a highlight in this field.

The rest of this paper is organized as the follows. Section 2 introduces some background information and related works in assembly planning field. In Section 3, the assembly semantic modeling approach of the proposed study is presented, and product's semantic information model is described in detailed. In Section 4, based on the proposed semantic modeling method, an assembly planer is presented and meanwhile, the detailed procedure of assembly planning is given, too. The architecture of this interactive planning system is discussed in Section 5. Finally, Section 6 summarizes the conclusion.

2. Related work

Much work has been done since the early 1980s on the assembly sequences generation (or assembly sequences planning). These researches focused on sequences generating and sequences representation.

In 1984, Bourjault [12] presented the liaisons diagram (the ''graphe de liaisons fonctionelles''), which is a graph devised to represent an assembly. The graph uses the nodes to represent the components of assembly and the arcs to establish the relations between the components. Based on this diagram, a list of ''Yes–No'' questions are generated, and by answering these questions about the assemblability of parts to determine the assembly sequences. De Fazio and Whitney [13] altered the question's form. Their questions are not ''yes–no'', and require geometric reasoning and anticipation by the user. This method reduced the number of questions significantly. They also used the assembly sequences diagram to represent assembly sequences.

In the early 1990s, Homem de Mello and Sanderson [14–16] presented a directed graph, called *and/or graph*, to represent assembly sequences. Meanwhile, they also gave a new method referred to as the ''cut-set method'' to process assembly precedence relations.

Gottipolua and Ghosh [9] used a relational model to describe various logical and physical relations among the components of the assembly. That is a two tuples $<P, U>$. P is a set of symbols and each symbol corresponds to one part in the assembly. U is a set of four tuples, representing the relations between components in the assembly. Based on this, he presented the assembly sequences table (AST) to represent assembly sequences and designed an algorithm to generate assembly sequences through three directions (X, Y, Z) in Cartesian coordinate system.

However, these works suffer from a series of difficulties. In most of these works, simple assembly relational model is used to represent assembly (assembly sequences). Assembly is described by a diagram, graph or table: assembly = a cluster of parts + geometric contacts. So for an assembly with a large number of parts, the liaison diagram, and/or graph and AST will be very complex, and it will be very difficult to search for feasible/optimal assembly sequence in a large search space.

These difficulties are partially due to the weakness in the research of assembly modeling. As Whitney pointed out [17], assembly information model must ''be capable of capturing a diverse set of information needed to describe the entities and activities associated with assemblies and assembling so that designers of products, assembly systems, logistic systems, supplier relations, field support, and finally disassembly and recycling, can have access to the information they need.'' Therefore, new approaches for studying assembly modeling and sequences planning are necessary.

Bronsvoort and van Holland [18,19] put much effort in assembly feature modeling which was a part of a project called the DIAC (Delft Intelligent Assembly Cell). Based on object-oriented modeling method, they presented assembly features for specific assembly-related information (handling features contain information for handling components and connection features contain information on connections between components), and showed that such a method was useful both in assembly modeling and planning—including stability analyses, grip planning, motion planning and assembly sequence planning, etc.

The goals of the proposed study are (a) to develop an assembly modeling theory (assembly semantic modeling) and (b) to apply the assembly model in assembly sequence planning.

3. Assembly semantic modeling

3.1. Semantic modeling

The term semantic modeling, or semantics, means that this convention closely captures necessary information and provides a concise, high-level description of that information [20].

As a tool of information description (we uses it at product level), semantic modeling method could offer a bridge to build direct relationships among all various information to support product design.

Assembly semantic is the abstract description of assembly information—such as assembly relations, which implies the constraint between parts, assembly rule, and assembly knowledge, etc. Assembly semantics, that is more suitable for the engineer to express design intention, has the abstract characters in expression and is dependent of application domain [21].

For assembly semantic modeling, it applies semantics analyzing/semantic representing method and Object-Modeling technology into product/assembly modeling, including object-modeling, relations building, function description and semantic analysis. That is, with semantics method, product's geometric/non-geometric features, constraint conditions and related knowledge/information in the product design, could be organized to construct and describe product information model concisely, and therefore, they could be applied into assembly planning research.

In the proposed study, at product level, the research focuses include, formalizing the knowledge/information of product/assembly as semantic objects, multi-level abstraction, Semantic

Interpreter, Semantic Dictionary, and applications of this method in the assembly planning [22,23].

For a product or an assembly, the relevant information could be organized and utilized as the following:

- Realize product's semantic model: Unite various product information (and technique files) with the format of semantic objects, into an integrated product semantic information model.
- Design Semantic Interpreter: Realize the mapping between a semantic word and its entity object with engineering meaning.
- Design product semantic objects set–Semantic Dictionary: By using Object-Modeling Technology, construct a series of objects to describe corresponding engineering meanings. All these objects have well-defined meaning, or semantics. And designer's conception, constraints and design knowledge can be encapsulated in an efficient form.

Totally, semantic abstract obtains the semantic information and logic relations (that is, content of relevant technologic information), and Object-Modeling Techniques could realize the information's organization and description (that is, content's formalization).

Therefore, in product's assembly (process) design, this method could offer much more support or information than traditional geometric information, which is defined as a series of semantic objects with corresponding engineering meanings.

In addition, these semantic objects, in product model or in semantic objects set (Semantic Dictionary), are all organized into a hierarchical structure, by multi-level semantic abstract. For example, a component's assembling process which is just a sub-component of the assembly process of a product (obviously, it is defined as a semantic object), may include several sub-components: assembling component, assembling path, assembly tools, and so on, each of which also is a semantic object. This is also a process of information abstracting which forms a multi-level object hierarchical structure.

3.2. Abstraction pattern for assembly information model

For product design, abstraction is the process of ignoring what is particular or incidental, and emphasizing what is general and essential [24]. The semantic abstraction of assembly information shows in three levels, *Concept/Function Level*, *Structure Level and Part/Feature Level*. As Feng and Song ever wrote [25], "to achieve truly collaborative design and manufacturing, information representations of both design and process information must support multiple levels of abstraction for bi-directional communication."

To support assembly (planning) design, this abstract approach is useful and necessary for it could help assembly designers to know the intention and functional system of product.

From the designer's point of view, in the concept design and function decomposing process, a designer initially thinks in an abstract, functional manner to satisfy the requirements of the product, which will form the conceptual product's prototype. Then, by decomposing the initial functional – highly conceptual – into sub-functions step by step, and behavioral modeling for these functions, product's structure will be shown. It is the structure design process. Based on the product's initial structure, to satisfy corresponding functions, in a hierarchical structure, the necessary parts' form features, precision features, assembly features, etc., are organized. Meanwhile, by analyzing many important factors of product, some shortcomings can be returned to designer for redesign, until all of product's functional requirements are satisfied. In the following, Fig. 1 is an instance for illustrating the thought of the methodology of assembly semantic modeling/abstraction by three-level abstraction of an assembly. And Fig. 2 shows the conceptual architecture of product information model based on the method.

At the conceptual level, semantic information objects are just used to show the main functions, basic framework, and design intention. At the structural level, the assembly's structure, assembly relations, and components will be modeled fully. At the part/feature level, all parts' geometric features and geometric constraints will be shown.

Moreover, it is obviously that the logic procedure of semantic abstraction is in harmony with the top-down design. This shows that the proposed model could be a potential bridge between the assembly planning and assembly design, hence, useful for Concurrent Engineering.

So, we can understand that, this model is an information integrated platform for relevant product information, particularly, for assembly-related information. From the view of supporting the assembly (process) design, it offers a mechanism to integrate relevant resources and could overcome the noticeable shortcomings of traditional assembly planning, limitations in the domain of product's geometric information.

Necessary to mention, different to the traditional work of feature modeling, which focus on how to cast whole product's geometric and no-geometric information (of course, they are organized as features) into a united model, the proposed semantic information model is an concise structure which is organized by a series of information objects with special connecting relationships. These information objects, based on the mechanism provided by Semantic Interpreter and Semantic Dictionary, could retrieve relevant information from files with various formats in the resource bank, e.g. product's CAD model, assistant design documents, process files, databases files and so on. Therefore, by this modeling method, huge amount of information could be organized much more than the traditional product models (CAD model, or related feature models which have been introduced and realized) could.

As we have discussed, the product's semantic information model is an information integrated platform, and by the various semantic objects and multi-level abstract, it offers a powerful information indexing mechanism for necessary information, knowledge and data, which may spread out in various files with different formats. That is, this model does not store the huge amount of necessary information in the product model (in fact, it is too difficult to realize, at now technologic conditions). So, this model could be regarded as a *concise or abstract* integrated

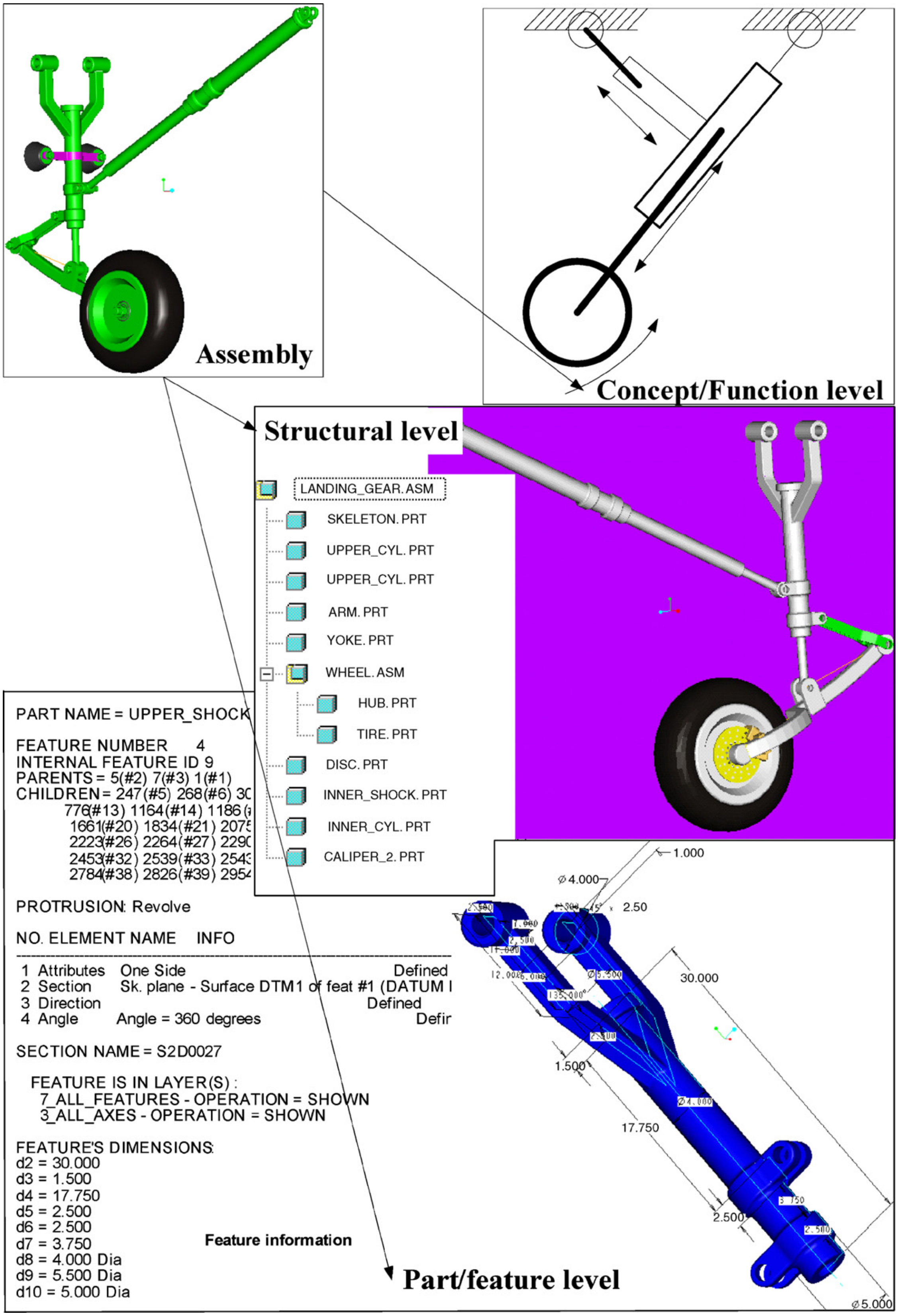

Fig. 1. Illustration for the conception of three-level abstraction of an assembly.

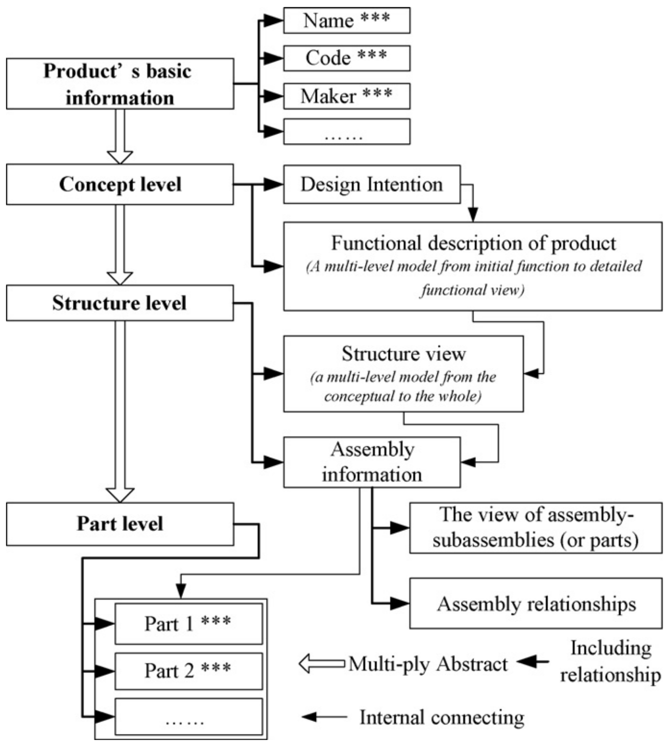

Fig. 2. Product semantic information model.

model with an ability to retrieve necessary information when necessary.

3.3. Semantic Interpreter and Semantic Dictionary

3.3.1. Semantic Dictionary

For Semantic Dictionary, in fact, it is a set of objects with corresponding engineering meanings. The basic framework of these objects is designed with Object-Modeling Technology. Based on a multi-level feature abstract, many fundamental classes are defined firstly, and then all kinds of applying objects are constructed. Fig. 3 shows the process of mapping from semantic object to real content in Resource Bank (*representing the place where resource is stored*, *such as a hard disk*).

In general, these objects, realized by Object-Modeling Technology, play a direct or assistant role in describing product's property. For example, for a product, we could define its *structure information* as an object *Structure_Property* using the following mode:

Object: Structure_Property
ObjectID: IDXXXXX

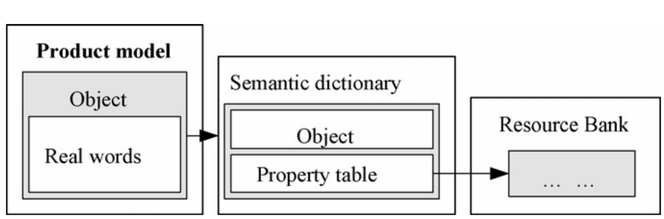

Fig. 3. Mapping from the semantic object in product model to real content.

Property Table:
Basic description
Structure model (*a multi-level abstract information object from initial structure draft to whole structure information*)
Structure view (*pointing to its 3D or 2D assembly model and relevant technologic files*)
Assembly relationships
Assembly tools
Tolerance information (*pointing to the model of tolerance chain*, *and relevant product tolerance requirement files*)
...

Obviously, the content of the Property Table needs more concrete description. And these items are objects, too, and they are defined in Semantic Dictionary with corresponding meaning. As a result, this forms a complex interpreting system and at the bottom, there are many real objects with simply engineering meaning.

Moreover, for the object in Semantic Dictionary, generally speaking, its property includes an address pointing to the Resource Bank, where the corresponding data file is stored. Such as, the property of *Assembly tools* may include an address where the technologic files relevant assembling equipments and tools (grasping or gripping tools) are stored. In addition, Semantic Dictionary, composed of semantics information objects, is also a flexible and extensible system to fit the complexity of industrial applications.

3.3.2. Semantic Interpreter

In a word, Semantic Interpreter offers a mechanism to build direct relation (mapping) between the semantic objects in product information model and the object in Semantic Dictionary. But how to realize this connecting mechanism is a problem. This problem is especially prominent in industrial applications where we have to face huge amount product information (data). Therefore, we try to design a flexible Semantic Interpreter, that is, it could adjust its two ends, as a convenient design for system evolution during industrial application.

The proposed way to realize the Semantic Interpreter could be illustrated as in the following. The Semantic Interpreter offers a series of semantic connecting relation objects, by which the interpretive relationship could be built between the objects

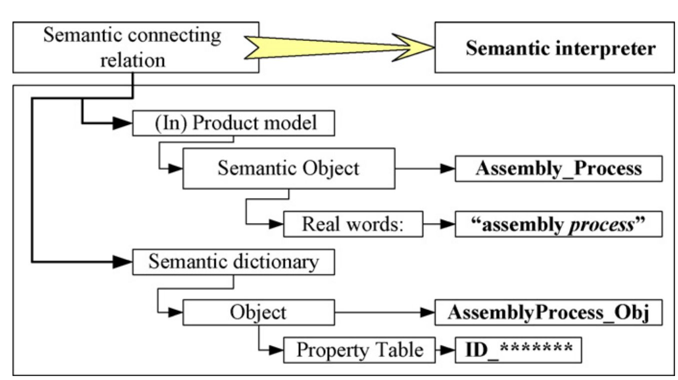

Fig. 4. The idea of Semantic Interpreter.

in product semantic model and objects in Semantic Dictionary. As the example of Fig. 4, a connecting relation object is defined to describe relevant information of assembly process. As it shows, this method, on one hand, could guarantee the concise structure of product information model, and on another hand, could offer an easy method (such as Assembly_Process → - Property_XXX) to seek relevant information in Semantic Dictionary, or deeply, in the resource bank.

3.3.3. Expandability

The expandability of object semantic information (of course, this is also a kind of flexibility) in Semantic Dictionary, is a key character of this method.

As above mentioned, the relationship between semantic object in product information model and its technique content in resource bank might be a multi-level mapping. Under the mechanism provided by Semantic Interpreter and Semantic Dictionary, any supplement or improvement, wherever it is taken, in object of product semantic model or Semantic Dictionary, in connecting objects of Semantic Interpreter, even in resource bank, could realized in an easy way. This change will just affect a limited scope, and not affect most of these relationships and the main structure of product semantic model.

This character is vital for engineering applications. Due to the fact of frequent change or improvement in applications, Semantic Dictionary's maintenance often is a laborious work. This method could reduce the burden, simplify the operations and improve the system's reliability.

3.3.4. Support assembly design and planning

As we know, if enough assembly-related information could be created and stored, then transferred from design stage to manufacture stage, much difficult and complex work now in assembly planning can be alleviated.

Based on this idea, we strive to develop related framework and mechanism of Semantic Interpreter and Semantic Dictionary. In fact, by this method of collecting assembly information, various complex objects are organized in product's information model. And the Semantic Dictionary and Semantic Interpreter offer the mechanism of connecting abstract name with the real content in resource bank (such as possible data in a technological file). Therefore this method's main goal is to collect and organize related information, and by the assembly information model, transfer the information from design to manufacture, for helping assembly designer.

3.4. Assembly information modeling approach

Based on all of these work, we define product's assembly information model as in the following form:

ASSEMBLY = <NAME, CONCEPT/FUNCTION, STRUCTURE, PART/FEATURE>

- *Name*: Name is an object which includes all the identifiers of assembly object, such as unique assembly name, classification name, assembly code, and others.
- *Concept/Function*: At the Concept/Function Level, product's design intent, initial conceptual prototype and multi-levels function representation information are captured and described.
- *Structure*: At the structural level, assembly's structure information and the semantic relations among the objects are described.
- *Part/Feature*: At the Part/Feature level, integrated with the feature-based modeling CAD system, the product digital model can be defined as input of the system, and its complex feature set is necessary to assembly planning system.

In the following parts, this model will be described more detailed.

3.4.1. Concept/Function Level

Customer's requirements are the origin of product's design, and by formalization, the requirements will be synthesized into the conceptual product prototype with functional information as the core.

Research on how to model the highly conceptual information, is sometimes called *Functional Modeling*. For the most commonly used methods for function representation, function is the predicate which specifies relations between input and output from physical structure. Such as the mapping: Function (structure, {input set}) → {output set}. According to the Functional Modeling methods, the product's function can be decomposed into many sub-functions continually, which will generates a hierarchical tree of function decomposition. One of the methods is Goal Tree-Success Tree (GTST). In the GTST method [26], the goal tree for a system is constructed by decomposing the overall goal of the system into a set of necessary and sufficient sub-goals, and continuing the task of decomposition for each sub-goal till physical components are needed to satisfy the sub-goal.

According to this view, multi-hierarchical mapping relationships could be built among semantic objects which are for describing design intention, mainly product's functions, sub-functions, and function-modules, etc. Meanwhile, by corresponding semantics and interpreting mechanism, objects for the lowest level of product's functions could realize connecting relationships with objects for assembly's structure.

3.4.2. Structure Level

At this level, two models are included, product's structural model and semantic relations model.

3.4.2.1. Assembly's structural model. Assembly structural model can capture and store assembly's hierarchical structure information, as a result of product structure analysis. This analysis is the necessary following process from conceptual design, functional analysis and behavior modeling. In this analyzing process, product's hierarchical structure relations become clear, which offer guidelines for assembly operations design.

The main approach of product's structure analysis is to decompose the product into groups of subassembly. Moreover,

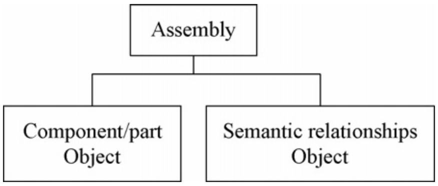

Fig. 5. Assembly is an integrated model of components and semantic relations.

one subassembly may be divided into several subassemblies, which will lead to a hierarchical structure. And by the assembly relations, these subassemblies are organized as an assembly. As the Fig. 5 shows, assembly could be represented as the components and the corresponding assembly semantic relations.

From the viewpoint of structure, attached by related assembly connecting information, the assembly could be organized as a tree, that is, the *Product Assembly Structural Model Tree*. In the tree model, the root node is the completed assembly, non-leaf nodes are various subassemblies and the leaf nodes are single parts. For the node, it is a complex class which comprises entity objects representing part and subassembly, and relation objects representing assembly relations. In result, assembly structural model can include the relations (connection, constraints and others) between parts, between subassemblies, which are key factors for the succeeding application in assembly reasoning.

Fig. 6 is the concise illustration of Product Assembly Structural Model Tree. And the Fig. 7 is a description for the data structure of PASMT and assembly geometric constraints.

3.4.2.2. Assembly semantic relations model. In short, by assembly semantic modeling approach, assembly can be referenced as "OBJECT + SEMANTIC RELATIONS." OBJECT includes all of objects in assembly design work which can be divided into several classes such as part class, tool class, process class, ... Assembly semantic relation is defined as the whole set of the information among the objects, and can be classified into organizing relations, dependent relations, connecting relations, etc., between the objects. Fig. 8 shows its basic framework.

Relations model = {semantic relations|organizing relation, dependent relation, connecting relation, ...}

Organizing relations. Organizing relations are the relation set which captures all structural information between parts or other objects. In addition, by organizing relations set the

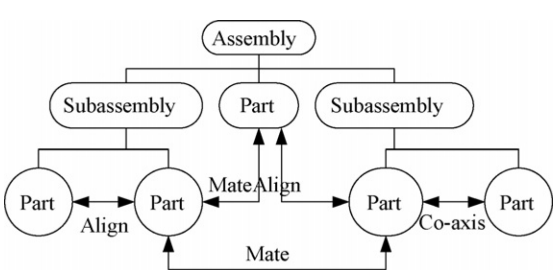

Fig. 6. Assembly Structural Model Tree.

```
//A concise data structure of the assembly

CLASS PASMT
{
STRING componentID ;
INTEGER Hierarchy ;
INTEGER Hierarchy_ Node ;
CLASS PASMT component[ ] ;

(CLASS) CONNECTION asm_conections [ ]  ;
//it includes some connection relationships
}
//if this node is the part, then component[ ]=NULL


 At the feature level, the geometric constraint relationship can be
expressed:
  //Assembly connection data structure
  CLASS GEOMETRIC_CONSTRAINT
  {
  STRING conection_type ;
  (CLASS) PASMT owner[] ;
  (CLASS) PASMT part[] ;
  (CLASS) RELATIONSHIP_DIRECTION constraint_direction;
  }
  /*------------------------------------
  As we know, keep in harmony with the CAD system, geometric
  constraint relationships can be classified as following:
  Mate,
  Align,
  Orient,
  Co-axis,
  Insert,
  Tangent
  ---------------------------------------*/
```

Fig. 7. Description for the data structure of PASMT and assembly geometric constraints.

product structural model can be formalized efficiently and used in assembly sequence planning system. Using "well formed formula" representing it, as following:

ORGANIZING (*product*, *assembly*, *part*, *part*, *subassembly*, *subassembly*, ...).
ORGANIZING (*finished process*, *process* [0], *process* [1], *process* [2], ...).

Dependent relations. In general, if the precondition that an object can play its role is the other existing or playing role, this kind of relations is defined as the dependent relations. For

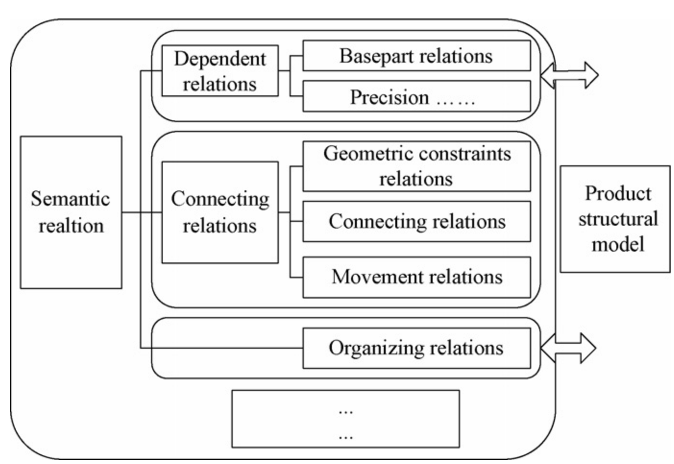

Fig. 8. Assembly semantic relations.

instance, in an assembly with several sub-parts, there are the dependent relations of assembling part to base part, the dependent relations of assembling action to assembly tools and the dependent relations of assembly tolerance to every part's tolerance, etc.

Connecting relations. Assembly connecting relations include the assembly constraints relations, assembly joint relations and mutual movement relations. For these three kinds of connecting relations, an abstraction also exists in them. Different abstract level corresponds with the different product designing and describing level.

For *Geometric Constraint Relations*, it is the relations set of basic geometric constraints in geometric entity level. That is:

> *Geometric Constraint Relations* = {*Mate*, *Align*, *Orient*, *Co-axis*, *Insert*, *Tangent*}. (*Use this kind of definition for keep harmony with CAD system*).

For *Assembly Joint Relations*, it is the set of more complex assembly joints which are composed of these basic geometric constraints, such as screw family joints and welding joints.

For *mutual movement relations*, it reflects the relations between objects from the product's functional view. It includes much information about product's function and can play an important role in product design and rectification.

3.4.3. Part/Feature Level

By multi-levels abstraction of assembly information, part/feature modeling becomes a natural extension of assembly information modeling. From conceptual product prototype, product function modeling and behavior representation to assembly structure, then to part/feature, this process is based on the united assembly information model. Owing to the rapid development of feature-based modeling and the application of corresponding CAD system, product design information and process planning information can be transferred bi-directionally, and therefore, the product digital model can be defined as input of the system. Meanwhile, CAD model's complex feature set is the necessary for whole assembly planning system, all of which would be reconstructed and written into assembly information model to support the system running.

The semantic objects describing information at part/feature level could build necessary mapping with the objects in product's CAD model and relevant files, by the Semantic Dictionary and interpreter. Therefore, it offers a mechanism to integrate this prototype with the CAD system.

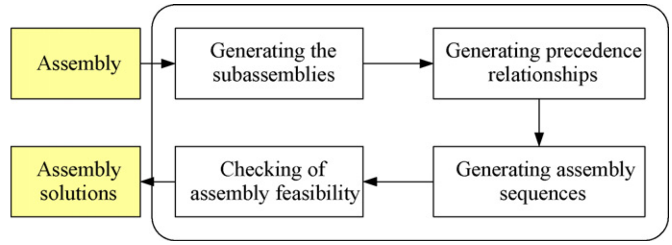

Fig. 9. The basic structure of assembly sequence planner.

4. Assembly planning

4.1. Assembly sequence planner

Generally speaking, the whole process of assembly sequence planning is complex. However, considering its main function, in most of relevant researches, it is often reduced to create a precedence relations graph (between the components of an assembly), to search the feasible (optimal) assembly sequence, and also to determine the feasible assembly path. However, the question how this precedence relations graph is created effectively is seldom described.

In our study, we design an assembly sequences planner, based on the well-known idea of assembly sequence research, but obtaining effective assistant from semantic methodology. Fig. 9 shows the basic structure of the planner which mainly includes following parts:

- *Generating subassemblies*. Divide assembly into many subassemblies with a multi-hierarchical structure, according to the rules related with product function, structure, or process, etc. This idea is one of the best techniques for handling assembly sequencing problems.
- *Generating precedence relations*. According to a flexible rules set, many precedence relations between components of the assembly could be determined from the multi-hierarchical assembly structure graph (including an assembly relations model).
- *Generating possible assembly sequences*.
- *Checking of assembly feasibility and assembly path planning*.

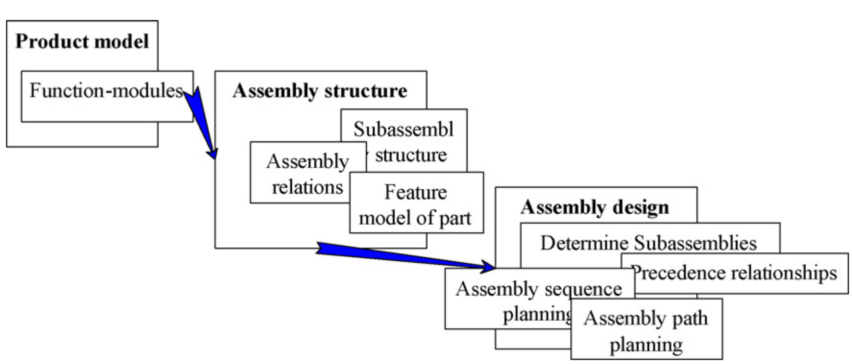

Fig. 10. The basic idea of retrieving and utilizing related information.

In the planner, the following procedure is taken to finish assembly planning, "generating subassemblies → assembly hierarchical structure/assembly relations model → utilize some rules to generate a possible assembly sequences set → chose a possible assembly sequence to check its assembly feasibility → evaluating the assemblability and search an optimal solution."

The basic idea of the planner is same with other researches, but the way how assembly specific information is retrieved and how to use, is very different. The following will show the proposed idea of assembly planning based on product semantic information model.

As we have said, product's semantic information model is an information integrated platform for a huge amount of product information, particularly, assembly-related information, and it offers a powerful information indexing mechanism by the various semantic objects and multi-level abstract. That is, this model does not store whole related information in product model but it has a powerful ability to retrieve all necessary information when necessary.

Fig. 10 shows the basic idea of related information retrieving and utilizing, based on the semantic model. As described in previous sections, the retrieving process of real technique information is a multiply searching of objects and relationships. And by this process, assembly-related objects are searched and relevant engineering technique information is explored.

Fig. 11 is a simple assembly model (CAD model) of a connector. It is used as an example for describing the thought of assembly (process) design based on product semantic modeling methodology in detailed, as Fig. 12.

In essential, this includes two stages: *product* (*assembly*) *information retrieving and assembly* (*process*) *design*.

For the first stage, product information retrieving, based on product's semantic information model, related assembly and structure information is obtained. Corresponding with the three-level abstract of relevant information, these semantic objects information are stored at three levels. For example, from the view of conceptual/functional level, the object of Basic_Function could give us the functional information of this connector, *Connecting part A and part B*, which shows in the semantic object Connecting (A, B). And specially, in Structure Level, this connecting relationship will be shown as assembly relationship objects. That is, the object of Connecting (A, B) is mapped as objects set, including Bolt-Nut Connecting relationship (C, D) and Insert relationship (B, A). Meanwhile, the information about assembly structure view (pointing to its 3D or 2D assembly model and relevant technologic files) also could be retrieved from this level. In fact, for a product with more complex structure, its assembly structure (or, modules information, sub-assemblies information), could be obtained, too. And as described, at the part/feature level, related information will be more clear and complex.

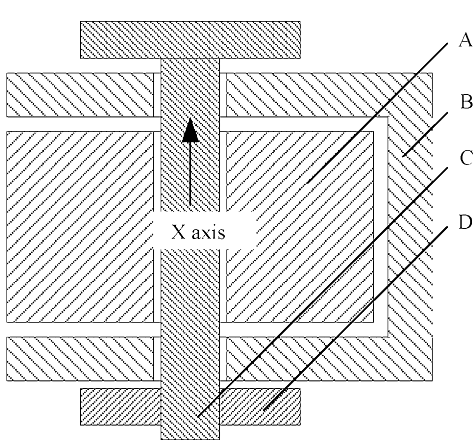

Fig. 11. 2D view of the connector.

For the second stage, assembly (process) design represents a process of analysis, determination and verifying. By collecting and analyzing assembly-related information, in particular, information of assembly relationships, many difficult works in traditional researches, will become easier. For instance:

- Functional-modules information could help to determine assembly → subassemblies structure.
- According to relevant information obtaining from semantic objects in Structure level, and Part/Feature level. Precedence relationships could be determined easily. Therefore, based on these precedence relationships, possible assembly sequences set (draft solutions), could be computed out. Of course, in the geometric sense, it may be a set with several probable solutions. One thing we still need to mention here is that, if the precedence relationships set can provide enough information, the possible disassembly sequence solutions will be very limited.
- Objects of assembly connecting relationships could provide guidelines for assembly operations. Moreover, assist designer to design, determine or optimize the assembly path in simulating system.

In total, by retrieving and analyzing related information, the planner offers a well mechanism to assist designer to finish assembly (process) design more efficiently than ever.

Fig. 13 shows the reasoning process of choosing a possible assembly sequence to check its assembly feasibility, a key part of assembly planning procedure.

4.2. Rule-based assembly sequences reasoning

By now, a rule-based reasoning (RBR) approach is used in the planner for assembly sequences reasoning. It is a developer designed procedure which can perform various tasks on a series of If-Then clauses, a set of forward chaining rules.

In the planner, there are two reasoning rules sets. One is for determining geometric precedence relations (auto generating or assist the designer to determine) in which most of the precedence relations between components in the product can be determined according to these reasoning rules and the other is for generating geometric feasible assembly processes in which the assembling path can be searched and determined whether

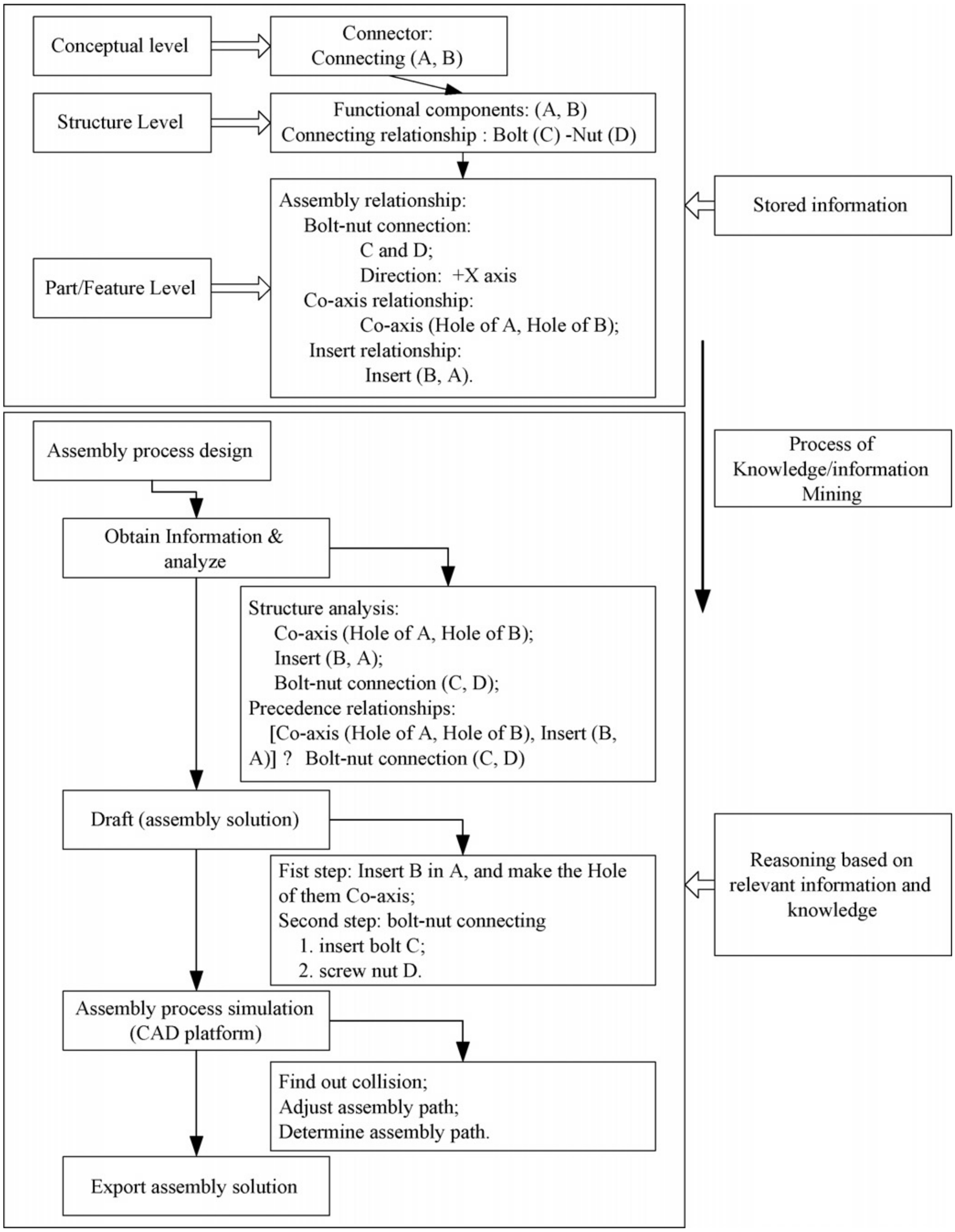

Fig. 12. Use knowledge (information) in product semantic model to design assembly solution.

this path is a free-collision path according to an automatic collision detection algorithm.

For the rules in the first application, samples as the following:

Rule 1 (*independent rule*): Based on the assembly information model, if one component (part or subassembly) belongs to a subassembly and the other belongs to another subassembly which does not connect with the prior, then it is not necessary to determine the precedence relations between them.

That is:

Rules model number 020

IF (*CHILD* (*TRUE*, *part* (*A*), *subasm* (*H*))) AND *CHILD* (*TRUE*, *part* (*B*), *subasm* (*G*))
AND *CONNECT* (*FALSE*, *part* (*A*), *part* (*B*))
THEN *UNDONE* (*PRECEDENCE*, *A*, *B*)
END

Rule 2 (*base part rule*): If one part is the base part of a subassembly, then the relations between the base part and any other part in that subassembly is clear.

That is:

Rules model number 022

IF (*BASEPART* (*TRUE*, *part* (*A*), *subasm* (*H*))
AND *Part*(*x*) $\in$ *subasm* (*H*))
THEN *PRECEDENCE* (*TRUE*, *part*(*x*), *part* (*A*))
END

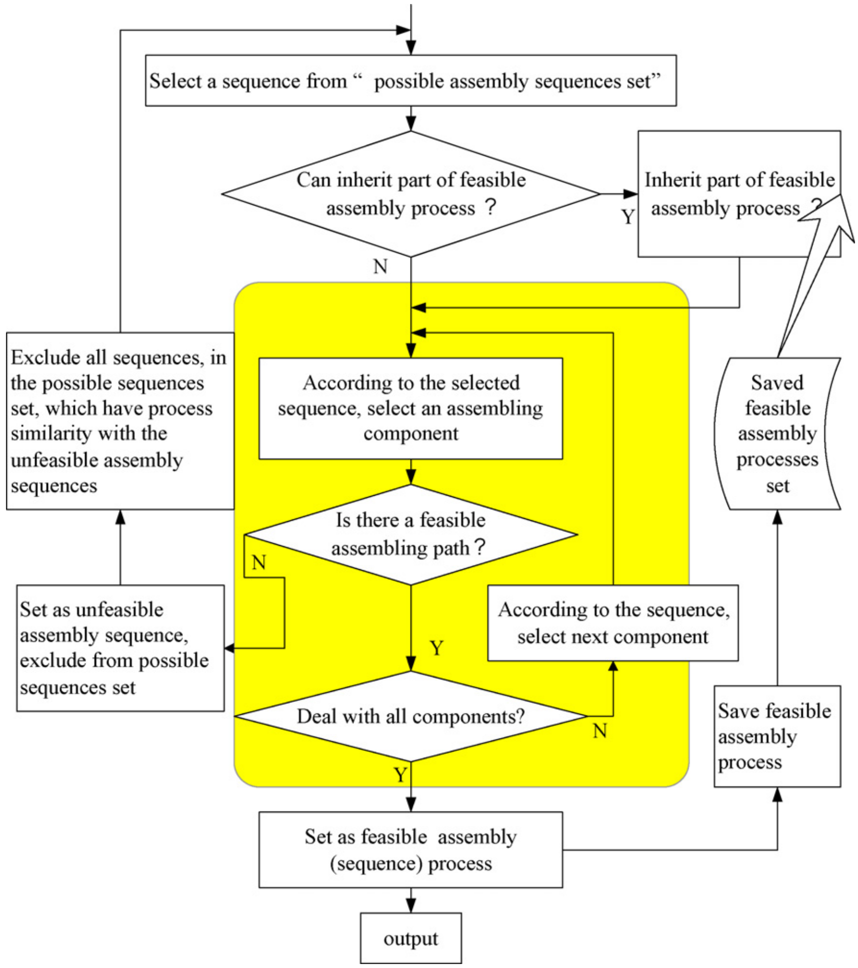

Fig. 13. The flowchart of the kernel of assembly sequence planning for geometric feasibility.

For the second application, these rules are integrated in the sequences and path planning algorithm (of course, including the collision detecting). Such as the following samples.

Rule 1: For a part in an assembly, if the interference always occurs for all of moving paths that system generating/guiding, then in this step, the part cannot be assembled or disassembled.

That is:

Rules model number 027

DEFINE step (A) = *MOVINGPART* (*part* (*A*), *PathSet* (Θ))
IF *INTERFERENCE* (*TRUE*, *part* (*A*), *path*(*X*))
AND *path*(*X*) $\in$ *PathSet* (Θ)
THEN *COLLISIONDETECTION* (*TRUE*, *Step* (*A*))
END

Rule 2: For a given assembly sequence, if one of its components could not be assembled or disassembled, according to the sequence, this sequence is geometric infeasible, that is, it should be excluded from potential solutions.

That is:

Rules model number 030

IF (*Step* (*A*) $\in$ *process* (Ω))
AND *COLLISIONDETECTION* (*TRUE*, *Step* (*A*))
THEN *GEOMETRICFEASIBLE* (*FALSE*, *process* (Ω))
END

5. Overview of system

The initial concerns of the proposed study are on assembly information modeling and interleaving assembly planning based on the modeling approach. And based on these researches, we present a prototype of interleaving assembly planning system. Illustrated as Fig. 14, it is introduced simply.

The system imports assembly (including parts' files) from CAD system, and reorganizes the assembly's representation according to previous discussed method—assembly semantic modeling.

- The module *assembly information modeling* uses the three-level semantic abstract approach to build the assembly information model and store relevant data information into the database *User assembly information database* which could support the system to run well, according to the defined assembly information model and related interpreting mechanism of semantics dictionary.

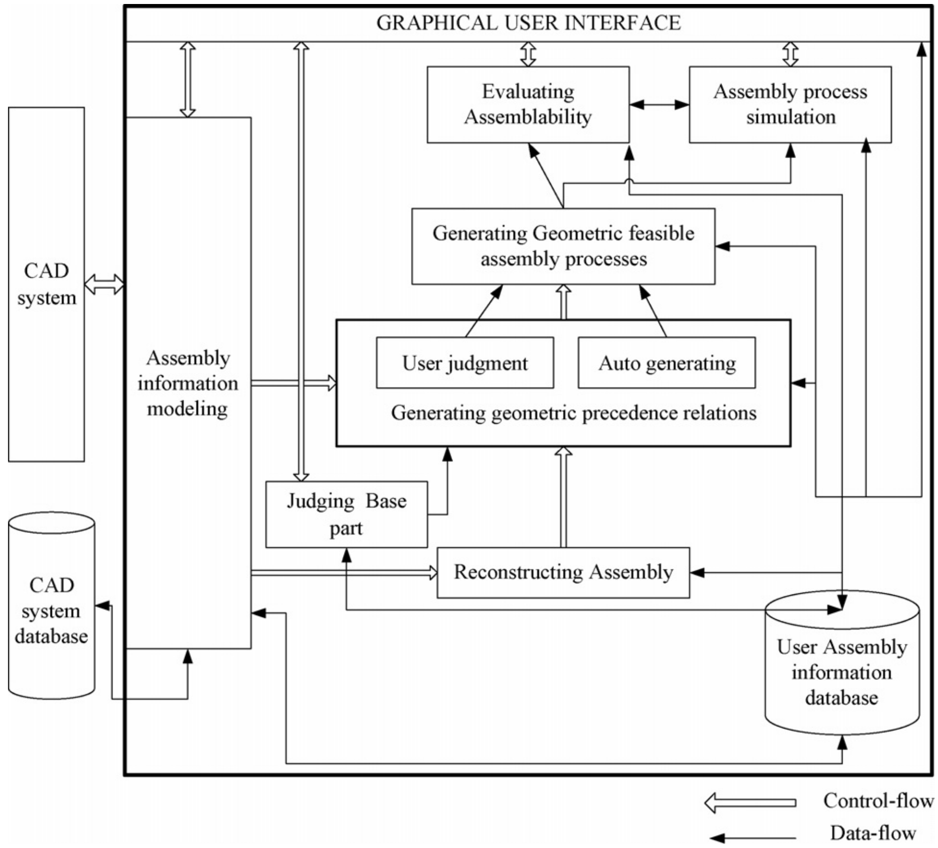

Fig. 14. The architecture of interactive assembly planning system.

- As one key part of the interactive assembly planning system, the module gen*erating Geometric Precedence Relations* is based on our rule-based reasoning approach. Part of the generating work could be obtained automatically, and the other needs the intervention of designer. It can offer an appropriate search space of assembly sequences, the set of *possible assembly sequences*.
- In the module of *Geometric Feasible Assembly Process*, according to the selected assembly sequences, product will be disassembled/assembled, as the flowchart of Fig. 13 shows. By using free-collision path planning algorithm, it can find out whether the possible assembly sequence is geometric feasible.
- In the module of *Evaluating Assemblability*, under the consideration of assemblability, cost and other factors, user can determine which is the most appropriate from all the geometric feasible assembly processes.

Moreover, in this system, an error feedback mechanism is included.

6. Conclusion

The semantic modeling approach, presented in this paper, for product information, in particular, for assembly relevant information, provides a feasible approach to unite various product information into one platform. Product semantic information model, composed of many semantic information objects, has a concise structure for describing product's information, by three-level semantic abstract. Semantic information objects, based on the mechanism provided by Semantic Interpreter and Semantic Dictionary, could retrieve relevant information from various format technique files, and thus, provides a method to describe much more information than traditional works ever could.

Therefore, based on this product information model, an assembly planner is designed, which could assist designers or specialists to finish assembly (process) solution more efficiently. In essential, this kind of assembly design procedure includes two stages: product (assembly) information retrieving and assembly (process) design. In the first stage, the mechanism provided by semantic modeling approach to obtain necessary information is utilized, while in second stage, conclusion to relevant information is analyzed, which could be very helpful to assembly design.

For future work, experiments to several business products under the interleaving system shall be taken. Based on these tests, these involving technologies such as assembly semantic modeling, semantic abstraction, and rules-based assembly sequences reasoning, etc., will be improved, so as to make it a valuable and effective tool to assembly sequences planning.

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Wang Hui is currently a PhD candidate in the Department of Precision Instruments and Mechanology, Tsinghua University, PR China. He received his BE and MSc in 2000 and 2003, respectively, from Northwestern Polytechnical University, Xi'an. His main research interests include assembly/disassembly planning, green design, and heuristic methods.

Xiang Dong received his PhD from Chongqing University. Now he is the Associate Professor in the Department of Precision Instruments and Mechanology of Tsinghua University. His main research interests include design for environment, cleaner production and recycling technology of e-wastes.

Duang Guanghong received his BE from Tsinghua University, PR China, in 1970. From that time, he has been a teacher and researcher in Tsinghua University. Now, he is a professor in the Department of Precision Instruments and Mechanology. He is also the Director of Research and a senior member of CASME. Prof. Duan's current research interests include CAD/CAM, green manufacturing, advanced manufacturing machine and NC technology.

Zhang Linxuan is currently an associate professor at Department of Automation, Tsinghua University. He received his PhD in Mechanical Engineering from Tsinghua University in 1999. His research interests mainly include Design for Assembly (DFA), Computer-Aided Assembly Process Planning (CAAPP), PDM-Based CAD/CAM/CAPP/CAE Integration.