编号：________________

毕业设计(论文)外文翻译

（原文）

学　　院：　机电工程学院

专　　业：　机械设计制造及其自动化

学生姓名：　谭志同

学　　号：　1000110127

指导教师单位：　机电工程学院

姓　　名：　唐焱

职　　称：　副教授

2014 年 5 月 26 日

A novel data decomposition and information translation method from CAD system to virtual assembly application

Abstract Virtual assembly (VA) is a key technology for virtual manufacturing systems. So far, CAD systems are still the main modeling tools for the VA system. There isn't a standard data ex-change criterion to transfer the data directly from CAD systems to VA applications, consequently an original data decomposition and information translation method (DDITM) was timely proposed to achieve the decomposition and translation. The information of the assembly bodies in the CAD system was divided into geometry information, topology information, and assembly information, etc., which were transferred to the VA application separately. The geometry information including the surface information was translated by the data translation interface (DTI) developed, the topology information was translated by a five-hierarchy topology structure (FHTS) constructed, and the assembly information was translated with database technology. A systematic architecture was formed with the interaction between the geometry information and the topology information, and the assembly information and the topology. Finally an experimental VA system was set up to verify the DDITM, and an assembly simulation was implemented to verify the assembly information further, which proves the translated information is precise and sufficient.

Keywords CAD · Data decomposition · Information translation · Virtual assembly

1 Introduction

Virtual environments (VE) are interactive virtual image graphics displays enhanced by special processing and non-visual tools, such as auditory and haptic ones, to realize the effect of immersion regarded as a natural extension to three-dimension graphics technology with advanced input and output equipments. There are four key characteristics – immersion, presence, navigation and interaction – that are usually used to measure and classify different VR systems and the applications [1], which have affected and changed people's ways of thought and action manners greatly. VR has already become one of the most advanced, powerful technologies, employed in a variety of fields, such as military, medicine, entertainment, architecture and mechanical manufacturing, etc.

Virtual assembly (VA) is a concrete application of VR. Assembly technology plays an important role in manufacturing, which is not only a key step in product design and producing, but also the last step in gaining a whole performance. Some analyses show that assembly-related activities in manufactured goods account for over 50% of the total production time and 20–40% of the unit production cost [2]. The development of VA based on VR provides us a low-cost and rapid method for assembly, which employs visualization technology, simulation technology, assembly technology and decision-making theory, etc. After the components' designs are finished, the data of these CAD models are transferred to the VA to implement assembly evaluation, assembly simulation, and assembly planning or assembly evaluation. Then invalid irrational structures are improved, and relative engineering decisions pertaining to assembly are made, so as to assure a success of actual assembly process. Consequently the product development cycle is shortened and costs are reduced, and the assembly efficiency is improved, too.

Assembly modeling is the first step to construct a VA system. Although VR software has a certain modeling ability to create some simple geometrical shapes (e.g., cylinder, cube, sphere etc.), it cannot meet the modeling requirements if relying only on VR software to build complex shapes or if thousands of components are to be built. So far 3D CAD softwares (e.g., SolidWorks, Pro/Engineer, and Unigraphics, etc.) are the still main modeling methods for VA system. In this paper we use SolidWorks to build CAD models.

There isn't a standard data exchange criterion between the CAD system and VA system, so the information of CAD models can't be transferred to VE directly. Although the CAD system can export the CAD graphical models in other formats (e.g., WRL, DXF, 3DS, SLP, etc.) imported into VE and displayed there. However, these formats can only keep partial geometry information etc. For example, the whole assembly body or a single component can be selected, but its surfaces cannot be selected, so the models in these formats are only of the concept of body and not of that of surface in VE. However surface is such an important concept in assembly, and it has to serve such functions as follows: (1) orienting components or assembly bodies, (2) defining constraints, (3) defining joints, (4) defining geometrical and dimensional tolerances, (5) defining precision or roughness, and (6) defining physical information (e.g., colors and materials etc.). Without the surface concept, the assembly concept becomes vague and the VA system is also reduced to a simple simulation application. In addition, the VA system needs not only geometry information, but also topology information, assembly information, etc. So transferring the information of these CAD models to VA is not only the first step of constructing a VA system, but also a key step having an influence on the display effect, the assembly effect, and the precision requirements of the VA system.

In the next section, several data translation methods of assembly-related VE are introduced. In Sect. 3 an introduction to the DDITM structure is given. In Sect. 4, a concrete realization algorithm for the DDITM is proposed. In Sect. 5 an experimental VA system and an assembly simulation system are setup to verify the translated information. Conclusions are made in Sect. 6.

2 Related works

The previous research on translating the information of CAD models into assembly-related VE can be classified into several categories. The first is about the use of the VRML file as a transformational file, as it is employed in most of the VA systems. One representative work of this category is from the National Institute of Standards and Technology [3], where they developed a VRML interface for a system called visual interface to manufacturing (VIM). This system provides visual access, using VRML, to a database containing manufacturing data. Antonishek [4] also used VRML as a bridge between the CAD system and Virtual Workbench. STEP, a graphical data exchange standard, forms the second category, which is employed to translate complex assembly data. Mok [5] developed a CAD/CAM/CAE product data management (C3P) tool based on a structural product coding system (SPCS). The C3P system analyzed a product by importing information from its STEP CAD data. Lee [6] presented a system focusing on shape representation and interoperability of product models for distributed virtual prototyping, where STEP was used as a means of transferring and sharing product models. Ikonomov et al. [7] proposed a virtual assembly model for concurrent engineering using STEP data exchange.

The third category integrates the modeling system with the VA system, both of which share a common database. Wan et al. [8] described VDVAS, an integrated multi-modal virtual design and virtual assembly environment. One important feature of VDVAS lies in that it allows designers to modify components of an assembly during the process of assembly modeling and simulation without the need of time-consuming data exchange between the virtual environment and other CAD applications.

The fourth category focuses on using the interface software. Two typical VA instances are introduced here. These two systems are virtual environment for design and manufacturing (VEDAM) [9] and virtual assembly development environment (VADE) [10]. VEDAM is a very general framework for virtual reality applications in design and manufacturing, whereas VADE is specifically designed for assembly planning. The two systems have chosen Pro/Engineering as their modeling systems and obtained the information through automated transfer from the CAD system using Pro/DEVELOP, the developer’s toolkit for accessing the Pro/Engineer database.

Many other formats are also used to transfer the information of CAD models into other VE, such as “OpenFlight”, “DXF”, “3DS”, “SLP”, and so on. Weyrich et al. [11] presented an approach of a “virtual workbench” and its application to virtual assembly. The system used the professional modeling tool Multigen II, and the “OpenFlight” format as its data interface with the virtual environment.

3 Structure of the DDITM

The methods introduced in Sect. 2 have both pros and cons. The first kind is easier to realize, but the VRML in this way doesn't provide assembly information and the surface concept is lost, so it is hard to perform complex assembly actions in VA. STEP includes almost all the information of CAD models from design period to assembly period, but its structure is so complex that the needed information is too difficult to extract. The third kind spends less time on data translation between the CAD system and VA system, but it needs to a create modeling system itself, so excessive time is spent on developing a modeling system, moreover the integration between the system and current CAD system is not good enough. Other formats have the same problem as VRML. In this paper, according to the research on the above techniques, an information decomposition and translation method (DDITM) is proposed to translate the information of CAD models to the VA system.

The DDITM divides the data into several sections: geometry information, topology information and assembly information, which are translated through different methods. Figure1 shows the translation flowchart of DDITM.

1. As for geometry information, the surfaces of the CAD models are discretized into triangle tessellations by means of the CAD forward development method, and then these tessellations' information is written into corresponding VR documents through the DTI. In VA, when all these triangle tessellations are displayed, continuous geometry entities

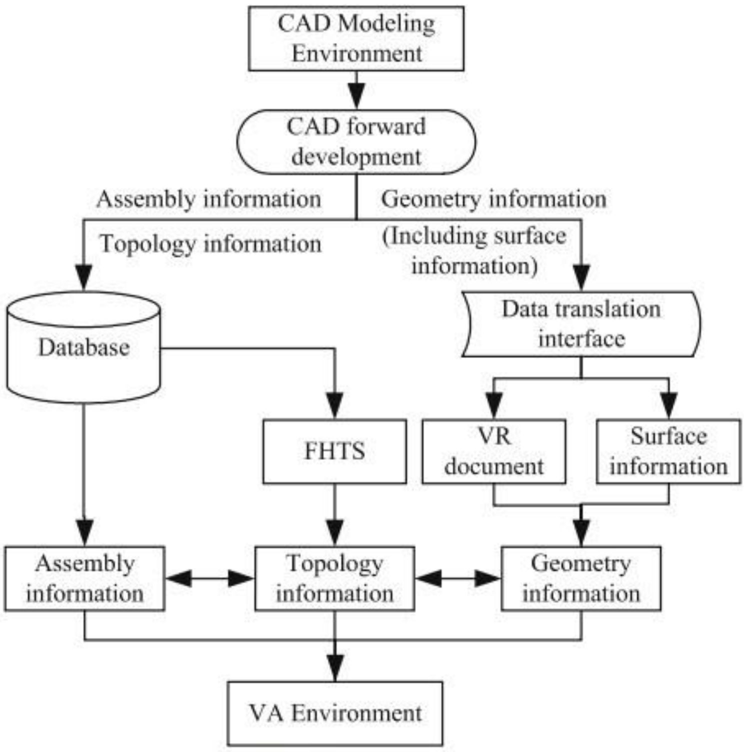


Fig. 1. Sketch map of the DDITM

are reconstructed. In addition, the surfaces of the CAD models are treated as separate objects in these VR documents. By creating the relations between surfaces and tessellations, the surface concept is constructed in VE.

2.As for topology information, this paper uses a topology structure named five-hierarchy topology structure (FHTS) to store the topology information of the CAD models. The FHTS includes five hierarchies, i.e., assembly, subassembly, part, surface, and tessellation. First, three tables are constructed to realize the FHTS, which are a subassembly table, a part table and a surface table. Then each hierarchy's information extracted from the CAD system is stored into the corresponding table by using the CAD forward development method.

3. As for assembly information, database technology is adopted. Two tables including mate table and tolerance table are constructed. Assembly information (including mate information, tolerance information) is taken out of the CAD system by using the CAD forward development method, and then stored into corresponding tables.

4. The assembly information, the geometry information and the topology information do not exist separately, instead they interact with each other. The FHTS is a kernel part of the DDITM, which is used as a bridge to link the geometry information and the assembly information, and both of them interact with the FHTS to share the information with each other. After constructing the surface concept, a surface will be treated as a basic unit to perform VA operations.

4. Realization of the DDITM

4.1 Software platform

To realize the DDITM SolidWorks [12] is selected as the assembly modeling platform, WorldToolKit (WTK) is selected as the platform for constructing the VA system [13], SQL Server is selected as the database platform, and Visual C++ is selected as theapplication developing platform. Both SolidWorks forward development method and the WTK select Visual C++ as a supporting platform, which can eliminate the compatibility problems between them.

4.2 Geometry information translation based on surface hierarchy

4.2.1 Selection of VR document format

The DDITM uses the DTI to write the geometry information of SolidWorks models into corresponding VR documents loaded into VA as geometry nodes. Then the geometry entities are displayed in VA with the display mechanism of WTK. VR document interfaces (e.g., NFF, 3DS, WRL, DXF, and SLP etc.) are used to transfer geometry information from any other kind of CAD modeling software to VA. Although WTK supports many VR formats, only the WRL format can be used to transfer geometry information from SolidWorks to VA, but in a practical application, the WRL document is of the following limitations in WTK [13]

1. In WRL documents, although CAD models are discretized to triangle tessellations based on a surface hierarchy, the surfaces have no identities, so WRL documents do not have the surface concept, consequently WTK can't modify the colors or the textures etc. of the surfaces. Therefore the surfaces in VA can't be picked up so that the assembly actions based on surfaces can't be performed.

2. WTK ignores scaling factors (if any) within a transform node's transformation. WTK can't perform scale operations on WRL virtual objects, so the size of virtual objects can't be changed according to the objects in VA or they can't make more examples of different sizes.

3. Virtual objects of WRL documents are of only the body concept and the tessellation concept, so if precise collision detection is performed, its efficiency will be low, for intersection test between every two tessellations has to be performed.

WTK Neutral File Format (NFF), another VR document format is adopted to discretize bodies into aggregates of triangle tessellations. The NFF format, written in ASCII format, is a neutral file format taken by WTK. Compared with the WRL documents, the NFF documents include all the geometry information that the WRL documents have. In addition, if every surface is treated as an separate object in NFF documents and identified by a unique identity, then the surface information is constructed. The surface information is very important because assembly information is based on the surfaces, and the assembly information, the topology information, and the geometry information communicate with each other based on surface hierarchy, too. Furthermore NFF documents are integrated into WTK closely, so there aren't any limitations for them in VA. In short, the NFF is the best VR format to store the geometry information including the surface information.

4.2.2 Creating NFF documents

Although NFF documents are selected to store the geometry in formation, SolidWorks doesn't provide the interface to export the NFF documents，hence the DTI is developed here. It extracts the information of the WRL documents created by SolidWorks and writes this

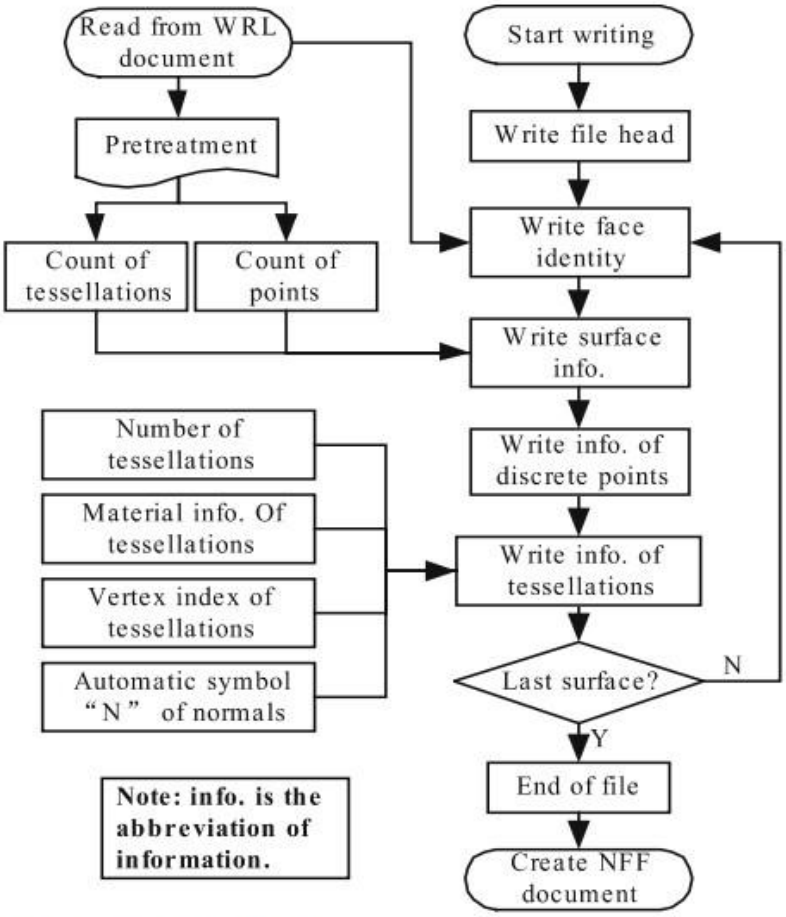
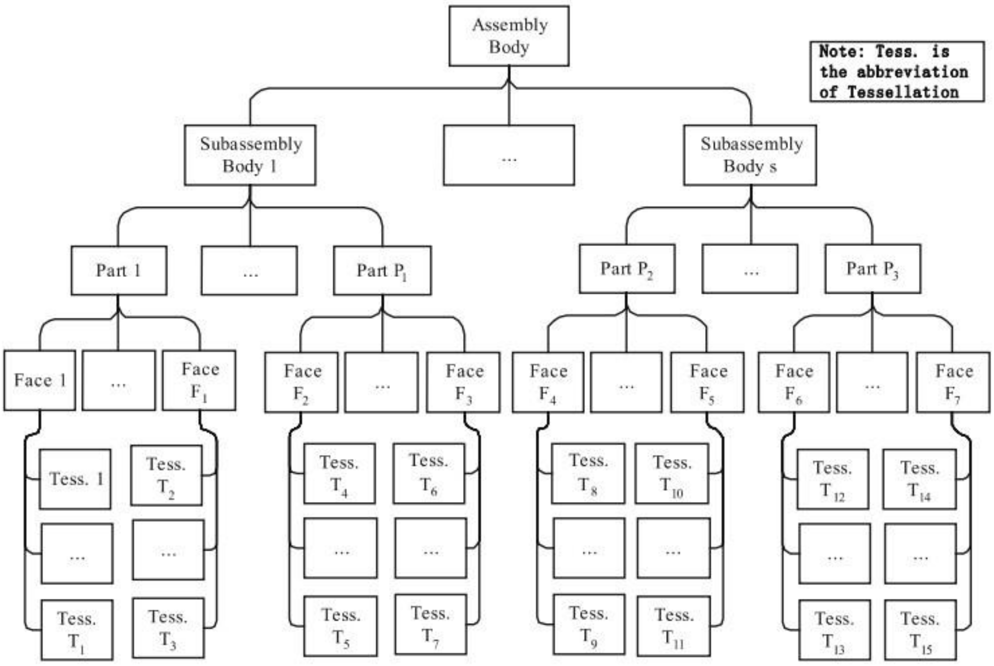


Fig. 2. Data translation interface

information into corresponding NFF documents. At the same time, the DTI employs the CAD forward development method to write other geometry information including surface in formation to corresponding NFF documents. The flow chart of the DTI is as shown in Fig. 2.

First, a pretreatment is implemented to record the count of discrete points and that of the triangle tessellations for each surface, which are stored in two variables. Second, write file heads that include some recognition information of NFF documents (e.g., NFF tag, NFF version number, position of view point, orientation of viewpoint, etc.). These file heads are used to mark the NFF documents. Third, the surfaces' information is extracted from WRL documents and written into corresponding NFF documents. In this stage, each surface of the CAD models is treated as an individual object numbered consecutively. We also need to write the information obtained from the pretreatment stage into a corresponding NFF document. Then, the concrete information is written into corresponding NFF documents extracted from the WRL documents by reading these WRL documents line by line. This information includes the number of the discrete points, their coordinate values, an automatic symbol "N" taken to calculate the normal of the tessellation automatically, the material information and tessellations' information etc. Each triangle tessellation has a unique identity numbered consecutively. Finally, judge whether it is the last surface, if it is false, repeat the former process, or else finish reading these WRL documents and creating the NFF documents at last.

Fig. 3. The five-hierarchy topology structure



In VA, a NFF document is loaded into WTK as a geometry node and all the objects in the document are displayed in VA respectively. Each surface includes corresponding tessellations. After constructing the FHTS, the relationship between a surface and tessellations will finally be constructed. Then the surfaces' information of these models will be built, and the operations on surfaces will be converted into the operations on corresponding tessellations. For example, the change of a surface's texture will be converted into the change of its corresponding tessellations' texture and the change of a surface's color will be converted into the change of its corresponding tessellations' color. Thus through the DTI we translate the geometry information based on surface hierarchy from the CAD system to VA system.

4.3 Translation of the topology information

The topology information is the kernel part of the DDITM, because the topology structure stores the relationship between assembly body, subassembly bodies, parts, surfaces and tessellations [14], and both the assembly information and the geometry information communicate with the structure. The topology structure is called FHTS, made up of five hierarchies, i.e., assembly, subassembly, part, surface, and tessellation. The FHTS is a relational structure, and among these five hierarchies there exist the following relationships: an assembly body is an aggregation of subassembly bodies, a subassembly body is an aggregation of parts, a part is an aggregation of surfaces, and a surface is an aggregation of tessellations. The structure is shown in Fig. 3. In another word, each tessellation corresponds to only one surface, each surface corresponds to only one part, each part corresponds to only one subassembly body, and a subassembly body corresponds to only one assembly body.

In order to construct the FHTS, three tables, i.e., a subassembly table, a part table, and a surface table need to be create in the database. The subassembly table is used to store the information of subassembly bodies in the current assembly body, the part table is used

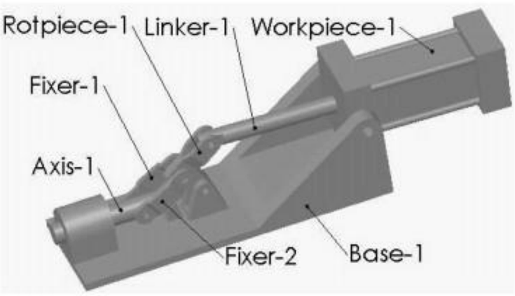


Fig. 4. Assembly models constructed by SolidWorks

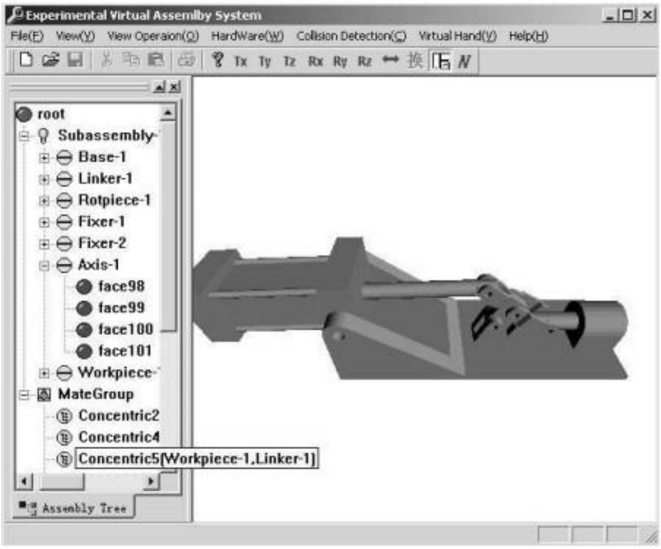


Fig. 5. Interface of the VA experimental system

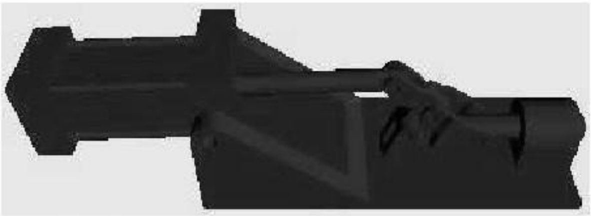


Fig. 6. Display effect while selecting the root node

to store the information of parts in the current subassembly body, and the surface table is used to store the information of surfaces in the current part. A surface is made up of a series of triangle tessellations numbered consecutively. Only one number marks each assembly body, each subassembly body, each part, each surface, and each tessellation. The FHTS constructs a clear topology structure to form a systematic architecture.

4.4 Translation of the assembly information

The DTI and the FHTS make the corresponding relationships between surfaces and tessellations, which creates the surface concept, by using operations on surfaces which can be translated to operations on corresponding tessellations. Because the CAD system defines assembly information [15–17] based on surface hierarchy, the assembly operations on parts are also based on the surface hierarchy in the VA system, and thus this paper will discuss the translation of assembly information based on the surface hierarchy.

While performing an assembly process simulation, a tolerance analysis or a path plan, etc., a VA system uses mainly two kinds of assembly information: mate information and tolerance information. In order to translate assembly information from the CAD system to VA environment, two tables should be constructed in the database first, which are a mate table and a tolerance table. The mate table is used to store the information of mates in current CAD assembly bodies; the tolerance table is used to store the information of tolerances. The mate information and the tolerance information are extracted by means of the API functions of SolidWorks. All this information is constructed based on the surface hierarchy.

4.4.1 Translation of the mate information

The mate information includes the following: the names of the mate features, the types of the mate features, the names of the mate surfaces, the identities of the mate surfaces, the types of the mate surfaces, the mate clearances, and the reference features etc. In SolidWorks there are the following objects related to the mate in formation, i.e., Mate, MateEntity, Feature, Face and Surface. The Mate object allows access to various assembly mate parameters. The MateEntity object allows access to mated objects and the assembly mate definition. The Feature object allows access to the feature type, name, parameter data, and to the next feature in the FeatureManager design tree. The Face object allows access to the information of surfaces related to the mate. The Surface object provides functions that allow you to get the surface type and various surface definition data, as well as, evaluate and reverse evaluate locations on the surface. Through these objects we gain access to the mate information in the FeatureManager design tree.

1. The mate entities. In SolidWorks, the current features of assembly bodies are obtained by traversing the FeatureManager tree. If the current feature is a “mategroup” where the sub-features are the mate sub-features, and the corresponding entities are the mate entities. An API function of the Mate object “GetMateEntities” is used to get the mate entities related to the current mate.

2. The mate types. SolidWorks defines the following mate relationships: perpendicular,， tangent, coaxial, parallel, distant, angular, symmetric, etc. The mate type of the mate entities related to the current mate is gained by means of an API function of the Feature object – “GetTypeName”.

3. The names and the identities of the mate surfaces. First, an API function of the MateEntity object, “GetComponent-Name”, is used to get the names of the mate surfaces. Then through an API function of the Face object, “GetFaceId”, can we get the face identities related to the mate entities.

4. The types of the mate surfaces. Only a regular-shape surface (e.g., cylinder, plane, cone, sphere, etc.) can be treated as a reference surface in principle. The following API functions of the Surface object are used to judge whether the type of the surface is cylindrical, plane, conic, or spherical, i.e., “IsCylinder”, “IsPlane”, “IsCone”, “IsSphere” etc. The parameters of these faces can be obtained by other API functions of the Surface object.

5. The mate clearances. A mate clearance is related to the Dragoperator object. Its attribute, “Clearance”, is used to get the mate clearances. Then the information of the clearances and their magnitudes are stored to the mate table.

6. The reference features. Some mate information are defined on some reference features, for instance, a reference axis, a reference plane etc. The reference geometry API functions of the Feature object are used to take out the parameters of these features. For example, an axis is expressed by using a starting point and an orientation vector. The parameters of this information are obtained by using the API functions of the RefAxis object and the RefPlane object.

4.4.2 Translation of the tolerance information

A tolerance includes a geometric tolerance and a dimensional tolerance, which is important in the assembly processes. The tolerance information relates to the Dimension object. Its information including the tolerance value, the tolerance type, the minimum value, the maximum value, the tolerance-related surfaces etc., were obtained by using the API functions of the Dimension object, i.e., “GetToleranceFitValues”, “GetToleranceType”, “GetToleranceValues”, and stored in the tolerance table.

5 Applications

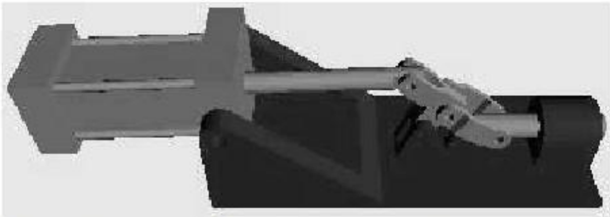


Fig. 7. A display effect while selecting the part Base-1

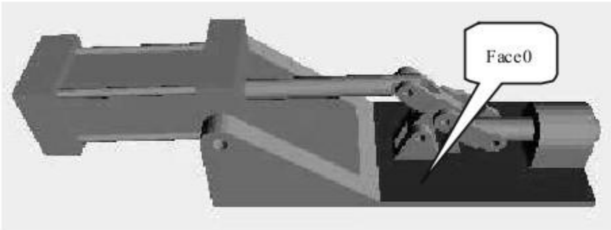


Fig. 8. A display effect while selecting the Face0

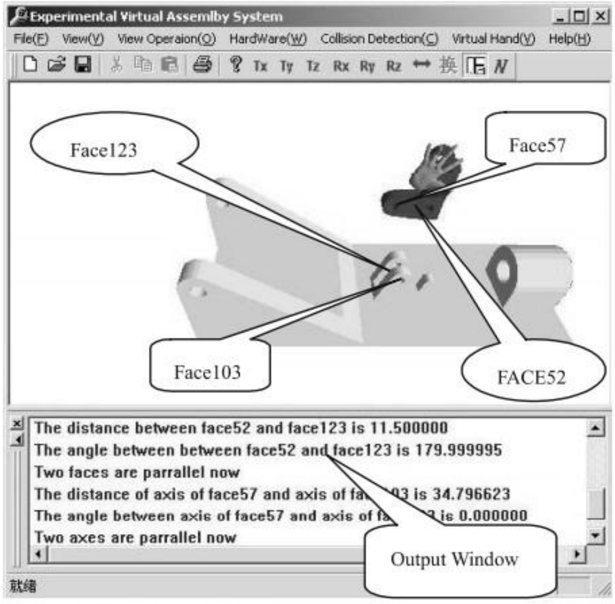


Fig. 10. An assembly simulation

An assembly body is created in SolidWorks, as shown in Fig. 4. The assembly body has only one subassembly, which includes seven parts: Base-1, Fixer-1, Fixer-2, Rotpiece-1, Linker-1 and Workpiece-1. Then the DTI is used to translate the geometry information of the assembly body into corresponding NFF documents. First we use the translation interface of SolidWorks to create seven WRL documents. The SolidWorks forward development method is used to write the geometry information including surface information of the WRL documents into corresponding NFF documents. Second, a subassembly table, a part table, and a surface table are constructed to build the FHTS, which stores the topology information of the assembly body. At last, a mate table and a tolerance table are constructed to store the assembly information, and the API functions of SolidWorks are used to write corresponding the information into the database.

In order to verify the validity of the DDITM, a VA experimental system (the operating interface is shown in Fig. 5) is developed. The assembly information tree, as shown on the left part in Fig. 5, makes use of a hierarchy structure to manage the geometry information, the topology information, and the assembly information in the VA system. The root node in the tree is the primary assembly node including seven parts. Each part is made up of many surfaces (only the surfaces of axis-1 are listed here). The node of “mate-group” includes the mate information of the assembly body (the mate types, the mate entities etc.). The tolerance information stored in the tolerance table is not listed here.

Figure 6 to Figure 8 give examples of selecting a root node, a part and a surface. From these three comparative effects, it is concluded that the geometry information based on surface hierarchy is reconstructed in WTK, which works well in WTK. The surface concept has been constructed in WTK already, so we can operate on bodies based on surface hierarchy and change the colors or textures of a surface freely in VA. From these effects it is easily seen that the display effect of geometry information is perfect.

Figure 9 shows a mate example. Two mates related to Base 1 and Rotpiece-1 are displayed in WTK. They are Distance5 and Cocentric8 as shown in Fig. 9. The tolerance information related to these mates or the assembly bodies is stored in the tolerance table.

In order to verify the mate information and the tolerance information in the VA experimental system further, an assembly simulation is performed in WTK, as shown in Fig. 10. A data glove is used to grasp a workpiece (Workpiece-1) and fix it to another workpiece (Base-1). There exist two mates related to them in the mate table, which are Cocentric8 and Distance5. The Cocentric8 relates to the surface Face57 and the other surface Face103, which are all cylindrical, and concentric. The start point and the orientation of both axes are stored in the database. The Distance5 relates to a surface named Face52 and another surface named Face123, both of which are plane. Both surfaces are parallel and the distance between them is zero. The output window at the bottom of Fig. 10 is used to watch the current constraints between these two workpieces. Watching the Cocentric8 is realized by watching the angle and the distance between the two center-axes of the Face57 and the Face103. Watching Distance5 is realized by watching the angle and the distance between the two normals of Face52 and Face123. When these angles and distances are in the range of the corresponding tolerance stored in the tolerance table, the two bodies are in their proper position. Figure 10 displays the case of two parallel axes and two parallel normals.

6 Conclusions

Data translation is carried out with the original method of DDITM to translate the information from the CAD models to VE and the concrete realization algorithm is given. The DDITM decomposes the information of CAD models into three parts: geometry information, topology information, and assembly information. The geometry information is translated by a DTI developed in this paper, and the important concept of surface is created in this section. The topology information is translated by constructing a five-hierarchy topology structure based on database technology. Three tables are made in this section, i.e., a subassembly table, a part table, and a surface table. The assembly information is translated by means of database technology, too. Two tables including a mate table and a tolerance table are constructed, where the mate information and the tolerance in formation are stored in the corresponding table relatively. In all the periods the SolidWorks forward development method plays an important role. The geometry information, the topology information, and the assembly information interact with each other to form an organic system. At last an experimental VA system is developed to verify the translated information and an assembly simulation is performed to attest the translated assembly information further. The display effect is proved to be excellent and the information is translated exactly, so DDITM is a better solution to translate between the CAD system and VE system.

References

1. Jayaram S, Connacher HI, Lyons KW (1997) Virtual assembly using virtual reality techniques. Comput Aided Des 29(8):575–584
2. Choi CK, Chan DSK, Yuen AMF (200") Application of virtual assembly tools for improving product design. Int J Adv Manuf Technol19:377–383
3. Resseler S, Wang Q (1997) Using VRML to access manufacturing data. In: Proc VRML 1997: Second Symposium of the Virtual Modeling Language, Monterey, CA
4. Antonishek B, Egts DD, Obeysekare UR (1998) Virtual assembly using two-handed interaction techniques on the virtual workbench. Proc 1998 ASME Design Engineering Technical Conference, Atlanta, GA
5. Mock SM (2003) A Structural Product Coding System (SPCS) for Intelligent Product Data Management. PhD thesis of Northwestern University, Evanston, Illnois, USA
6. Lee JY (2001) Shape representation and interoperability for virtual prototyping in a distributed design environment. Int J Manuf Technol17:425–434
7. Ikonomov PG, Kishinami T, Tanaka F (1996) Virtual assembly using STEP data. Proc Third ISPE International Conference on Concurrent Engineering, Toronto, Canada
8. Huagen W, Shuming G, Qunsheng (1999) An integrated virtual design and virtual assembly environment. Proc CAD/Graphics99, Shanghai, China
9. Angster SR (1996) VEDAM: virtual environment for design and manufacturing. Dissertation, Washington State University
10. Jayaram S, Jayaram U, Wang Y, Tirumali H (1999) VADE: a virtualassembly design environment. Comput Graph Appl 19(6):44–50

11. Weyrich M, Drews P (1999) An interactive environment for virtual manufacturing: the virtual workbench. Comput Ind 38:5–15
12. SolidWorks API manual (2001) web site at: http://www.solidworks.com/html/products/api/ last visited in May 2003
13. WorldToolKit Reference Manual (1999) Release 9, Sense8 Corporation, Mill Valley, CA
14. Roy U, Liu CR (1988) Establishment of functional relationships between product components in assembly database. Comput Aided Des20(10):570–580
15. Steffan R, Schull U, Kuhlen T (1998) Integration of virtual reality based assembly simulation into CAD/CAM environments. Proceedings of 24th Annual Conference of IECON 98, Aachen Germany
16. Eng T-H, Ling Z-K, Olson W, McLean C (1999) Feature-based assembly modeling and sequence generation. Comput Ind Eng 36: 17–33
17. Huagen W, Shuming G, Qunsheng P (2000) An approach to solid modeling in a semi-immersive virtual environment. Comput Graph 24:191–202