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ORIGINAL ARTICLE

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A pragmatic system to support interactive assembly planning and training in an immersive virtual environment (I-VAPTS)

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Abstract Assembly planning for complex products is a difficult task requiring both intensive knowledge and experience. Computer aided assembly planning (CAAP) systems have been the subject of considerable research in recent years without achieving a wide application in manufacturing industry. In this paper an alternative approach to the generation of an optimal assembly planning scheme is presented based on the adoption of immersive virtual reality. A product is assembled from CAD models by providing a CAD interface to transfer assembly constraint information from the CAD system to a virtual environment. In the virtual environment an efficient dynamic recognition and management method based on surface geometry is employed, and a process-oriented assembly task model is established to support interactive assembly planning and evaluation. The system is implemented using an object oriented methodology, and has been successfully applied to train and guide the assembly workers in a pump assembly process.

Keywords Virtual reality · Assembly planning and training · CAD

1 Introduction

Assembly planning for complex products is not easy. Traditionally experienced workers complete the assembly design by fabricating a physical model. However, this leads to an increased product lifespan and cost, especially when there are no available advanced methods for checking and evaluating the assembly process. Even though computer aided assembly planning (CAAP) with CAD systems has been the subject of much recent research, it has not achieved a significant take-up in manufacturing industry. The main reason for this is that the 3D visualization in the CAD system is limited, and an automatic generation of the assembly sequence is too expensive for complex products. At the same time, the human assembly experience and knowledge is difficult to exert in a traditional CAD environment, and some factors such as quality testing, shop floor layout and human ergonomics can't be taken into account for assembly evaluation. Now the successful applications of virtual reality (VR) in engineering provide a new low cost method to solve these problems. In an immersive virtual environment, the designer can not only visualize the product to appreciate the inner structure and spatial relationships of components, but also interactively plan an assembly sequence and path for the product and then obtain an optimal assembly scheme for assembly workers.

A number of research groups in different parts of the world have proposed the use of virtual reality systems for engineering assembly tasks. For example, the Fraunhofer Institute for Industrial Engineering (IAO) in Germany proposed the first virtual assembly planning prototyping system by applying a virtual model of a person, VirtualANTHROPOS [1], to carry out an assembly operation and, based on user interactions with the virtual objects, a precedence graph is generated and the time of assembly and cost is determined. Jayaram et al. [2] developed a virtual assembly design environment (VADE) to allow engineers to plan, evaluate, and verify the assembly of mechanical systems. Rajan et al. [3] designed a virtual assembly planning and jig design system (JIGPRO) to evaluate the alternate assembly sequence and jig design, and Chryssolouris et al. [4] developed a virtual assembly work cell. Bound et al. [5] focused their research on assembly task training in a traditional environment (2D drawings), immersive virtual environment (VE) and augmented reality environment (AR); their results indicated that the assembly quality and assembly efficiency in the immersive VE and AR environments are much better than in the traditional environment.

Although these studies have made evident progress in this area, there is still a long way to go before VR-based virtual assembly technology gets a wide application in

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industry production. This paper proposes a CAD-based virtual assembly planning and training system, and introduces its application in a pump assembly process.

2 System architecture of I-VAPTS

The immersive virtual assembly planning and training system (I-VAPTS) proposed in this paper integrates the following three functions:

- Visualization: the system can provide the user with a 3D display for navigating and manipulating the models in a virtual environment. With a view to visualizing the entire system and its environment, the planner can exert assembly experience and knowledge to carry out proper assembly operations and, with the interactive hardware, the engineers can also freely navigate in the virtual environment.
- Operation: the user can not only view the generated computer simulation world, but also interact with it actively using a data glove and work as if in reality. He can indicate a base part, perform virtual assembly and disassembly, and rotate the part or assembly to get a better view. Based on the interactive assembly operation, a process-oriented assembly task model is established to express and record assembly process information and, further, to evaluate and select the optimal assembly scheme.
- Training: virtual reality can be an efficient tool to support training for complex tasks. The system can train the assembly staff before actual assembly production. On the other hand, it can guide and teach the assembly workers on the assembly floor.

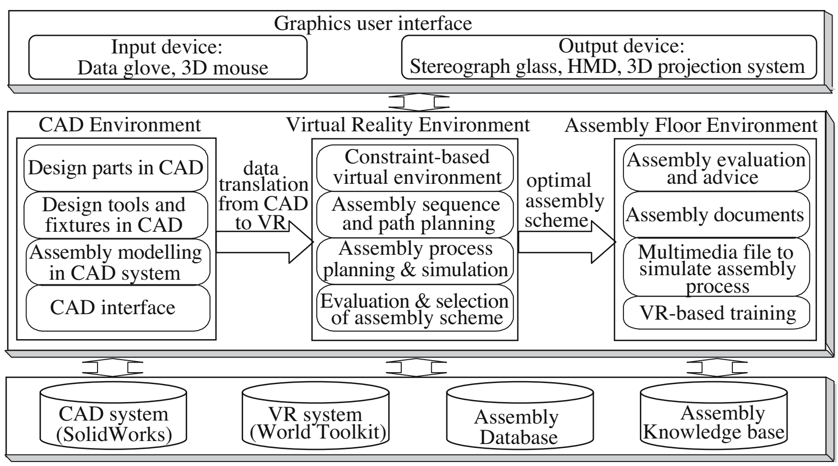
The system architecture of I-VAPTS, which has been modularized based on the functional requirements, can be summarized by dividing it into three aspects (Fig. 1).

In the CAD environment, the parts, tools and fixtures are designed and stored in an assembly database. By defining a series of mate constraint relationships, which recognize the positioning of parts relative to one another, parts are assembled together and a CAD model of the product is obtained. Only the final position of the part in the assembly model is important, the assembly sequence and assembly process are not taken into account in the CAD system. These CAD models are loaded into the virtual environment. Because the virtual reality environment uses a polygon representation to visualize objects, relevant information must be extracted from the CAD model and exported into the virtual environment to support interactive assembly planning and evaluation. All of these steps are part of assembly modeling, which is now exemplified in SolidWorks, a commercial CAD software which provides powerful API functions to access its inner CAD database.

In the virtual reality environment, an efficient geometry constraint recognition and management method is provided to support interactive assembly planning and evaluation. By simulating the process of how the constraints are applied and realized, the system can provide a valuable way to analyze and evaluate the assembly design, and further optimize the assembly operation processes. This involves planning the assembly sequence and path, selecting the assembly tools and fixtures, determining a convenient point for quality testing and surface preparation, obtaining a time and cost estimation for assembly operation, then providing an optimal assembly planning scheme and reference documents to assembly workers.

In the assembly floor environment, the workers carry out the actual production assembly after assembly task training in a virtual environment. For a complex product, there are a number of assembly operations that require dexterous operation skills, and it is a time-consuming process for workers to master these skills, especially for a new member of staff or when a new product comes into production. A multimedia file is clipped and synthesized to simulate the dynamic assembly process derived from the optimal assembly scheme obtained in the virtual environment, including the optimal assembly sequence, assembly path and assembly operation. This multimedia video file is output and played on the assembly floor to teach and guide the assembly production workers.

Fig. 1 System architecture



3 Object oriented system implementation of I-VAPTS

The proposed virtual assembly planning and training system is designed using object oriented software design methodology and implemented with the object oriented programming language, Visual C++ and World Toolkit.

3.1 Data translation from CAD to VE

The virtual reality software (World Toolkit) uses a polygonal representation to visualize objects; the polygon model used in most VR systems provides the illusion of being immersed, but it may not be able to precisely define the object geometry. On the other hand, it is difficult to carry out assembly modelling operations due to the lack of topological relationship and constraint information. So a method called IDM (information decomposition method) is developed to translate CAD data into the virtual environment. All the assembly information defined in the CAD system is decomposed as geometry, topology and constraint information. These three different types of information are translated by a CAD interface from CAD to VR respectively, on the other hand they are related with each other to constitute an integrated assembly model to support interactive assembly planning and evaluation in the virtual environment. The data flow in the information decomposition method is shown in Fig. 2.

The parts are designed in a CAD package such as SolidWorks, the results can be saved as a .wrl file or a .sldprt file. Although WTK can load parts from .wrl files, there are many limitations in the .wrl files generated by SolidWorks — for example, the material and color information are not included. A neutral file format (.nff) is created by reading the triangle polygons from the .wrl file, and a CAD database is connected to the .nff file through SolidWorks API.

A file translator is developed, as shown in Fig. 3, to translate geometry information from CAD to VR. This reads geometrical data from the .wrl file output by SolidWorks, and the geometry data is reordered to generate a .nff document. At the same time, every geometry surface is given a name, every polygon is given an identity number, and the material, colour and texture information for every polygon is also written using the SolidWorks API function. The generated .nff document (Fig. 4) is a triangle-based polygon representation, it describes each geometry surface as a common array of triangles together with a connection list that defines each surface as a set of indices and associated array of vertices.

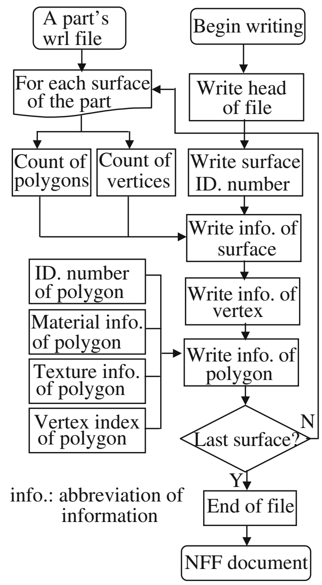


Fig. 3 Geometry information translation

The topology relationship of the part must be rebuilt in the virtual environment. A hierarchical map structure is set up as shown in Fig. 5. An assembly object is composed of many parts, a part object is the aggregation of geometrical surfaces, and a surface object is the aggregation of a series of polygons. The polygons are the mesh unit to visualize in the virtual environment, and the surface object is the foundation to define geometry constraints, such as parallel surfaces, perpendicular surfaces, etc. The assembly object, each part object, each surface object and each polygon object are given an identity number as written into the .nff file, for example, a polygon recognized by the identity number in the virtual environment corresponds to a unique surface object, and a surface corresponds to a unique part, and a part object corresponds to a unique assembly object. The hierarchical map structure is an important representation for constraint recognition and assembly operation in the virtual environment.

Geometry constraints are other important information defined in the CAD system. Constraints play a critical role in assembly design, because the designers usually use con-

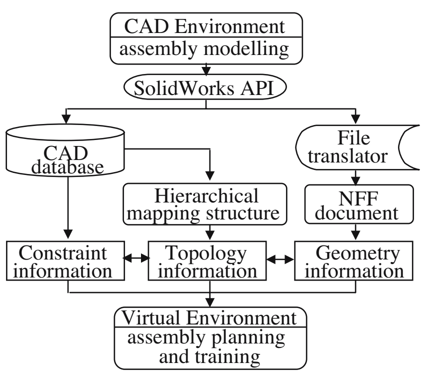


Fig. 2 Data flow in IDM

Surface Id: S_1
Total number of vertices in S_1
Vertex 1, V_{x1}, V_{y1}, V_{z1}, Normal_definition
Vertex 2, V_{x2}, V_{y2}, V_{z2}, Normal_definition
…
Total number of polygons in S_1
Type=3, V_1,V_2,V_3, material, colour, polygon id=P_{11}
Type=3, V_2,V_4,V_5, material, colour, polygon id=P_{12}
…

Fig. 4 NFF file syntax

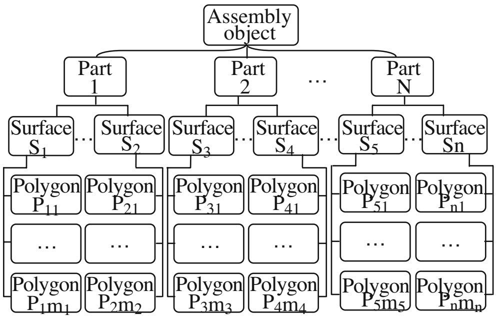


Fig. 5 Hierarchical mapping structure

straints to realize the positioning of parts relative to one another. Most CAD systems represent the assembly using constraint relationships between parts. In SolidWorks, after the parts are assembled together, a mate feature tree is obtained. Using SolidWorks API functions the mate constraints information can be extracted by recursively traversing the mate feature tree object; these geometry constraints can then be represented in a constraint manager, as discussed in the next section.

In the constraint manager (Fig. 6), a mate surface is a geometry surface of a part that has mate relationships with other parts. A part may be composed of many surfaces, but only a few surfaces have mate relationships with other parts. These mate surfaces are included in the constraint manager, whereas other surfaces are excluded in order to simplify the constraint manager structure and thus improve efficiency during the constraint recognition process. Each mate surface is represented by specific elements that define its parametric equation. For example, a point on the plane and its normal vector defines a planar surface while a point on the cylinder axis, its direction and the radius of the cylinder value, define a cylinder surface. Besides the surface specific elements, each surface has a bounding volume, this volume defines a surface's borders because the equations define limitless surfaces. The constraint list includes all the geometrical constraints defined in the CAD model; each constraint node in the list includes the constraint type, such as concentric, against and collinear, and mate tolerance, etc. All this information is extracted from the CAD database by using SolidWorks API functions.

3.2 Dynamic constraint recognition and management in virtual environment

Virtual assembly applications now mainly serve as a visualization tool to examine the geometrical representation of the assembly design and provide a 3D view of the assembly process. This technology is not yet at a stage where it can be implemented and used in industry for a number of reasons, one of which is the lack of physical constraints that the user depends upon in the real world. To compensate for this, the user needs to provide the constraints required for the precise manipulation of the virtual objects. On the other hand, to guide interactive assembly, the planner should analyze the mating constraints between the parts, their relative position, orientation, etc.

The automatic recognition of geometric constraints can simulate realistic behaviour interactively. While an object is being manipulated, the position of the moving object is sampled to identify new constraints between the manipulated object and the surrounding objects. This is performed in five steps:

Step1 When the user grabs a part using the data glove, the system searches all other objects in the constraint manager that exhibit a mate relationship with the manipulated object, and the mate surfaces in these mate objects are highlighted.

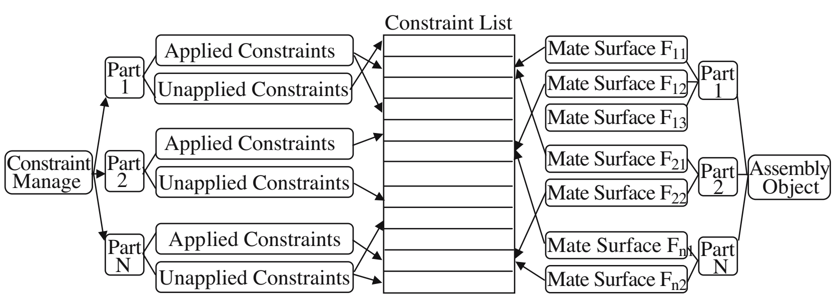
Step2 When the user moves the object, collision detection between the manipulated object and the surrounding objects continues until a collision occurs.

Step3 Further collision testing is made to recognize possible geometry constraints between the surfaces of the collided objects. A constraint is recognized if the geometric surface elements of the collided objects satisfy conditions of a particular constraint type within a predefined tolerance.

Step4 When a constraint is recognized, feedback is provided to the user by highlighting the only two mating surfaces while the other highlighted faces in Step1 are removed.

Step5 If the user decides to accept the new constraint, the precise position of the manipulated part is calculated and it is transformed to its proper position. If the user continues to move the object to invalidate the condition for that constraint, the newly identified constraint is ignored.

Fig. 6 Constraint manager structure



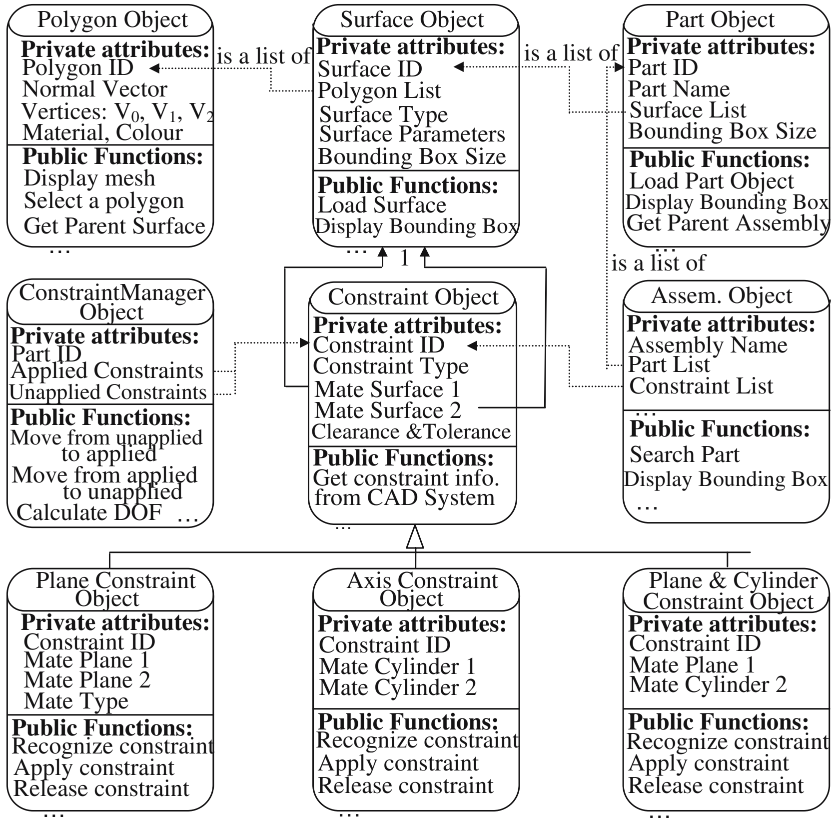


Fig. 7 The object hierarchy of I_VAPTS

A constraint is recognized between two planes when the angle between their normals is less than the angular tolerance and the distance between the planes is less than the linear tolerance. Two cylinders have a potential constraint when their axes make an angle within the angular tolerance and are less than the linear tolerance apart. The constraint between a plane and a cylinder is recognized if a plane's normal is perpendicular within the angular tolerance to the cylinder's axis and if the distance between the cylindrical and the planar surfaces is less than the linear tolerance.

A further surface collision detection is needed when two objects collide. Traditionally, VR toolkits use polygonal representation to visualize objects; similarly, the collision detection for VR applications is based on triangles. When two objects are tested for collision, the algorithm returns all intersecting triangles first. These triangles are then processed to identify all the colliding surface pairs. This approach is time consuming because a potentially large amount of redundant computation is required to check collisions between all the possible polygonal pairs. A geometrical surface based collision algorithm is implemented to associate polygons with their surfaces. According to the hierarchical mapping structure, each part object is considered as a collection of surfaces and each surface is maintained within the scène graph as a separate node. Each surface node in the scene graph maintains the surface information and its corresponding polygonal data. For example, for a planar surface point, normal, bounding box and polygonal data information for that surface are maintained. The collision algorithm is described by the following three steps.

Step1 Collision detection occurs between the bounding boxes of the two parts.

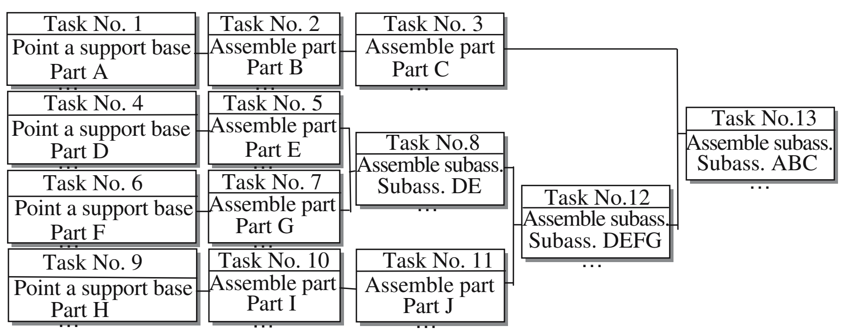


Fig. 8 Assembly task description and assembly task model

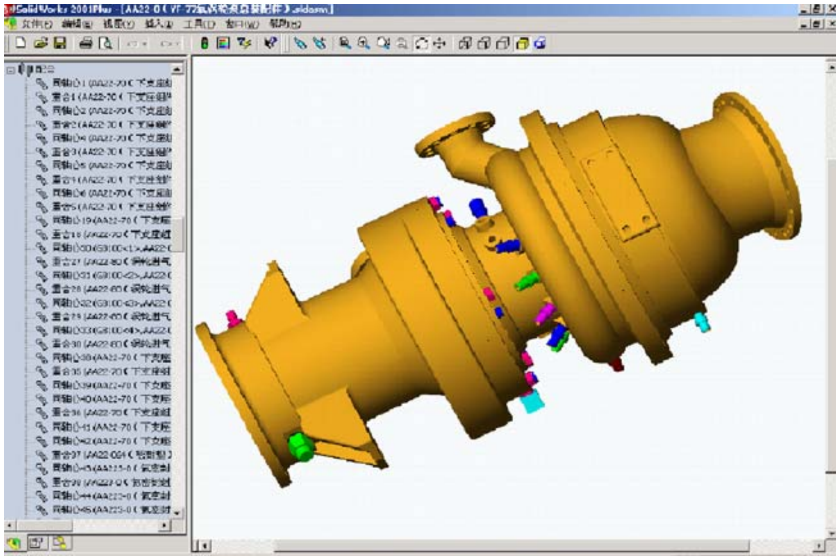


Fig. 9 CAD model of pump in SolidWorks

Step2 Does each surface in one part's surface list collide with the other part's bounding box? If it collides, the surface is stored into a list called result surfaces.

Step3 Surface collision detection occurs between the two part's surfaces, and the colliding surface pairs are returned for constraint recognition.

During the assembly process, the parts can be in various stages in the virtual environment, e.g. perhaps only one constraint is applied, or two constraints are applied, or maybe a part just lies on the table. As the constraint status of different parts are different, the status of the constraint information and the constrained degrees of freedom of the parts need to be known so that the assembly operation can be properly guided in the virtual environment. A constraint manager is set up as shown in Fig. 6. The constraints of a part have two different statuses—already applied or going to be applied—which are called applied constraints and unapplied constraints, respectively. At first when a part is not constrained and can move in the global space freely, all the constraints will be unapplied constraints. When a new geometry constraint is recognized and applied, this constraint information moves from unapplied constraints to applied constraints. When a geometry constraint is released during disassembly, the corresponding constraint information also moves from applied constraints back to unapplied constraints. After the part is fully constrained and placed on the base part, there should be no unapplied constraints.

The object hierarchy of I-VAPTS is shown in Fig. 7. With the system module property identified, a set of objects can then be designed to implement it.

Fig. 10 CAD models loaded in VR

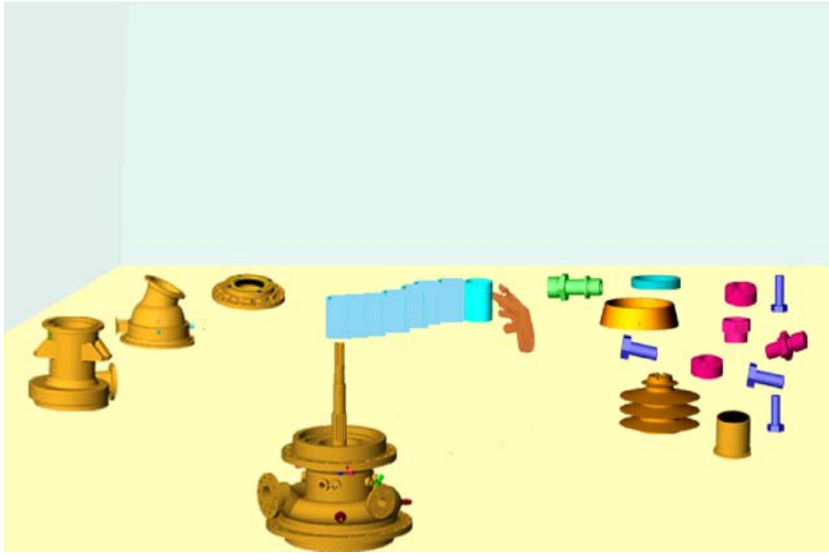


Fig. 11 Interactive assembly planning in VR

3.3 Process-oriented interactive assembly task planning and evaluation

In a constraint-based virtual environment, the planner should not only check the collision-free mate paths between the parts, the virtual tools and the environment during interactive assembly, but also ensure that the parts are designed for ease of assembly, that the assembly space is sufficient for the tools, and that the ergonomics is sound. The assembly knowledge base supplies on-line help and advice to the planner, such as using the heavy and large part as the support base, working form heavy to light, working from inside to out, and installing identical parts simultaneously, etc.

Traditionally, virtual assembly simulations focus on a 3D graphics display, and some useful assembly information and assembly knowledge during the assembly process isn't taken into account. A process-oriented virtual assembly task planning and evaluation method is present here. For each step in a product's assembly sequence, we define the assembly operations of installing a part in this step as an assembly task. An assembly task is described in Fig. 8. Based on the user interaction with the virtual object, an assembly task model graph is generated interactively.

The process-oriented assembly task model supplies the following advantages to support the interactive assembly planning and evaluation:

1) An assembly task includes a series of assembly actions. For example, an assembly task can be divided into six basic activities such as reach, select, grasp, move, position and assemble. The assembly operations, including the corresponding operation time and constraint status, are stored in an assembly action list.

Fig. 12 Assembly reference documents

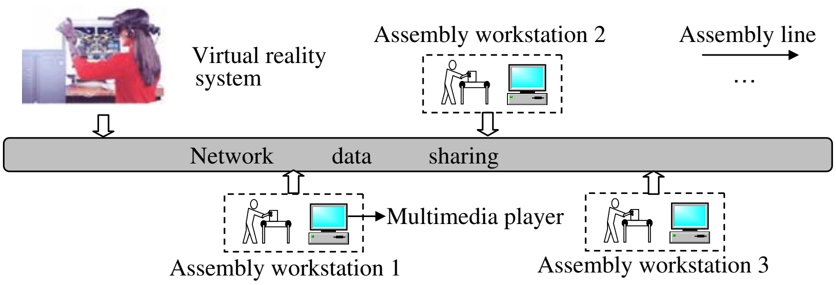


Fig. 13 An application structure of I_VAPTS in assembly floor

2) The part's assembly path and sweep volume can be used to evaluate the assembly space complexity.
3) Assembly hierarchical tree information, such as the division of subassemblies, can be used to measure the parallelism of assembly tasks.
4) Assembly precedence constraint relationships between parts can be used to evaluate and select an efficient assembly sequence. For example, if part A must be assembled before part B, the precedence constraint relationship can be denoted as A>B; if part B must be

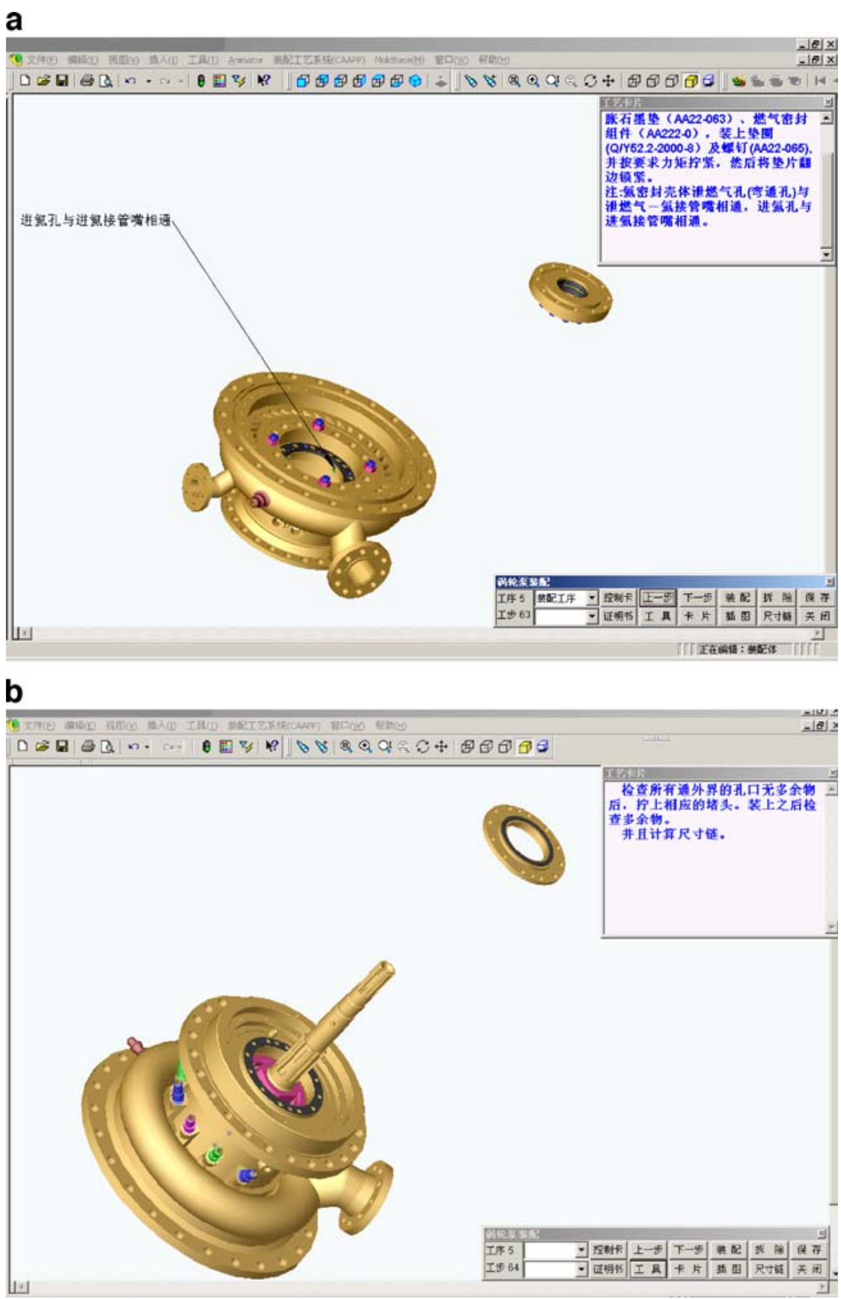


Fig. 14 Multimedia file simulating assembly process

assembled immediately following part A, then the precedence constraint relationship can be denoted as A→B, etc.

5) Assembly tools and fixtures, assembly time, etc. can be used to evaluate and select an optimal assembly planning scheme.

4 Application

The system has been applied to an industrial product successfully, and a case study for a pump assembly in an aeronautic engine is used here to demonstrate the assembly planning and training functionality of the I-VAPTS system. The pump is a key subassembly in the engine, which includes many parts and components. The CAD model of the pump in SolidWorks is shown in Fig. 9. After loading the CAD models into the virtual environment (Fig. 10), the planner can interactively plan the assembly sequence and path for the product, visualize the assembly operation process and evaluate and select the optimal operation method. Then an optimal assembly scheme and assembly documents are provided to assembly workers (Figs. 11 and 12).

An application structure of the system is given by Fig. 13. An assembly process multimedia simulation movie file (including text, voice and graphics) is played to display the assembly operation process in the workshop (Fig. 14). The workers watch the assembly simulation movie for help and instruction on how to carry out the actual product assembly. The assembly performance and assembly efficiency can be improved more easily than with the traditional assembly methods, where the workers can only reference 2D drawings and assembly handbooks.

5 Conclusion

Assembly process planning is both knowledge and experience intensive. Automated or semi-automated CAAPP systems do not appear to have made a significant impact within the manufacturing industry. The immersive virtual environment developed in this research provides an alternative model for the generation of an optimal assembly planning scheme. On the one hand it can be used to train assembly staff, new staff in particular, who need to undergo rigorous training so as to improve their knowledge and skills for assembly tasks. On the other hand, it can be used to guide the workers to undertake practical assembly production in the workshop. The application to a pump assembly process indicates that the system is valuable and pragmatic.

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