3-D Design Review System in Collaborative Design of Process Plant

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Abstract. Design review is important in collaborative design of process plants. To satisfy the actual work demands of design review, a 3-d design review system is developed and the key technologies such as information organization model and multi-resolution rendering approach are proposed. The information organization model combining scene tree and attribute tree can organize the information from different CAD systems with a unified structure, and optimize the information query speed. The multi-resolution rendering approach based on programmable graphics pipeline can improve rendering efficiency within less preprocessing time, without using extra hard-disk space. Examples show that the 3-d design review system can work on a general PC to review a large quantity of design information from different subjects, and ensure real-time interaction at the same time.

Keywords: Design review · Information organization model · Multi-resolution rendering · Collaborative design

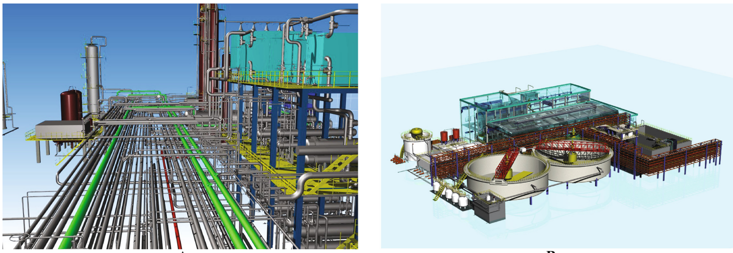
1 Introduction

Process plants, such as refineries and petrochemical plants, are complex facilities mainly consisting of pipelines and equipment [1]. As shown in Fig. 1, process plants are used in industries such as petrochemical, power, metallurgical industries. With increasing product complexity and intensive global competition in the process plant industry, companies are increasingly relying on collaborative design techniques to shorten the design cycle and to sustain the optimum productivity [2].

In collaborative design of process plants, there are constraints among stages or subjects. The relevant design must meet the constraints, otherwise there will be confliction. So design review is important in collaborative design of process plants. A reviewer has to check the results of different stages or subjects to find the design errors and conflicts, and then inform relevant designers the review results. When the review efficiency is improved, the rework in construction and the corresponding cost waste can be reduced, which helps to avoid the extension of period. So far, many review systems have

S. Wang and A. Zhou (Eds.): CollaborateCom 2016, LNICST 201, pp. 439–450, 2017.
DOI: 10.1007/978-3-319-59288-6_40

been developed by major CAD companies for their own CAD products, e.g. Navis-Works, SmartPlant Review and PDMS Review. But none of them works well in large CAD datasets especially on current desktop PCs.



A
Urumqi Petrochemical Company Refinery 110 million tons / year delayed coking unit expansion project

B
Wastewater treatment project in Shanghai Baoshan Iron and Steel Dedigned by South Metallurgical Engineering design Company

Fig. 1. Instances of process plants

First, the design institutes adopt different CAD systems, leading to the heterogeneity of design information. Second, limited by economic conditions, the design institutes usually work with general PC. Finally, as the collaborative design technology is getting more widely used in design of large-scale process plants, the quantity and complexity of information in design review have been raised rapidly [1]. To solve the problems mentioned above, a new 3-d design review system needs to be developed, which can process large quantity of design information from different CAD systems while working on a general PC.

The remainder of this paper is structured as follows. We introduce the problems and some related works in Sect. 2. The architecture of our review system is described in Sect. 3. In Sect. 4, the key technologies such as information organization model and multi-resolution rendering approach are proposed. Section 5 presents and discusses the function and the performance of our review system. Finally, conclusions are drawn in Sect. 6.

2 Problems and Related Work

During design review, the reviewer could find the design errors and conflicts among subjects or stages by real-time 3-d navigation, either by referring to the attributes and design conditions, or through automatic collision check and design condition check by the computer. To achieve the above functions, some technologies must be improved and adopted in review system, e.g., fast rendering, human-computer interaction, information organization and collision detection. In this paper, we focus on two problems, how to organize the design information from different CAD systems, and how to fast render a large-scale process plant model.

2.1 Information Organization Model

The information of graphics, topology, attributes and design conditions should be included in design review. The model of triangular surface piece, which is usually used in virtual environment, is not suitable for design review because it has lost topological information and attribute information [3]. Various information organization models have been proposed to solve this problem [4–7], and most of them were oriented to satisfy the requirements for application of virtual assembly. Compared to virtual assembly, the structure of graphics information is much simpler, and no behavior information is required. But there are a large number of graphics in design review, with more complex topological relations and a large quantity of engineering attributes. Therefore, neither the triangular surface piece model nor the information organization model for virtual assembly can satisfy the demands of design review, so it is important to study the information organization model that can simultaneously organize the information from different CAD systems with a unified structure and optimize the information query speed.

2.2 Multi-resolution Rendering Approach

During design review, a large-scale process plant model usually involves hundreds of millions, even thousands of millions of triangular faces. In order to improve the real-time performance of human-computer interaction, the number of polygons rendered in each frame should be reduced while the realisticness of the scene has been satisfied. Level-of-Detail (LOD) proposed by Clark [8] in 1976 is an effective method. There are two types of LOD: static LOD and dynamic LOD. Although the latter provides high quality images, it increases the computing cost in the rendering process. On the contrary, the static LOD could reduce the computing cost by constructing a multi-resolution model in advance. Therefore the static LOD is usually preferred in an actual real-time rendering system for a large-scale complex scene. On one hand, it takes a long time to preprocess a multi-resolution model with the traditional static LOD. To solve this problem, multi-resolution model in parallel with PC cluster [9, 10] or with GPU [11, 12] were constructed. However, it still takes minutes or even hours. In order to improve the design review efficiency, the preprocessing time on general PC should be reduced effectively. On the other hand, main memory could not contain large quantity of multi-resolution model of large-scale complex scene with the traditional static LOD. To solve this problem by out-of-core techniques, experts [13–15] start to develop multi-resolution rendering approaches based on external memory. But these approaches require large extra hard-disk space. Therefore, a new multi-resolution rendering approach which requires less preprocessing time and less hard-disk space for design review of process plants should be studied.

3 Architecture of 3-D Design Review System

A new 3-d design review system which adopts novel information organization model and multi-resolution rendering approach is developed in this paper, and its bottom-up structure includes layers of "resource supply", "review data", "review core service", and "review functional application". "Resource supply" derives the design information from different CAD systems and transports to "review data". "Review data" stores and manages the design information using database. "Review core service" acquires the information and organizes it by access to "review data", and provides "review functional application" services for querying. Reviewers use the functions provided by "review functional application", and return the results to the data layer.

The design information includes graphics, topology, attributes and design conditions. These types of information would be queried real time but not be modified in design review of process plants.

Graphic information describes the geometric figure of an object. In this paper, "Object" is the minimum unit in engineering description, e.g. a pipe and a valve. In design review, what the reviewer concerns about is only the graphic's surface information of an object, rather than the internal conditions. An object is mainly composed of basic voxels, such as box, cylinder, prism, and sphere. Figure 2 shows the basic voxels used in our process plant model.

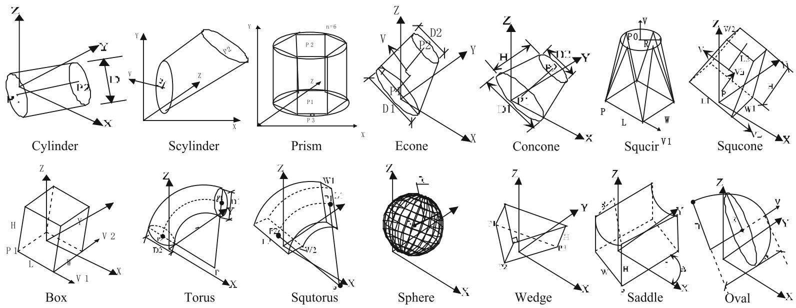


Fig. 2. Basic voxels used in process plant model

Topological information describes the connection relation between objects. As shown in Fig. 3, pipe A1 is connected with valve B, and valve B is also connected with pipe A2. In hard collision check, it is supposed that no collision occurs between the connected objects.

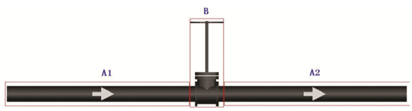


Fig. 3. Topological information in one particular pipe

Attribute information includes category attribute and engineering property. Category attribute is the category which the objects belong to and hierarchical relations between the categories. Engineering property is the object's attributes and corresponding value in the engineering application, e.g. pipeline rank, size, end-category, thickness, material, and flow direction.

Design condition information describes a related design condition for other design subjects requested. For example, equipment subject requests structure subject in ground bearing ability, due to the need of using large equipment.

4 Key Technology

4.1 Information Organization for Design Review

On one hand, design information is from different CAD systems and in this way it has problem of information heterogeneity. On the other hand, the efficiency of design review depends on the efficiency of information queries. Therefore, an information organization model combining scene tree and attribute tree is proposed in this paper. We use this model to organize the design information with a unified structure, and optimize the information query speed.

4.1.1 Information Organization Mode Combining Scene Tree and Attribute Tree

The information organization mode combining scene tree and attribute tree is shown in Fig. 4, with objects as the minimum organizational unit. Under the subject node, the scene tree is on the left and the attribute tree on the right. The subject node is used to describe the corresponding information and address of review database of the subject. The scene tree describes the subject's graphic information and topological information, using the octree structure to organize the objects. The octree structure helps in view frustum culling and occlusion culling, which can finally improve the rendering speed. The attribute tree describes the category attribute and engineering property, using category to organize objects. Due to the large quantity of engineering property information and low using frequency, on-demand mode is applied to read in the engineering property, thereby saving the cost on main memory.

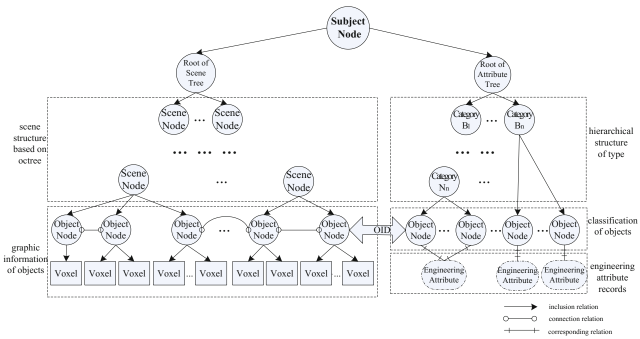


Fig. 4. Information organization model combining scene tree and attribute tree

4.1.2 Storage and Acquisition of Design Information

Database has some advantages, such as accurate data retrieval, convenient remote access, reasonable resource utilization and easy data recovery. In this paper, the design information extracted from CAD systems and the results returned from review are stored in database in the form of tables. An independent database is established for each subject, and the structure of the tables is shown in Table 1. The information organization mode combining scene tree and attribute tree is constructed according to information in the tables.

Table 1. Information in the tables of database

Table name	Table description
Meta	Subject information, including name, CAD system, version, and units
Category	Category information, including category id (cid), category name, father category id and engineering property table id (pdid)
Property_*	Engineering property information, including engineering property id (pid) and fields of engineering attribute. * means pdid
Object	Relationship between object and category, and engineering property, including object id (oid), the corresponding cid and pid
Graph	Graphic and topological information of an object, including oid, RGB valuet, axis-aligned bounding box, and the voxels included in the object
Condition	Design condition information proposed for other subjects, including design condition id, other subjects' names, oid of the subject corresponded and text description of the design conditions
Result	Review results, including review result id, type, location, and set of objects related to the problem

The review system is not required to build model. The design information is acquired from CAD system and reconstructed in review system. A CAD system usually provides a development interface, such as ObjectArx provided by AutoCAD and Pro/ToolKit provided by Pro/Engineer. In this paper, information is exported through the development interface, based on the category definition files (XML format) provided by each design subject.

4.1.3 Query of Information

In 3-d design review, we query engineering property by obtaining the objects according to human-computer interaction. The specific steps are as follows:

Step 1. Intersection of ray with scene node's axis-aligned bounding box of scene tree in the information organization mode. If there's no intersection, traverse process ends. If the intersection obtained, then traverse the child nodes of this node. If the child node is a scene node, repeat Step 1. If the child node is an object node, execute Step 2.

Step 2. Intersection of ray with object node's axis-aligned bounding box. If intersection obtained, then traverse the child nodes of this node. Otherwise the traverse process ends.

Step 3. Intersection of ray with voxel node's oriented bounding box. If intersection obtained, then traverse the corresponding triangular faces of this voxel node. Otherwise the traverse process ends.

Step 4. Intersection of ray with triangular faces. If intersection obtained, then record the oid of the object which the voxel belongs to. Otherwise the traverse process ends.

Step 5. Acquire the corresponding pid and pdid of the object by oid, according to the structure of attribute tree in the information organization mode.

Step 6. Acquire the engineering property by querying the "Property_pdid" table in the object database based on pid.

4.2 Multi-resolution Rendering Approach for Design Review

In recent years, fixed graphics pipeline has been replaced by programmable graphics pipeline in GPU, which provides a flexible control interface to vertex buffer and index buffer in display memory [16]. It provides good opportunity for solving the problems in fast rendering of large-scale complex scene. A multi-resolution rendering approach of large-scale process plant model based on programmable graphics pipeline is proposed in this paper.

4.2.1 Construction of Multi-resolution Model

As mentioned above, an object is mainly composed of basic voxels. A multi-resolution model of objects is constructed according to the multi-resolution model of the basic voxels. In the generation of multi-resolution model, the proposed approach ensures that the vertex set of a low resolution model is the subset of that of a high resolution model. So only the vertex information of its highest resolution mode and some of the vertex indexes are needed to be saved for each object.

In advance, a multi-resolution model of the basic voxels is constructed on basis of the number of subdivisions in the following steps:

Step 1. The voxel is subdivided uniformly. In a cylinder, for example, both its bottom and top circles are divided into N sections, then its flank is turned into $2 \times N$ rectangular meshes, and the two circles are turned into regular N-polygon with totally $4 \times N$ vertexes. The multi-resolution model of the basic voxels is constructed by the number of subdivisions (N).

Step 2. The maximum and minimum of N ($N_{\max}$ and $N_{\min}$ respectively) are obtained based on the voxel size. In order to subdivide a voxel uniformly, we define $N_{\max} = 2^{n_{\max}}, N_{\min} = 2^{n_{\min}}$, where $n_{\max} \geq n_{\min} \geq 2$ are integers.

Step 3. Define N of the *i-th* resolution model of voxels as $N_i = 2^{n_i}$, where $n_i = n_{\min} + \lfloor i \cdot (n_{\max} - n_{\min})/(L-1) \rfloor$ is an integer, and L is the number of multi-resolution model. The first subdivision points of different resolution models are the same.

If the voxel subdivision number is larger, the voxel has more triangular faces, and the resolution of the model is higher. The voxel is symmetric, and subdivision number of a high resolution model of voxels is 2^x times that of a low resolution model. So the vertex set of the low resolution model is the sub-set of that of the high resolution model.

In a cylinder, for example, its size is determined by diameter D. If $D \in [0, 1]$ (meter), then $N_{\text{max}} = 2^5 = 32, N_{\text{min}} = 2^2 = 4$. The subdivision of the circles and cylinder graphics of a multi-resolution model when $L = 4$ are shown in Fig. 5.

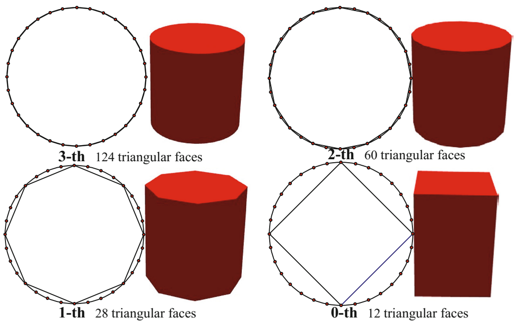


Fig. 5. Subdivision of the circles and cylinder graphics of multi-resolution model

4.2.2 Transformation of Multi-resolution Model

Based on the construction of a multi-resolution model, with effective management of vertex buffer and index buffer, a multi-resolution model can be transformed according to the vertex index transform in the rendering process. The relationship between main memory, display memory and graphics pipeline is shown in Fig. 6.

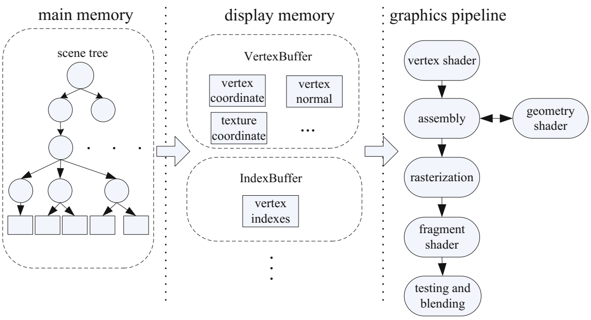


Fig. 6. Relationship between main memory, display memory and graphics pipeline

Concrete steps are as follows:

Step 1. Generate vertex information (vertex coordinate, vertex normal and texture coordinate) of the objects and vertex indexes of the resolutions, which are stored in the object nodes. Suppose the total size of the vertex information is M.

Step 2. Suppose $S_{VertexBuffer}$ is the size of the vertex buffer in display memory. If $M < S_\partial < S_{VertexBuffer}$ (S_∂ is a threshold), the vertex information of all objects is sent to the vertex buffer by main memory before rendering and is kept there the whole duration. Otherwise, combine the visibility culling and prefetching policy, transport the vertex indexes of objects which are visible or might visible into the vertex buffer from main memory.

Step 3. In the rendering process, determine the resolution model which should be used by the object, referring to the ratio of distance of viewpoint to its bounding box to the volume of its bounding box. Suppose the *l-th* resolution model should be used currently. If the current resolution is not l, go to Step 4.

Step 4. Delete the vertex indexes and triangular faces information of the object in the display memory, and send $Index_l$ stored in the object node to the index buffer in the display memory directly. Organize the triangular faces of the current resolution in the assemble stage of graphics pipeline, according to the vertex information in the vertex buffer and the new vertex indexes in the index buffer.

Since LOD does not need to be stored on hard drive, data exchange with external storage can be avoided. Since the multi-resolution model of the basic voxels is created by rule, the preprocessing time can be reduced. With this approach, data exchange between the main memory and display memory during the rendering process can be reduced effectively. During the whole rendering process, the vertex coordinate, vertex normal and texture coordinate of the objects do not need to be recalculated, although the resolution might change dynamically. Therefore, this approach can improve the rendering efficiency.

5 System and Applications

The 3-d design review system is developed by C++ and Open GL on Windows. And the derived plug-in of design information on AutoCAD is developed based on ObjectArx, using MySQL as database.

5.1 Function

In the design review of multi-subjects of one chemical plant for example, it refers to subjects of pipe, equipment and structure. The three subjects are all designed on AutoCAD. Review database, CAD systems and review system are all deployed in LAN. First, designers of each subject derive the design information of its own subject from CAD system by the derived plug-in. Then the reviewer acquires the information from the database through the review system and reviews the design of multi-subjects, with the help of functions, such as real-time 3-d navigation, attribute query, and collision check. As shown in Fig. 7 A, the reviewer queries the design conflict manually in long distance by 3-d navigation with the review system. As shown in Fig. 7 B, the reviewer queries the engineering property of one particular valve in short distance with the review system.

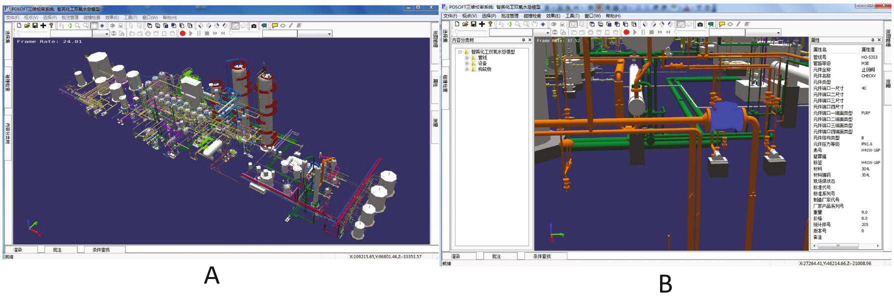


Fig. 7. Reviewer views the model with the review system

5.2 Performance

In review of subjects such as pipe, equipment and structure, the number of triangular faces will be larger than 21 million, and the data of engineering property will be larger than 300 M bytes. Meanwhile, the 3-d design review system developed in this paper is applied, with the computer configuration: CPU, IntelCore2 2.2 GHz; graphics card, GeForce9400 (512 M); and 2G RAM. Each object has 4 LODs with average distances of [0 m, 50 m), [50 m, 75 m), [75 m, 100 m), [100 m, +∞). Our approach preprocesses this model within 10 s and achieves an average smooth frame rate of 31 fps, without using extra hard-disk space. The query time for engineering property of a single object could be reduced to less than 0.1 s, and the requirement of real-time interactive could be satisfied. Table 2 illustrates the performance of our approach by rendering this model over the same path on the same PC, compared with other approaches.

Table 2. Results of comparison

	Average frame rate/f/s	Preprocessing time/s	Extra hard-disk space/M
LOD is not used	9.3	5	0
Approach in paper [17]	40.3	336	932
Our approach	31.7	7	0

Table 2 shows that the rendering performance of our approach is not as high as that in paper [17]. However, the real-time interaction can be satisfied with our approach. It is significant that the preprocessing time is controlled within 10 s and no extra hard-disk space is required with our approach, while the preprocessing time is more than 5 min and more than 900 M hard-disk is required with the approach in paper [17].

In a piece of pipe including multi-objects and multi-voxels, for example, the models of the highest resolution and the lowest resolution are compared as shown in Fig. 8a and b. Obviously, model simplification leads to deformed appearance, but the graphics characteristics and topological relation are still clear. The low resolution models are used in long distance (Fig. 8c), and in that condition, this type of model will not be the subject concern of the reviewer. Therefore, vision errors caused by simplification are acceptable.

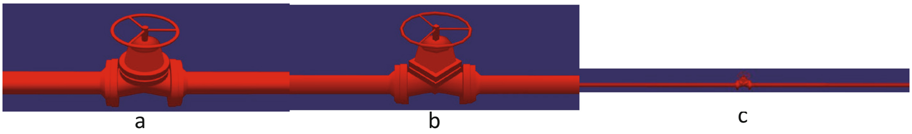


Fig. 8. Multi-resolution model of one particular pipeline

6 Conclusions

Process plants are used in many industries which have a significant effect on the national economy sectors. Design review is important in the collaborative design of process plant. A 3-d design review system is developed to improve review efficiency in this paper. The key technologies of this system are proposed, such as information organization model and multi-resolution rendering approach. This information organization model organizes the information from different CAD systems with a unified structure, and optimizes the design information query speed through the good organization structure. This multi-resolution rendering approach based on programmable graphics pipeline ensures that the vertex set of a low resolution model is the subset of that of a high resolution model, so only the vertex information of its highest resolution mode and some of the vertex indexes need to be saved for each object. On this basis, with effective management of the vertex buffer and the index buffer, multi-resolution model transform can be implemented according to the vertex index transform in the rendering process. Examples prove that our review system could satisfy actual work demands of design review. It could work on a general PC to review a large quantity of design information from different subjects, and ensure real-time interaction at the same time. Our review system is used currently in many design institutes in China.

Acknowledgements. This work is sponsored by the National Natural Science Foundation of China (No. 71301081, 61373139, 61300165, 61572261), Natural Science Foundation of Jiangsu Province (No. BK20130877, BK20140895), Postdoctoral Science Foundation of China (No. 2014M551637), Postdoctoral Science Foundation of Jiangsu Province (No. 1401046C).

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