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Interactive Rendering and Modification of Massive Aircraft CAD Models in Immersive Environment

Junjie Xue[1,2] and Gang Zhao[1,2]

[1]State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, Beijing, China, bitxue@gmail.com

[2]School of Mechanical Engineering and Automation, Beihang University, Beijing, China, zhaog@buaa.edu.cn

ABSTRACT

This paper proposes a new system framework for the interactive rendering and modification of massive aircraft models. Compared with the existing massive model visualization systems, the framework has higher preprocessing efficiency by employing an automatic LOD generation algorithm while retaining the assembly tree information. The hybrid representation of geometry node based on mesh and B-Rep enables direct and intuitive CAD modification on model nodes in VR environment, which brings faster update speed to massive aircraft models data in comparison with utilizing the traditional preprocessing pipeline.

Keywords: massive aircraft models, interactive rendering, model modification, virtual environment (VE), CAD-VR integration.

1. INTRODUCTION

1.1. Background and Problem

Aircraft CAD models have been recognized as one of the most complex and largest datasets in the world which consist of millions of parts and have complicated topology. The model data storage can be up to gigabyte and the number of the triangular faces within the visualization geometry can be hundreds of millions. For example, the Boeing 777 model has over 6 million parts and connectors, 350 million triangular faces, 12GB geometry data storage, which has far more exceeded the performance of common visualization methods.

Many research works have been done toward real-time visualization of such massive models. In general, the visualization of large-scale datasets contains two phases: preprocessing and rendering. A preprocessing phase is required to do model format converting, model simplification and partition, LOD generation, etc. Depending on the scale of the model data and the performance of computing systems, preprocessing can take between few hours up to several days. The rendering phase ensures the high fresh rate of the graphics display and functions of transparency, clipping, node picking and manipulating and the model assembly tree information display. The visualization system can be used in different phases of the aircraft lifecycle, such as design review, assembly simulation, and maintenance training. During these applications, the CAD part/product design may need to be modified due to the identification of potential design problems. Every time the CAD design changes the preprocessing procedure must be conducted to synchronize the modifications into the visualization system. Particularly in the case of small modifications to large and complex models, this is really a time-consuming and tedious work. The concept of direct modification of CAD models in VR environment can be an attractive alternative.

Several research efforts in such CAD-VR integration have been directed toward virtual reality approaches for immersive design [18], in which, VR-CAD framework is combined with multimodal immersive interaction to gain direct and intuitive deformation of the objects' shapes within VE [17]. These approaches, however, lack generality, flexibility, and most importantly, the large-scale model dataset visualization ability. Existing researches on massive model visualization mainly deal with interactive ray tracing [14], scalable rendering architecture [8] and parallel visualization and graphics clusters [9], few of them have involved the integration of interactive modification of the models and the non-geometric data loss in the model preprocessing phase.

1.2. Our Work

In this paper, the authors present a new system framework to combine the massive models visualization together with VR based CAD model modification, and ensure the real-time interactive feature. We employ an automatic LOD generation algorithm to improve efficiency of model preprocessing, meanwhile, the file hierarchy of operating system is utilized to guarantee the lossless transmission of assembly tree information. Hybrid representation of geometry nodes based on mesh and B-Rep provides good basis for the model modification in VR. VR devices are used as both visualization and modification tools of the aircraft CAD models. The interactive modification is implemented with OpenCASCADE API and model construction history graph inquiry. The direct and intuitive model modification in VR can avoid the time consuming to create and pre-process the new models in traditional way.

1.3. Paper Overview

The remainder of the paper is organized as follows: Section 2 starts with a brief overview of the existing research works on visualization of large-scale aircraft CAD models and CAD-VR integration. Section 3 introduces our interactive rendering system framework, the automatic LOD generation algorithm, and the assembly tree information lossless transmission. Section 4 describes Interactive modification of aircraft cad models in VR environment. Section 5 gives the results and analysis. Section 6 discusses the conclusions.

2. RELATED WORK

CAD has been widely applied in aircraft design and manufacturing process, the aircraft designers created an unprecedented complex aircraft models. Despite the rapid development of computer hardware, it still cannot meet the real-time rendering needs of such large-scale dataset and special visualization techniques is required.

2.1. Visualization of Large-scale Aircraft CAD Models

Research work on massive aircraft cad models visualization is not much, Boeing Company and other research institutions have carried out some exploration on this topic. The existing visualization systems mainly focus on the Boeing 777 model, and there are mainly six research cases which can be retrieved: 1) UNC's GigaWalk system [1], 2) Italy CRS4's Far Voxels system [6], 3) Saarland University's OpenRT system [16], 4) Utah SCI institute's Manta system [14], 5) Zhejiang University's Adaptive voxels system [15] and 6) Virginia Tech's Parallel LOD system [11]. Throughout these systems, most of them have applied model simplification, LOD, visibility culling, model partition, dynamic memory scheduling, and real-time ray tracing techniques [7]. These systems make it possible to visualize massive aircraft models.

However, these research works have limitations: 1) only static models can be visualized within these systems; 2) most of the research combine the models as a whole, and split the model according to the spatial location. The preprocessing undermined the assembly tree information which is crucially important for aircraft assembly, simulation and analysis; 3) the preprocessing efficiency is still low, the existing systems, GigaWalk, FarVoxels, OpenRT, and Adaptive voxels, etc. need from several hours up to days to complete model partition, LOD generation and other preprocessing task; 4) some of the systems have high hardware and software requirements. OpenRT runs on 64 bit Linux operating system and Manta runs on a super computer with 128 processors and 256 GB memory.

2.2. CAD-VR Integration

Due to the different purposes of CAD and VR, there are big differences between CAD models and VR models. CAD created detailed models aimed at subsequent process, e.g. NC, and manufacturing; while VR serves high visualization demand and it uses simplified models. The complexity of the CAD model is a major obstacle of the real-time interaction. VR file format does not support expression of engineering semantic information; while CAD models lack material and texture attributes. And in the process of converting CAD models to VR models, the problem of geometric precision and non-geometry information loss exists frequently [12].

Related research work can be broadly divided into two categories: 1) to directly integrate CAD systems with VR environment. For example, Chromium [9], which intercepts, and moves the OpenGL command stream to other OpenGL implementations, brings high performance visualization of CAD models. However, these research mainly address the graphics rendering aspect, and ignore the non-geometry information loss problem; 2) to add certain CAD functions to VR environment [2, 3, 13, 17], e.g. CNRS/LIMSI VENISE team developed a VR-CAD framework which makes user intuitively and directly edit CAD objects in virtual environment [2]. However, the framework can only handle editing operation on simple CAD models, and cannot handle massive CAD models.

3. INTERACTIVE RENDERING OF AIRCRAFT CAD MODELS

3.1. System Framework Overview

We introduce our system framework for interactive rendering and modification of large-scale aircraft CAD models (see Fig. 1). In the model preprocessing stage,

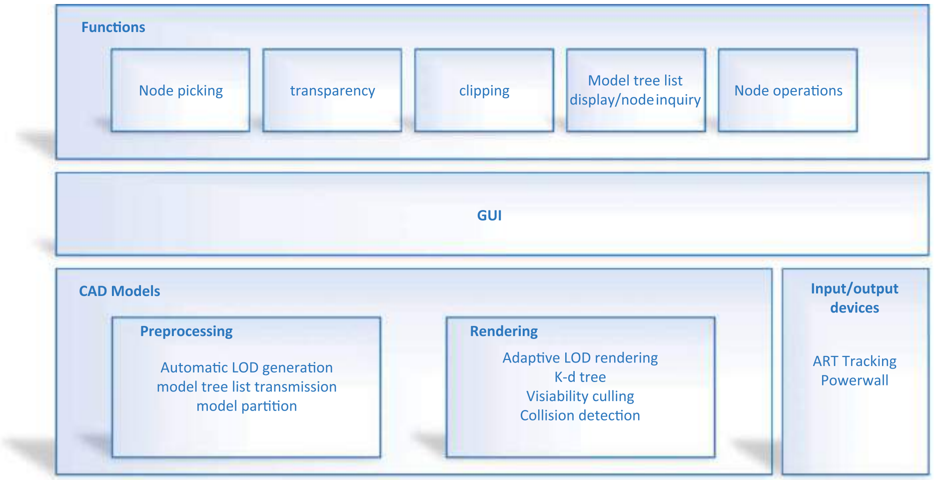

Fig. 1: The system framework of our rendering system for massive aircraft CAD models.

we propose an automatic LOD generation algorithm to improve time efficiency, and we perform model partition based on the famous surface area heuristic (SAH) algorithm. The file folder hierarchy mechanism of operating system is utilized to ensure the assembly tree information transmission during the model format conversion and LOD generation process. In the rendering stage, adaptive LOD rendering adopts the proper level of LOD of each part based on both the distance from the part to viewport, and the mesh density based on accurate occlusion query. LOD levels are adjusted according to the real-time rendering load. Meshes invisible are culled to reduce computation load.

The node picking function has two picking patterns. One is the normal rendering node picking using intersection algorithm, which determines the selected scene node to be transparent or other node operations like translation, rotation and scaling. The other pattern is the picking of B-Rep elements utilizing a collision detection algorithm between B-Rep meshes and virtual hand driven by a tracking device, which let the system know which CAD operation the user want to be modified. These two picking patterns can be switch through a button on the system GUI.

KD-tree of the model scene graph can be built to improve the time complexity in the node picking selection. Transparency and clipping effect with dynamic adjustment ensure the inner of the aircraft model to be easily examined. These make it easier for users to explore massive aircraft models.

3.2. Automatic LOD Generation of Massive Aircraft CAD Model

The display precision and real-time rendering efficiency have always been a contradiction in the process of massive CAD models visualization. The most effective way to address this problem is to apply LOD techniques. LOD can be a multi-resolution representation of a geometry model. Models with different precision levels can be generated using model simplification algorithm, e.g. the famous QEM algorithm [5]. At the rendering stage, higher precision level model with more faces is adopted when the geometry is closer to the viewport. On the contrary, low precision level model with less faces is adopted when the geometry is farther to the viewport [10].

LOD generation and rendering algorithms have wide range applications especially in the field of large-scale terrain rendering. However, as it comes to automatic LOD generation of massive aircraft CAD models, no existing methods have been proposed as equally effective. The geometry topology of large-scale terrain is regular uniform mesh, while the geometry topology of massive aircraft CAD models is more complicated. Most of existing research works used an interactive setting way to set the simplification ratio or directly create models with different precision levels. But the number of levels and the number of triangular faces within each level have no theoretical basis. And the number of parts within aircraft CAD models can be millions, LOD generation cannot be done manually by user.

We propose an automatic batch LOD generation algorithm to improve the efficiency of LOD generation of massive CAD models. The algorithm goes as follows:

- Compute the total triangular face number N_{total} of the model to be processed.
- Set the geometrical simplification ratio $s = 0.25$ (considering that surface model are mostly used in computer graphics fields, the triangular faces are distributed on the model surface. According to the large terrain simplification method, for each adjacent LOD level, the number of triangular patches on x, y direction should be

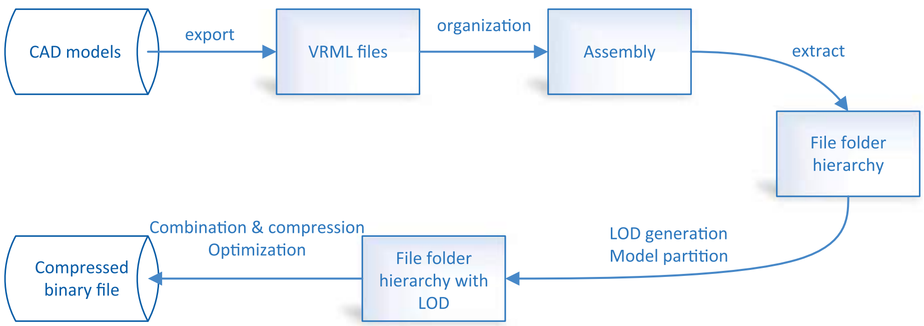

Fig. 2: Model preprocessing pipeline.

both halved. The simplification ratio s between the two levels equals$1:2^2$. Similarly, if we use volume data model, for each adjacent LOD level, the number of triangular patches on x, y, z direction should be all halved. The simplification ratio s between the two levels equals$1:2^3$.).

- Compute the total triangular face number within the highest precision level LOD model $N_{highest}$. Suppose the total size of system memory is M, memory size for each triangular face is M_0, then the maximum number of triangular faces which the can be loaded by the system is $N_{\max}$, where $N_{\max} = M/M_0$. And the total number of triangular faces within all levels of LOD should not be greater than $N_{\max}$. So we have $N_{\max} \geq N_{highest}/(1-s)$.
- If $N_{total} > N_{highest}$, do simplification until $N_{total} \leq N_{highest}$.
- Compute the number of LOD levels n. Suppose that the maximum number of triangular faces the system can render in interactive frame rate is N_{render}, which can be get through experiments. Then the total triangular faces number within the lowest precision level LOD model should not be greater than N_{render}. So we have $N_{render} \geq N_{highest} \cdot s^n$.
- For every leave node of the model, do simplification using simplification ratio s until the number of triangular faces within it is too small or the total number of LOD levels have been greater than n.

3.3. Assembly Tree Information Transmission

Massive CAD model visualization has been a traditional topic in both CAD and computer graphics research field. Many institutions have made great achievement on it, such as Utah University's Manta system, Saarland University's real-time ray tracing system. However, few of them have addressed the problem of model tree list information loss in the preprocessing phase.

Model tree list is important for part location especially in real-time visualization of large models like aircraft models, which have millions of parts and they may occlude with each other. We want a lossless transmission of the model tree list information from the original CAD models to the polygon models throughout the preprocessing phase.

In this paper, we make use of the file folder hierarchy mechanism of operating system to transfer the assembly tree information during the model format conversion and LOD generation process. CAD files are firstly exported into a 3rd party file format, e.g. VRML files, which contain the assembly tree information. These files are organized together into one assembly by using a model explorer, e.g. Right Hemisphere's Deep Exploration software. Then the assembly is extracted into a file folder hierarchy, which has the same hierarchical relationship with the original assembly tree in CAD systems. LOD generation is done at each leaf node rather than the whole model to avoid hierarchy changes. Finally the file folder hierarchy is combined and compressed into a binary file to reduce memory usage and accelerate data loading. Fig. 2 shows the model preprocessing pipeline used in our system.

4. INTERACTIVE MODIFICATION OF AIRCRAFT CAD MODELS IN VR

In solid modeling and computer-aided design, boundary representation (B-Rep) method is widely applied to represent solid shapes. A solid shape is described with vertices, edges, and faces. CAD systems give users the ability to design model shape by using basic CAD operations, e.g. curve interpolation, surface fitting, extrusion, Boolean operations. These operations are stored in a construction history graph (CHG). And in Most CAD system a B-Rep is attached to each solid node of CHG. A mesh (usually triangular or quadrilateral mesh) is associated with each B-Rep for display or interference detection purposes.

However, in VR and other visualization applications, polygon models, especially the triangular-face form models, are mostly used because the display hardware are designed to render triangles more efficiently. But the problem is that these polygon models are difficult to be further modified. The conventional way is to modify the original model with

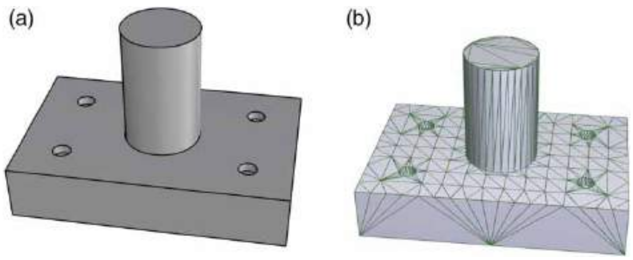

Fig. 3: Different representation of a model. (a) The B-Rep shaded model in CAD, (b) polygon model in VR.

CAD software and then do a lot time-consuming preprocessing work and finally render them. Fig. 3 shows the different representation of a model.

4.1. Hybrid Representation of Geometry Node Based on Mesh and B-Rep

In order to modify CAD models in VR environment, the B-Rep and CHG information of the specific models to be edited is required. These data should be acquired through CAD systems like CATIA which is mostly used in aircraft design.

We designed a new scene graph organization method which utilizes a hybrid representation based on mesh and B-Rep for specific geometry node in the graph. The scene graph contains root node, group nodes and geometry node. The geometry node may contains mesh data and the B-Rep and CHG information, or mesh data only depending on whether the geometry node need to be edited. Geometry nodes with only mesh data cannot be modified. Also the mesh data contains multiple LOD levels of each geometry node. Fig. 4 shows the scene graph of the massive aircraft CAD models used in our system.

We do not attach B-Rep and CHG information to all the geometry nodes based on the following considerations.

- The data storage may be too large.
- The process of generating these information is time-consuming.
- The number of geometry nodes in the scene graph can vary from thousands to millions. Not all the models of the entire aircraft design need to be interactively modified in VR environment.

4.2. Implementation of Model Modification in VR Environment

In this research, we implement the combination of massive models visualization with VR based CAD model modification, the original CAD model can be loaded and then modified directly in VE with NURBS methods. The B-Rep meshes of the new model can be applied to replace the old polygon meshes in the virtual scene.

With the VR devices, e.g. an ART Flystick or data glove, intuitive and interactive modification of the models can be enabled in an immersive way, such as picking a B-Rep element, extruding a curve, making holes on a model, or even editing control points of a model, etc. Therefore, there is no need for a preprocessing phase to modify massive aircraft models, which is much more efficient than the conventional way. The new model generated in our virtual environment can also be exported for other use.

4.2.1. Modeling parameters selection and modification

The mesh data of the geometry node is used to visualize the model shape and detect collision when we

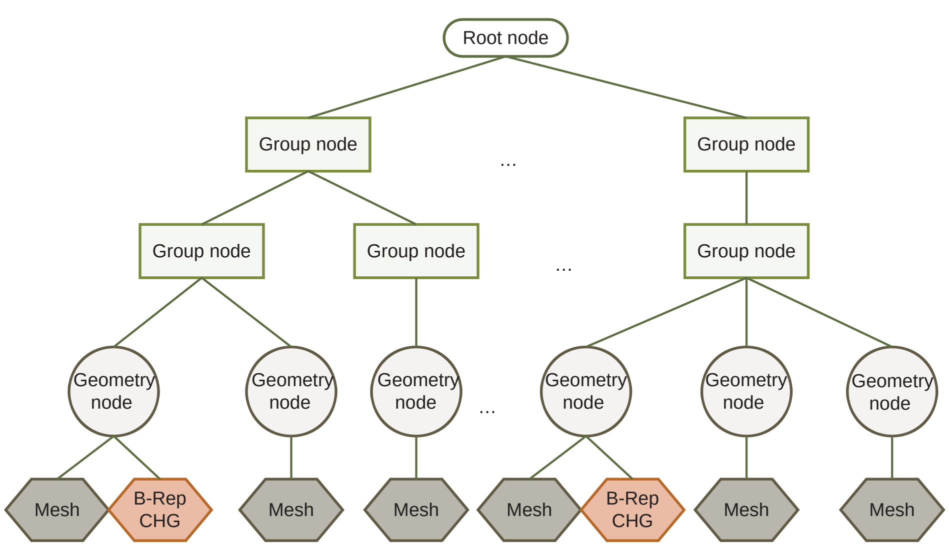

Fig. 4: The scene graph of the massive aircraft CAD models used in our system.

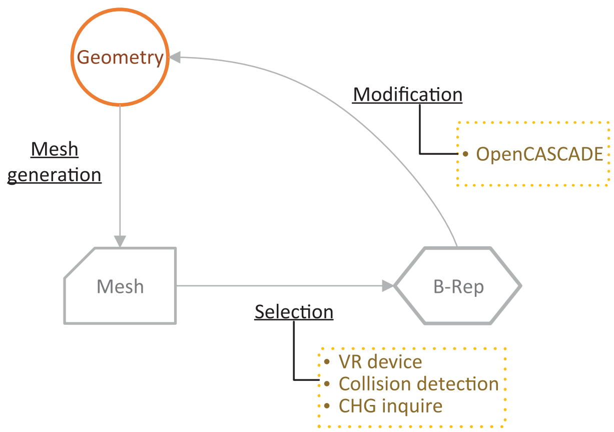

Fig. 5: The model modification pipeline.

pick the B-Rep elements with VR devices. The most critical part of model modification is the modeling parameters selection (see Fig. 5).

The process of selecting a modeling parameter in VR environment goes as follows:

- The user use a virtual hand to pick a B-Rep element of a geometry node.
- Collision detection algorithm determine which part of the mesh has collide with the virtual hand and which B-Rep element is picked since each of the mesh model nodes has the same ID with corresponding B-Rep element.
- Inquiry the CHG to determine which modeling operation to modify and the relate B-Rep elements.

The CHG information is generated by monitoring every CAD operations when the CAD model is created. We use a table to record which B-Rep elements are generated and removed after each operation (as shown in Fig. 6). Thus, if a face of the model is picked, then the corresponding B-Rep can be determined and the CAD operation and its parameter can be selected by inquiring the CHG table.

After the modeling parameter is selected, the modification of the parameter value is relatively easy to conduct and with the use of VR devices this procedure can be implemented intuitively (see Fig. 7). The displacement of the ART Flystick in the physical 3D space can be transform to the value variation of the selected parameter.

4.2.2. Geometry computing and mesh generation

We use open-source OpenCASCADE as the geometry modelling kernel to compute the new CAD model after interactive modification. Also new meshes can be generated by calling the built-in B-Rep functions of OpenCASCADE. According to the demand of visualization, we can generate multi-resolution meshes using different deflection values and these meshes can be used as different levels of LOD models for further rendering purpose (see Fig. 8). The newly generated meshes together with the old meshes are added into a switch node which enables inspecting of different versions of the CAD model.

5. DISCUSSION AND RESULTS

5.1. Interactive rendering of large-scale Aircraft CAD models

We carried out tests of automatic LOD generation algorithm and interactive rendering method. The test system uses a gas turbine model with 4,502,793 triangles and a regional jet model with 19,445,309

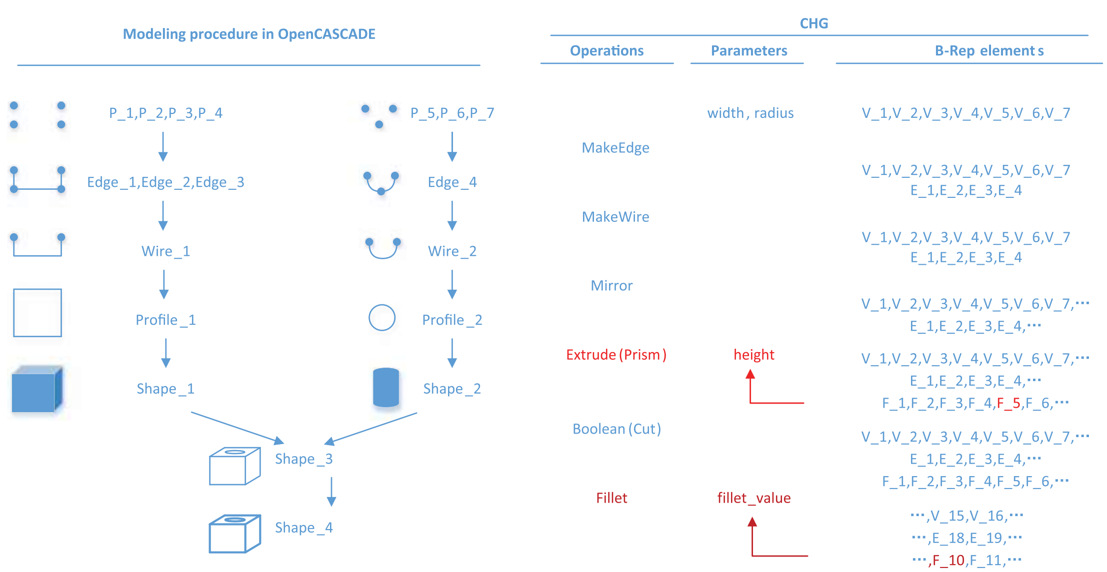

Fig. 6: Modeling parameters selection through CHG inquirying.

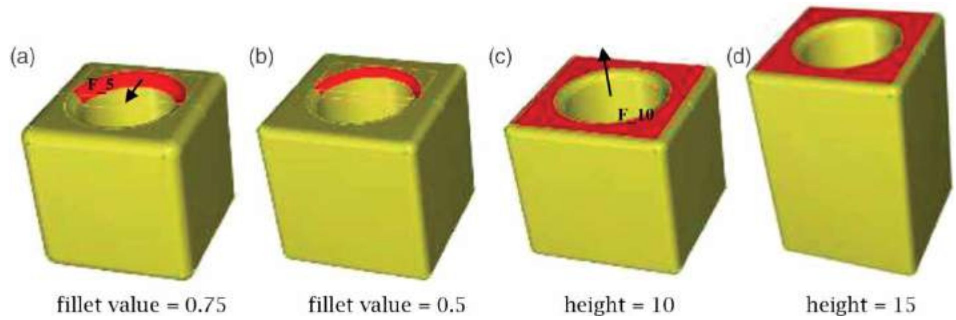

Fig. 7: Modeling parameters modifications in VR. (a) Pick the fillet face (highlighted) and drag inward, (b) The fillet value is reduced and new model is generated, (c) Pick the top face (highlighted) and drag upward, (d) The extruding hight is increased and new model is generated.

triangles. The interactive rendering results are shown in Fig. 9.

We tested our algorithm with both the regional jet model above (20M TRI, 1.13 GB) and the Boeing 777 model (350M TRI, 13.7 GB) to compare the preprocessing performance with other systems. The test results show that preprocessing time is in proportion to the total number of triangular faces within the CAD models as well as the density of faces. The regional jet model is exported from modeling software directly without simplification, and it has higher face density than the Boeing 777 model. The core components and systems of the jet model need 10 ∼ 20 minutes, and the whole jet model can be preprocessed within one hour (as shown in Tab. 1).

The time-consuming comes mainly from the large-scale triangular faces within CAD models. On the other hand, in order to retain assembly tree information, all the components are stored by the nested folders in accordance with the assembly hierarchy, these data is not contiguously stored in the system hard disk, the random read and write data on hard disk requires a certain storage time. Particularly model simplification in LOD generation process takes a long time even more, accounting for over 50% of

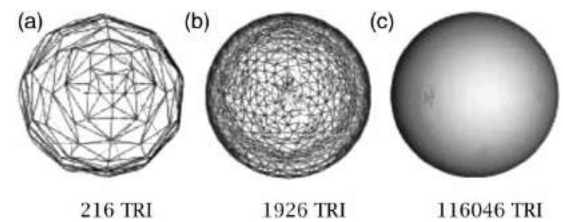

Fig. 8: Sphere meshes generated with different deflection values. From left to right, the deflection values are 1.0, 0.1, and 0.001 respectively.

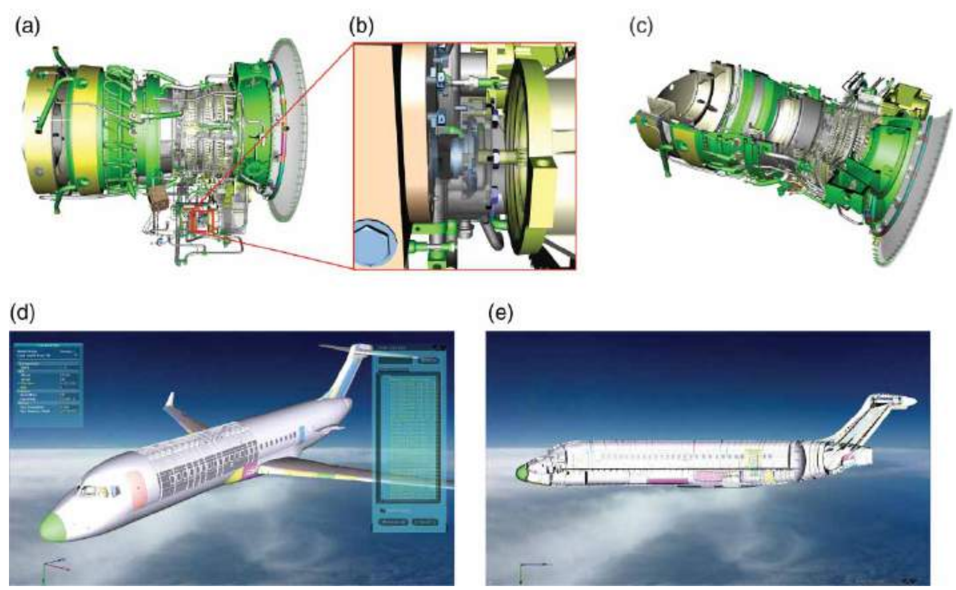

Fig. 9: Interactive rendering results of the gas turbine model and jet model: (a) Node transparency, (b) Details of the transparency, (c) Clipping with transparency, (d) Aircraft model visualization with model tree list, and (e) Clipping view of the aircraft model.

Algorithms	*Processor (GHz*cores)*	*Memory (GB)*	*Model*	*File size (GB)*	*Time (h)*	*Speed GB/(h*core)*
Far Voxels [Gobbetti + 2005]	1.8*32	1*16	Boeing 777	13.7	4.57	0.09
Adaptive Voxels[Tian + 2010]	2.83*4	4	Boeing 777	13.7	40.36	0.08
Our method	2.67*8	16	Boeing 777/ Regional jet	13.7/1.13	5.37/0.83	0.32/0.17

Tab. 1: Preprocessing speed comparisons.

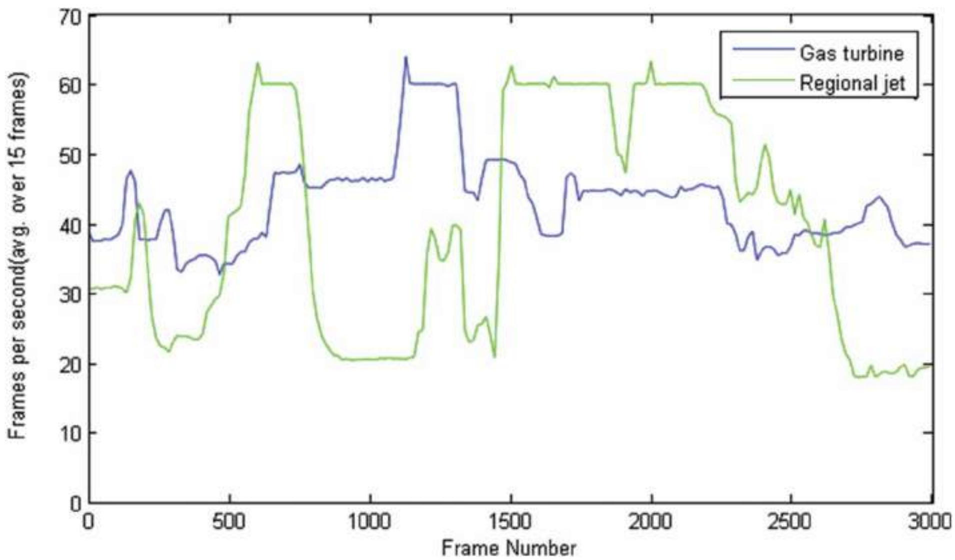

Fig. 10: Rendering performance statistics.

the preprocessing time. Even so, the speed of preprocessing by employing our method is almost twice the speed of Far Voxels and Adaptive Voxels.

Fig. 10 shows the interactive rendering performance of our system. We recorded FPS value for each frame when the user interacts with the models using node picking, transparency, clipping adjustment, navigation and node operations functions. Throughout all the 3000 frames, the average FPS value fluctuates between 20 and 60. The results also show that rendering FPS of the aircraft model is slightly lower than the gas turbine model by average due to larger scale triangular faces within it. But both of them have met the interactive frame rate requirement.

5.2. Interactive Modification of CAD Models in VR

User studies are conducted to test the update efficiency of aircraft visualization model in our system and to perform comparison with traditional approach. The results show that with the use of our system, modifying a CAD model and updating the whole aircraft visualization model can be done within one minute. Also, users can switch between different versions of the model, each of which has several levels of LOD to balance the rendering speed and visual quality. However, when users update the visualization model with traditional methods, the user 1) first go back to CAD software system to modify the model, 2) and then export the model into a generic 3D format file, 3) follow with the preprocessing pipeline to generate LOD, 4) and finally load and render the visualization model. It takes about one hour for the entire process. The update efficiency of aircraft visualization model has been greatly improved by employing our system.

However, limitations exist in our system. Aircraft CAD models may be created with different CAD software (CATIA, UG, etc.). The CHG table should be generated when the model is created. Currently models built with our OpenCASCADE based system are supported to be interactively modified. Generating CHG table in CATIA/UG still need to be implemented through CAD software secondary development based on their open API (e.g. CAA).

6. CONCLUSIONS

The experimental results using our approach and system show that high FPS can be gained with CAD models consist of 20M triangles on a commodity PC. The VR based CAD model interactive modification can save a lot of time compared with the traditional way of updating model changes in VR by preprocessing. The interactive rendering feature makes it more efficient for users to inspect the aircraft models. Our approach has demonstrated that an interactive rendering and modification of massive aircraft models is feasible, and that it can improve the efficiency of the creation of aircraft visualization system and benefit the aircraft design and manufacturing cycle. In the future, larger-scale aircraft datasets should be tested to further enhance the rendering efficiency. And the generation of CHG information from other mainstream CAD modeling software should be supported by the system framework to expand the application range of our system.

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