

PERCEPTION-DRIVEN SIMPLIFICATION METHODOLOGY OF 3D COMPLEX BUILDING MODELS*

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ABSTRACT:

The 3D complex building models are commonly of massive data, detailed appearance and sophisticated topology. The LOD modelling and real-time visualization of such models have hampered the wider applications of Virtual Geographic Environments. Aimed at the drawback of traditional simplification methods—difficult to locate the components, primitives that have to be decimated, this paper proposes a novel simplification method to locate the model portions need to be simplified based on the rendered image analysis. The main idea is to convert the recognition and assessment of the complex object's geometric features in 3D object space to the 2D image space, and to use the image filtering based on Human Visual System (HVS) model to guide the simplification operations in 3D space. Taking a complex timber-frame building model as an example, the experiment suggests that the method can effectively reduce the imperceptible details on the model surface, so that the data volume is decreased dramatically and the model's shape is hold well.

1. INTRODUCTION

1.1 Motivation and Aims

With the development of geospatial information technology, the age for wide use of 3D geographic information system (3D GIS) is coming up (Butler, 2006). As the core technique to support 3D Virtual Geographic Environments (VGEs), 3D GIS should offer the most foundational spatial data processing functions such as data acquiring, arrangement and management, data analysis and visualization presentation.

In the process to build VGEs, the fidelity requirements of different city models are increasing dramatically. Better incorporate presentation for inner and outer building model is desired, so more attentions are paid on constructing integrated inner building 3D model besides its surface reality representation, which benefits a lot in fields like virtual cultural heritage protection, 3D cadastre management and city disaster prevention. As a way of abstract presentation for real buildings, the block models built up based on different measuring means is far behind various requirements, especially for the high fidelity in large-scale Virtual Architecture Environments (VAEs). Thus, the modelling means based on CAD and LIDAR techniques are widely used in real 3D information acquiring and representing for complex buildings. By the introduction of these two modelling ways, a sharp increasing amount of model data has caused tremendous difficulties for smooth real-time roaming in various virtual environments.

The complex building models mainly acquired and built by LIDAR or CAD techniques have highly detailed appearance and complicated inner structure, highly complex topological

relationship inside and complex semantic relationship among the parts. And this kind of model is made up of various independent parts owning different types and configurations. A single building model, for instance, has such a huge data amount as millions of triangles.

Now, the bottle-neck problem that restricts the wide use of 3D virtual geographic environment is the multi-detail level expression for those various natural and human high-precision 3D models. But, the complexity of 3D models seems to grow faster than the ability of the hardware to render them. Thus no matter how to accelerate the tremendous improvement of computer graphic hardware, LOD modelling technique is also tightly correlated with the conflicts between the fidelity of protracting effect and the rendering speed. And because the higher detail the object has, the bigger its data amount would be, the more elaborate it can describe, vice versa. The fundamental aim of LOD modelling is to realize to express the most complex target by using the smallest data volume and to render the fidelity.

1.2 Related Works

The transformation from the highest detail model to the lowest is mainly by the way of model simplification. In order to automatically create LOD models, researchers have brought forward many kinds of simplification algorithm for polygon mesh in recent 30 years, and then the automatic creating LOD model is transformed into simplification of 3D polygon mesh, the common way in it is to decimate the unimportant primitive (e.g. vertices, edges and triangles) from the polygon mesh. The methods work well on the simplification for consecutive free curved surfaces such as terrain surface denoted by grid/TIN

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DEM, but for an irregular geometry body like a building and its corresponding appearance attributes, for instance, the texture image. This work is still not satisfactory, and it always needs plenty of human-computer interactions to get a content result.

1.2.1 Simplification Considering Semantics

Based on web 3D GIS environment, this method embeds *vd* as the characteristic dominant value in vertex attributes by Quadric Error Metric (QEM), and it also translates the semantic inhibit into the simplification for 3D object by means of figure distilling. Combined with the model's semantic characteristic, it has well kept the model's spatial characteristics in the process (Coors, 2001). This method has imported the concepts of *focus structure* and *graphical abstraction* to separately describe a sort of expressing way and the semantic simplification, the former has the most visual importance in the objects and the latter can converse the semantic restricts into 3D objects under a consideration of the background environment.

But this algorithm couldn't directly create each building model's *focus structure*, because it may differ among every object. Furthermore, the *graphical abstraction* may be difficult to accord with the description of the *focus structure*, which means *what details should be saved* is still not solved. Another drawback is the neglect of the impact from the building's inner complex structure in its simplification method and process.

1.2.2 Simplification Considering Features

Martin Kada put forward a simplification algorithm aiming at 3D city building models, in which three kinds of characteristics like co-planarity, parallelism and uprightness among surfaces are detected and adopted by the edge collapse to simplify. This method can well keep the shape and relational surface attributes after removing some of the building's characters such as texture (Kada, 2002, 2007).

Its drawback is obvious: Firstly, the experimental model is so simply that it couldn't roundly represent the building model's complexity. Secondly, the drawback of co-planar contracting is still unsolved, thus it is not fit for the simplification of the complex building model in VGEs. Thirdly, the process is strongly restricted by the minimum measurement of the original building model's components, and then its ability of reduction is so limited. Furthermore, its simplifying ability is really limited neither for arbitrary fold meshes nor for unfold meshes.

Besides, Thiemann has divided the model according to characteristics checked out and express them in the CGS way. And then, he made the simplification operation through the CGS tree (Thiemann, 2002; Thiemann et al., 2004). Its excellence is that simplification is on consecutive scale and also owns the possibility for semantic expanding. But considered as a method for generalization, it couldn't combine the neighbourhood buildings (Sester, 2007).

1.2.3 Simplification Based on Scale Space

Aiming at the building model data, Andrea Forberg brought forward a 3D model simplification method based scale space (Forberg, 2004, 2007; Forberg et al., 2002). Its main academic foundation of is the mature scale space theory, including mathematic morphology and curvature space theory. It has used different form operation such as Erosion, Dilation, Opening and Closing to control the unit and separate among different parts.

This method is developed and realized on ACIS 3D Geometric Modeller and VRML.

The simplification method based on scale spatial theory gets its prodigious limits in simplification. For instance, it sometimes needs other means to deal with no-orthogonal characteristics like housetop, including rotating, correcting and so on (Sester, 2007). Besides, this algorithm can't assure the maintenance of the building's characteristics, and it neglects consider some attribute contents like material and texture.

Facing with the models, in summary, the traditional simplification methods have three drawbacks. Firstly, methods above can not accurately locate the portions needed to be simplified. Secondly, the most traditional simplification methods in computer graphics are restricted to simplify a *single* 3D object with continuous surface mesh but not a set of meshes, but a complex building model is just a set of mesh because each component is a mesh. Thirdly, due to the simplification methods do not take human perception information to drive the simplification operations, so that the simplified results can not accord with the rule of human perception, and the LOD models derived from the simplification methods are difficult to ensure the continuity on visual effect.

2. PERCEPTION-DRIVEN SIMPLIFICATION FRAMEWORK

2.1 Perceptual Details of 3D Building Models

Two choices are given to us for exploration of perceptual details of 3D building models: one is to do the detail analysis based on a geometry definition of an object, such as analyzing the geometrical characteristics represented by the building model's geometrical primitives (vertex, edge, triangle, or body, etc.); the other is to enter on the object's 2D rendering image. Both these methods own their excellences and shortcomings.

Geometrical Characteristics: Now, these 3D models are expressed in the form of geometrical primitives, after which it is possible to compute various geometrical details of the 3D model, such as curvature, length.

But, any geometrical details can not avoid the problem. A 3D model is not only totally expressed by geometrical primitives, but also by textures reflected to the material attributes on the model's surface. For those geometrical models with textures, the textures contain a great lot of visual information having a deep influence on the perception, while the pure geometrical details' calculation entirely neglects these visual details.

Rendered Image: It is possible to gain a model's rendered image by setting a camera and its parameters and pre-choose a rendering mode. Because the human beings are acquiring an all-sided perception directly by looking into the rendering images using their naked eyes, it is possible to extract the 3D model's perceptual details by detecting the situation from human eyes to models reflected by the model's rendered images. The rendered images have more accurately and integrally reflected the information on the model's surface, such as its figures, natures, textures, illuminations, all of which are factors having a deep impact on human perception. And the integrity of information laid a foundation for the model perception.

In summary, the perception-driven simplification method for complex buildings should extract the perception details from rendering images, not from geometrical characteristic. The geometrical characteristic of the model can't offer credible and perception information, while the rendered images can not only reflect on features of the Human Visual System (HVS), but also the perceptual details of the model exactly.

2.2 The Framework of Perception-driven Simplification

As shown in Figure 1, there are 5 main steps in this method from the original complex building model M_0 to simplified model M_1 :

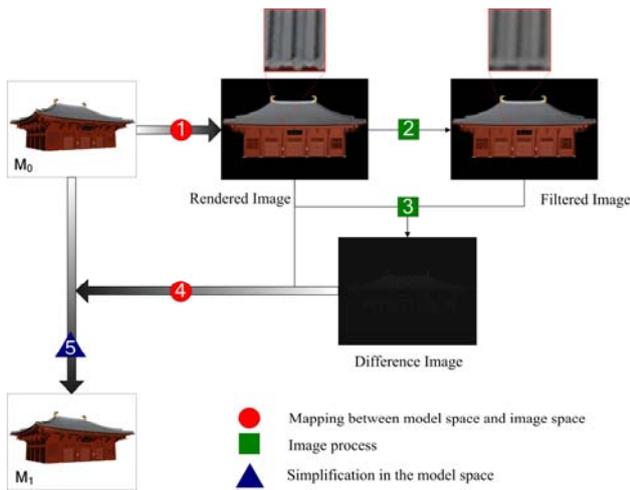


Figure 1. Sketch map of perception-driven simplification

2.2.1 Acquire the Rendered Image

It is possible to get the rendered image I_{render} in certain view point by setting the complex building model M_0 and the light, camera parameters, place, the relational rendering algorithm in its virtual scene. It can all-sided detect the 3D building model's perception information by using the rendered images under multi-viewpoints.

2.2.2 Simulate the Human Eyes' Perceptual Images

Discrete wavelet transformation (DWT) can ensure a good multi-resolution analysing function as well as makes the CSF function, used to describe human eye perceptual characteristic, possible to map with subbands of frequencies in different ranges.

2.2.3 Extract and Classify the Perception Information

The difference image $I_{difference}$ between image I_{render} and $I_{filtered}$ contains some details unobservable to human eyes, which can be classified into four groups of change, as tiny, light, moderate and heavy. Thus the change of pixels' grey levels effectively reflect out the visual difference.

2.2.4 Transmit the Perception Information

By ray casting, the perception information will be transmitted to the triangles on the model surface. And the rank of change is recorded into the attribute of the triangle.

2.2.5 Simplify Models

According to the perception attribute of triangles, edge-collapse operation will be executed, so that the imperceptible details on model surface will be removed dramatically.

3. PERCEPTION INFORMATION AQUIREMENT BASED HVS FILTERING

3.1 HVS Filtering

The perception-driven simplification methodology of 3D complex building models applies the HVS to filter the image. Firstly, it simulates the image information human eye received. Then the perceptual knowledge is extracted by comparing the original render image with the vision simulated image. Finally, the perceptual knowledge can be used to conduct the simplification. The most important thing of above is the vision simulation.

One of the most important issues in HVS application is to reduce the contrast sensitivity of the high spatial frequency in the image (Nadenau et al., 2003). The common used way is to compute and quantify the spatial frequency by Contrast Sensitivity Function (CSF) (Figure 2).

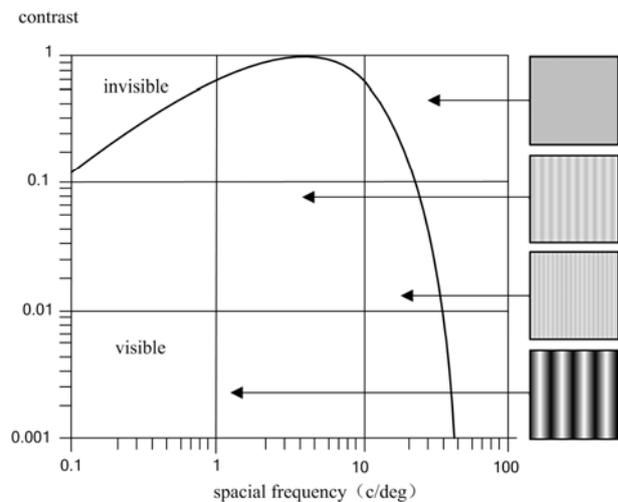


Figure 2. Contrast Sensitivity Function (Reddy, 2001)

The CSF explains the relationship between the contrast sensitivity and spatial frequency, and describes the range of the gratings that can be perceived by HVS. The contrast threshold is also given at certain spatial frequency and contrast for the viewers.

Mannos and Sakrison propose a general formula (1) to compute the contrast sensitivity (Mannos et al., 1974), which has been testified and quoted by many other researchers (Meng et al., 2004; Qu et al., 2006; Watson et al., 2004)..

$$A(\alpha) = 2.6(0.0192 + 0.144\alpha)e^{-(0.144\alpha)^{1.1}} \quad (1)$$

Where α = the spatial frequency, taking cycle per degree (cpd) as the unit;

$A(\alpha)$ = the Michelson contrast

If the CSF under all condition such as static and motion is defined, then the details viewer perceived can be predicted.

3.2 Clustering Perception Information

Because the rendered image I_{render} contains all the details that can be display on the screen, while the vision simulated image $I_{filtered}$ only contains the perceptible details. To detect the unperceived details, the $I_{difference}$ is defined as:

$$I_{difference} = I_{render} - I_{filtered} \quad (2)$$

The $I_{difference}$ takes the advantage of the dissimilar pixels in the I_{render} and $I_{filtered}$ to indicate the unperceived details in the image. Because the gradation difference of the pixel is related to the changes of the spatial frequency and contrast sensitivity. As a result, the degree of the gradation difference is also corresponding to certain spatial frequency and contrast sensitivity range. In another word, the gradation difference reflects the viewers' perceive capacity to certain details.

Use the MLC (maximum likelihood classification) method to classify the pixels in $I_{difference}$ into four classes: none change, slight change, moderate change and dramatic change. The relation between the visual perceive capacity and classes is show in table 1.

Idifference	HVS filtering	CSF Feature	Vision
no change	No filtering	Lowest CS and SF	Highest sensitive
slight change	Slight filtering	Low CS and SF	High sensitive
moderate change	Moderate filtering	High CS and SF	Low sensitive
dramatic change	Heavy filtering	Highest CS and SF	Lowest sensitive

Table 1. The relationship between perceptual degree and the difference image

According to the table 1, the dramatic change of the gradation is corresponding to the lowest sensitive details in the image while the no change to the highest sensitive details, therefore the result is the foundation of the following grating of the triangle perceptual importance.

4. PERCEPTION-DRIVEN SIMPLIFICATION ALGORITHM

4.1 Transmission of Perception Information

After the classification, the imperceptible details should be transmitted to the model's geometry, and the mapping relations between the 2D space and 3D space should be established.

In the real world, vision is formed when the light reflects into the retina. Likewise, the 3D models are displayed on the screen through pipelines of the display hardware, which transform the vertexes to various coordinates. Finally, the reader images are generated and displayed.

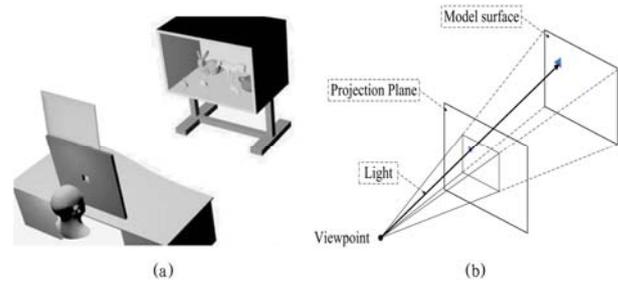


Figure 3. The principle of ray casting

According to the principle of ray projection and the render pipeline, given the camera position and the projecting plane, a radial through the pixel can link to the primitive of the geometry. This method is termed ray casting (Figure 3).

The projection relationship is established between image space and model space through ray casting. Perceptual information is passed to the primitives can causes that primitive is of perceptual information according with it in the image.

4.2 Aggregation Operation

Based on plenty of the experiments, Kobbelt's group discovered that the quality of the simplification has little to do with the way choosing the new vertex, but rather the order of the fold or contracting. This order is defined under the rule of error measurement (Kobbelt et al., 1998). Therefore, they suggest paying more attention to find the proper measurement.

Although the minimized geometric error guarantees the fidelity of the simplified model, and the results are also predictable. The perceptual differences caused by the operations of simplification are ignored, which means the perceptual differences can not be predicted in the simplification. Be similar with the assumptions as the geometric error measurement, we make the assumption that if the perceptual error is the minimum during every simplification step, then the total perceptual error minimizing is going to be achieved. As a result, we propose that the simplify operations should fully consider about the perceptual change of the 3D model, and integrate the geometry with the perceptual error to measure the budget of the simplification.

Based on the QEM proposed by Garland, the geometric error is calculated using a Q-matrix, this paper adopts the ratio of the new vertex's geometric error and the diagonal line length of the minimum bounding box (MBB) of the triangles as the geometric budget of the merging operation $(v_1, v_2) \rightarrow \bar{v}$.

$$Cost_G = \frac{\bar{v}^T Q \bar{v}}{L} = \frac{\bar{v}^T (Q_1 + Q_2) \bar{v}}{L} \quad (3)$$

Where $Cost_G$ = the simplified budget of the folding operation $(v_1, v_2) \rightarrow \bar{v}$;

L = the length of the diagonal line of the MBB

4.2.1 Perception Weight Factors

In the simplification process, those operations on geometrical such primitives as vertices, edges and surfaces have not only brought in geometrical errors, what's more, the results after geometrical transformation can cause perception diversity. Therefore, this method chooses the sum of the change degrees between the new vertex brightness and those in the vertex-pair as the weight and makes adjustment only by geometrical cost.

This article has chosen the complex timber-frame building as its testing object, most of whose appearance is made up of walls, cements, woods and so on which do not have highlight effect and this is rightly fit for the characteristic of Lambert illumination model. So, according to the analysis of light setting in the virtual scene, in the effect of three fixed spotlights, the expression to calculate vertex V brightness by using Lambert diffuse reflection model is:

$$I_v = k_a I_a + k_d \sum_{i=1}^n f_i I_{li} (N \cdot L_i), \quad n = 3 \quad (4)$$

Where f_i = attenuation factors

I_{li} = light intensity

L_i = incident direction's unit vector

In the process of confirming vertex-pair contracting $(v_1, v_2) \rightarrow \bar{v}$, it separately calculates vertex v_1 , v_2 and the new vertex \bar{v} average normal along with its brightness, after that the perception weight of the geometric cost in the contracting process is:

$$\varphi = \left| \frac{(I_{v1} + I_{v2})}{I_{v1} I_{v2}} I_{\bar{v}} - 2 \right| \quad (5)$$

Which separately weight the change degrees of the new vertex \bar{v} brightness and vertex v_1 , v_2 brightness, where it may come that the brightness of new vertex turns to be lower than its original, $I_{\bar{v}} \leq I_{v1}$ or $I_{\bar{v}} \leq I_{v2}$, so it chose the absolute value of perceptive weight gene to eliminate the influence of the minus value calculated.

After the analysis and calculation above, it separately defines the geometric cost and perception weight for the vertex-pair contracting $(v_1, v_2) \rightarrow \bar{v}$, and then the cost of the vertex-pair contracting operation is:

$$Cost_{(v1, v2 \rightarrow \bar{v})} = \varphi Cost_G \quad (6)$$

The perception weight factor φ based on the change of vertex brightness can reorder the simplification operation by adjusting vertex-pair contracting cost, consequently realize optimization for the whole simplification operation of the triangle cluster.

5. EXPERIMENTAL ANALYSIS AND DISCUSSION

5.1 Description of Test Data

A 3D model of Chinese classic building is chosen in the experiment, which has many components. This type of 3D model takes its characters, the model is made up of components having tenon. The Chinese ancient buildings' structure is mainly formed by pillars, beams, arches and tiles, where every component is jointed with a tenon, composing bouncy frame. And this type of joining in timber-frame buildings has shaped plenty of depressed characters in the components, which benefits a lot to correctly meet and fix all the components. But, this tenon structure is entirely needless for real time virtualization and building its LOD model, thus it becomes the chief aim for simplification.

5.2 Experimental Results and Discussions

A prototype is developed to create multiple levels of building models. As analysed above, this article chooses tracing results from nonconservative strategies to guide the simplifying experiment for the whole model.

During it, the whole triangles, which had a possibility to be simplified, acquired by the tracing results from all the effective elements of the rendered image account to 97,266, it has used the acuity degree shown in Figure 4 as the foundation to guide the simplification work, and then gained simplified result in Figure 4(c), where you can see the number been simplified accounts to 11,074 so the simplified rate is 11.39%. In Figure 4, it is clear that the model simplified driven by apperception has kept a high comparability with the original one. And the comparison in amplificatory details in Figure 4 (b)(d) has effectively explained the model has been simplified according to pre-assigned perception information.

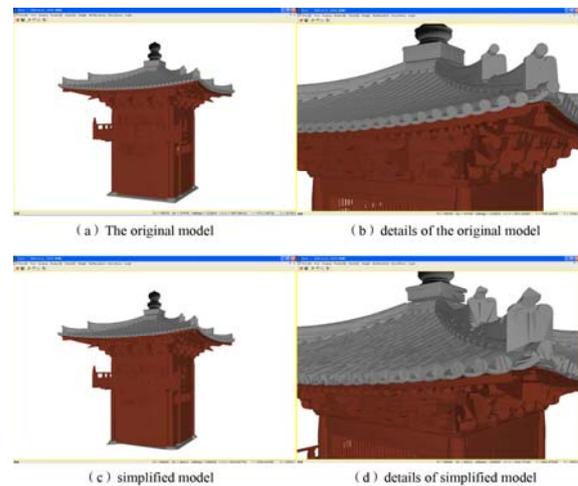


Figure 4. The effect of simplified model

Corresponding to perception ranks of the image elements, the triangles' perception information can be classified into four groups, while only the *heavy*, *moderate*, *light* ranks need to be simplified, so that there are only three kinds of simplifying strategies, namely: First stair simplification, only to do with the triangles of the rank *heavy*; similarly, the second stair is for the rank *heavy and moderate*; and the third stair for all of three

ranks above. During the experiment it has separately done the simplification in three ways under the single condition and got three different simplified models of their own effects. These three simplifying strategies have some diversity in both simplifying effect (Figure 5) and efficiency (Table 2), which give an opportunity for realizing personality to the clients and own a good flexibility.



Figure 5. The effect of 3 simplification strategies

name stair	Latency triangle number	simplified triangle number	Simplified rate (%)	remark
First stair	97,266	11,074	11.39	only for the triangles of <i>heavy</i>
Second stair	97,266	27,522	28.30	for <i>heavy</i> and <i>moderate</i>
Third stair	97,266	46,296	47.60	for all

Table 2. The comparison for different strategies' efficiency

The experiment indicates that:

- In the aspect of simplification effect, the model simplification driven by perception can well keep the surface characters of the components, which ensures the consistency on the surface of the whole building before and after the simplification.
- In the aspect of efficiency, together with the effort of simplification threshold value, the simplification operation driven by perception has sharply cut down the whole model data amount, and the model simplified rate is ranging from 10% to 50% according to different simplification strategies.
- For the LOD model of the highest level which needs to be built, it can sharply reduce the model's data volume; meanwhile well keep the shape of the whole model.
- Those three kinds of simplifying strategies in the process offer many choices to the clients, and they can flexibly choose a suitable way according to their hardware and software conditions and their grasps to the granularities for model representing.

6. CONCLUSION

In currently, complex building models are widely used in various fields, such as VGEs, cyber city, and culture heritage documentation, with well development of the virtual reality and

3D GIS technologies. But such high complexity and huge data volume of building models can not meet the real-time and interactive application requirements in virtual environments.

Perception-driven simplification in this paper is founded on the image process that rendered image of building models are filtered by HVS filter based on wavelet transformation. The perceptual information is acquired and passed to model surface by ray casting through finding the difference between rendered image and filtered image. The model surface's perceptual information drives simplification operation directly to reduce the imperceptible details on model surface.

A prototype is developed to create multiple levels of building models. The simplification experiment of a complex ancient building model proves that the simplified models not only preserve the perceptually details of the model, but also minimize the amount of triangles and keep high geometric fidelity.

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