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Technical Section

Quantitative analysis of discrete 3D geometrical detail levels based on perceptual metric

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A B S T R A C T

Aiming at the fundamental issue of optimal design of discrete levels of detail (LOD) for the visualization of complicated 3D building façades, this paper presents a new quantitative analytical method of perceptible 3D details based on perceptual metric. First, the perceptual metric is defined as the quantitative indicator of the visual perceptibility of façade details at a given viewing distance. Then, according to the human vision system, an algorithm employing 2D discrete wavelet transform and contrast sensitivity function is developed to extract the value of perceptual metric from the rendered image of the façade. Finally, a perceptual metric function is defined, based on the perceptual metric values extracted at equal interval viewing distances. The minimum detail redundancy model is then proposed for the optimal design of discrete LODs. This method provides a quantitative instruction for generating discrete LODs. The experimental results prove the effectiveness and great potential of this method.

1. Introduction

Online virtual globe tools, led by Google Earth, are dramatically changing the way we interact with spatial data from 2D maps to the 3D Virtual Geographic Environments (VGEs) [1,2]. Up to now, 3D representations of geographic information in computers have been known as VGEs, which are of increasing importance in urban areas and provide more accurate and flexible mathematical models, effective tools, and user interfaces for geospatial communication. Therefore, 3D models in VGEs do not just have photorealistic appearances, but they are also accurate, with credible geometry and topology information of the built environment, achieved by making full use of advanced 3D measurement (such as imaging, LIDAR, GIS, and CAD) [3].

When representing a building, façades are often the most important elements, as they contain the exterior geometric details of the building. However, the number of polygons that represents the 3D geometry of complicated façades always exceeds the rendering capability of the hardware; a trade-off between complexity and performance is required. A preferred solution is the level of detail (LOD) technique, which increases the efficiency of rendering by reducing insignificant geometry for visualization [4]. One of the bottlenecks of this technology for complicated 3D façades is the automatic generation of discrete levels of detail (LODs). Given the target number of detail levels, a collection of LODs are produced based on manually assigned control factors, such as a target number of polygons with equal interval partitions, or exponential interval partitions, or employing trial and error based on plenty of pre-simplified models [5]. However, assigning various factors manually to generate LODs for the original model is usually not optimal. Inevitable detail redundancy between LODs brings about excessive rendering cost. This paper proposes an optimal design approach for discrete LODs of complicated 3D façades based on analyzing the perceptibility of façade details at various viewing distances, which prevents the costly pre-simplification stage and provides quantitative instructions for the construction and management of discrete LODs.

This paper is organized as follows. The related work on discrete LOD is reviewed in Section 2. Section 3 introduces the definition of the perceptual metric and perceptual metric function. Section 4 presents the algorithm based on the perceptual metric function for LOD optimization, and Section 5 discusses the experimental results. Finally, the conclusions are presented in Section 6.

2. Related work

Discrete LOD is a traditional approach of the LOD technique, first proposed by Clark in 1976 [6]. The most important advantages of this kind of LOD are its simplicity, high efficiency, and the support of offline preprocessing [4], which make it suitable for visualization of complicated 3D façades. The

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generation of a collection of discrete LODs for such models comprises the following steps: first, determine the target number of detail levels; second, determine the proper control factor for each detail level, such as the number of polygons; and third, generate the LODs [3].

The proper target number of detail levels depends on various factors including the rendering capacity of the visualization system, the complexity of model, etc. As a result, it is hard to determine fully automatically. Moreover, the visualization system usually supports a fixed number of LODs, so the target number has to be selected manually.

Determining the control factor for each detail level is very important to the discrete LOD since models are often too complex to be simplified in real-time or for the simplification operations to be pre-recorded by progressive meshes [7]. As a result, most of the existing approaches for determining the detail level are based on pre-simplification processes. The original model is simplified to produce plenty of candidate LODs according to certain criteria, such as screen-space errors or object-space errors. Then proper LODs are selected by evaluating the errors of the candidates [4,8]. Although more sophisticated approaches based on the human vision system (HVS) have been proposed [9–11], it is too costly to pre-simplify a complicated 3D façade into a number of candidates. On the other hand, the target number of polygons and other control factors are also adopted to define each detail level, such as generating a collection of LODs based on pre-estimated runtime budgets [12], but it is hard to estimate the budgets accurately in an offline fashion.

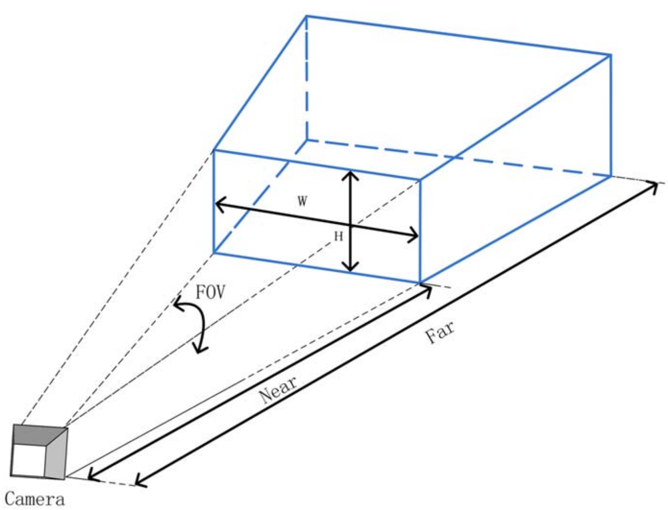

Fig. 1. The viewing frustum.

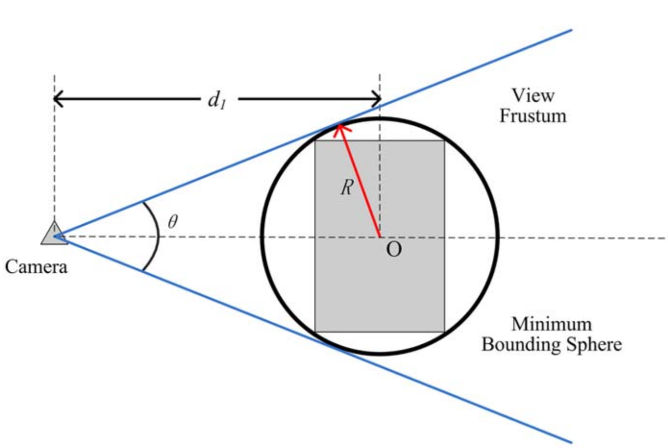

Fig. 2. The computing of d_1.

To produce the LODs, various automatic or semi-automatic simplification algorithms have been comprehensively reviewed by David et al. and Cohen and Manocha [4,13].

In conclusion, there is still no good solution to the precise analysis and design of LODs for complex 3D models such as component-structured building façades, which hinders the practical use of discrete LOD. In the following sections, a new idea about the quantitative analysis of the perceptibility of geometric details is presented; such perceptual knowledge is extracted from the rendered images of a 3D facade, which is useful to guide the design of the LODs.

3. Perceptual metric and perceptual metric function

3.1. Definition of perceptual metric

The process of human visual perception of 3D models consists of two successive stages. First, based on given parameters, a virtual camera samples the 3D model. This is called the 3D projection. Its result is a rendered image on the screen in which primitives less than the pixel resolution of the display are invisible to the viewers. Second, visual perception of the rendered image is generated through the retina, visual pathways, and finally the visual cortex [14]. This stage is modeled by the human vision system (HVS). Details displayed on the screen that are beyond the capacity of human visual perception are filtered out in this stage.

In order to quantify the visual perceptibility of the details in the 3D model, a perceptual metric (PM) is defined as

$$PM = VPs/TPs \tag{1}$$

where VPs is the number of pixels representing the perceptible details of the model in the rendered image and TPs is the number of pixels representing the total details of the model in the rendered image. These two numbers of pixels indicate the quantitative difference between the two stages of visual perception. The ratio between these two numbers, called PM, therefore indicates the perceptibility of geometric details. By means of PM, the geometric LODs of a 3D model can thus be quantitatively and intuitively analyzed.

3.2. Calculation of perceptual metric

In order to obtain a reliable and accurate PM, the two stages of perception should be quantified. Before rendering, a view frustum is defined as illustrated in Fig. 1 [15]. The 3D model is then projected onto the projection plane according to the perspective projection transformation. Placing the model in the center of the sight, the number of non-background pixels can be counted as the number of pixels that represent the object in the rendered image.

However, restricted by the viewing frustum, this evaluation is not accurate when the model is near to the camera because the clipping plane will eliminate that part of the model outside the view frustum. Therefore, d_1, where the model is shown maximally on the screen, is set as the beginning of the evaluation, as illustrated in Fig. 2. The equation to calculate d_1 is as follows:

$$d_1 = R/\sin(\theta/2) \tag{2}$$

where R is the radius of the minimum bounding sphere of the model measured in meters and θ is the field of view (FOV) of the virtual camera. The details of the visible surface of the model are considered to be entirely displayed at d_1. Then,

$$TPs = Pn_1 \tag{3}$$