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Multi-level models for reverse engineering and rapid prototyping in remote CAD systems

A. Fischer*

Laboratory for Computer Graphics and CAD, Department of Mechanical Engineering, Technion, Haifa, Israel

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Abstract

This paper proposes a multi-level CAD system based on remote reverse engineering (RE) used for "3D scanning" and remote rapid prototyping (RP) used for "3D printing". This integrated system can be conceptually considered a "3D faxing" system. At the core of the system is an advanced multi-level of detail (LOD) representation for remote CAD systems. The LOD is represented through hierarchical nested bi-variant surfaces.

With the proposed multi-level approach, the entire process from RE to RP takes tens of seconds for tens of thousands of sampled points. Results for the LOD extraction stage (RE and modeling) were faster, with an order of seconds rather than the tens of seconds achieved by other systems. The advantages of the proposed LOD method include the following: (1) due to multiresolution capabilities, an object can be directly and robustly modeled or manufactured using RP from sampled data, in real-time at different levels of details; (2) local or global error control can be applied according to an error estimator at each node. Therefore, the geometric details can be preserved even at a low level of resolution; (3) selective refinement can be applied by modifying selected areas at different levels of detail. Therefore, an object can be modeled with rough, fine or mixed detail resolution; (4) multi-level meshing can be performed according to color/texture criteria that are independent of the geometry criteria.

The feasibility of LOD "3D faxing" is demonstrated on several freeform objects.

Keywords: Remote CAD systems; 3D faxing; Reverse engineering; Rapid prototyping; Level of detail; Progressive models; Traingulated surfaces; Quadtrees; Continuity; Terrain

1. Introduction

Current remote CAD systems that are oriented to "3D faxing" are based on three modules: (1) reverse engineering (RE), (2) modeling, and (3) rapid prototyping (RP). In such systems, reverse engineering is used for remote "3D scanning" of a 3D part, and rapid prototyping is used for remote "3D printing" of the object model.

In **reverse engineering**, a model is reconstructed from dense sampled points. Points are sampled at high density in order to achieve accurate reconstructed products. However, to simplify the reconstruction process, the data is then reduced. The most common data reduction methods are based on surface simplification techniques. These techniques preserve the shape and usually control the error locally. In most common data reduction processes, only one mesh is constructed, and intermediate meshes cannot be retrieved. Therefore, a fast transformation between meshes with different levels of detail (LOD) is not possible. However, some changes might be required by the modeling analysis, which would make it necessary to reduce the original digitized data again. In order to improve efficiency, a new representation is needed that allows adaptive changes in the reduction density in both directions, from rough to refined details and vice versa. Moreover, mixed LOD areas should be represented in one data structure.

In the **modeling** stage, the object can be modified using a set of transformations and geometrical operations. In this paper we deal with mesh representation, so that the operations are applied on vertices, edges and facets. During design, different areas are selected and focused on. Therefore, for efficiency the modifications must be made at rough or fine mixed levels of details. The option of mesh modeling enables direct sampling, modeling and manufacture of the object. However, when parametric CAD modeling with a symbolic geometrical computational environment is needed, a conversion from mesh representation to surface representation is required. In such a case, a fitting algorithm can be applied and a parametric surface is reconstructed.

* Tel.: +972-4-8293260; fax: +972-4-8324533.
E-mail address: meranath@tx.technion.ac.il (A. Fischer).

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This is an indirect approach that leads to fitting in one direction (from sampling to modeling) and faceting in the other direction (from modeling to RP). The computational complexity increases and approximation errors are accumulated. Therefore, the direct approach of LOD mesh modeling is advantageous for applications where basic deformations and modeling are needed.

In **rapid prototyping** based on manufacturing, the layered model is produced from a 3D mesh, usually in triangular STL format. Again, according to manufacturing analysis, remodeling might be required, refining or smoothing a selected area. Moreover, during the design stage, an intermediate prototype should be manufactured, including some areas with schematic rough shapes that were not yet designed in detail, as well as areas focused on by the designer which are detailed, accurate and contain functional geometry. Therefore, a representation that allows manufacturing of mixed **rough** and **fine** details is needed. Moreover, it is essential that the prototype be sent to RP progressively and compactly, transferring only the updated parts from the design module.

Current RE and RP processes rely mostly on a conventional CAD representation. This representation has no inherent multiresolution capabilities and therefore leads to expensive remodeling computations and to large file transmissions. In both RE and RP processes, these operations are extremely time consuming for typical engineering parts that consist of hundreds of thousands of mesh elements, creating files of the order of tens of MBs.

To cope with RE and RP processes, a remote CAD system with multi-level representation is proposed. The two most common multi-level structures are the multiresolution wavelet model used for surfaces [1,2] and the LOD (level of detail) model used for meshes representation [3,4]. The multi-level model is reconstructed a priori; then, any level of detail can be accessed directly, according to process requirements such as data reduction, modeling, analysis or rapid prototyping.

This paper proposes a system based on remote reverse engineering used for "3D scanning" and remote rapid prototyping used for "3D printing". This integrated system can be conceptually considered a "3D faxing" system. At the core of the system is an advanced multi-level of detail (LOD) representation for remote CAD systems. Since in our approach we deal with discrete data and digitized points for RE and with STL triangular mesh for RP, the LOD multilevel data structure was chosen, developed and implemented. The LOD is represented as hierarchical nested bi-variant surfaces.

The entire process from RE to RP takes tens of seconds for tens of thousands of sampled points. Results achieved by the proposed LOD method for the extraction stage (RE and modeling) were faster, with an order of seconds rather than the tens of seconds achieved by other systems. The advantages of the proposed LOD method include the following: (1) due to multiresolution capabilities, an object can be directly and robustly modeled or manufactured using RP from sampled data, in real-time at different levels of details; (2) local or global error control can be applied according to an error estimator at each node. Therefore, the geometric details can be preserved even at a low level of resolution; (3) selective refinement can be applied by modifying selected areas at different levels of detail. Therefore, an object can be modeled with rough, fine or mixed detail resolution; (4) multi-level meshing can be performed according to color/texture criteria that are independent of the geometry criteria.

In Section 2, a detailed overview of surface simplification and multiresolution methods is provided. Section 3 describes the LOD technique and discusses the LOD construction and extraction algorithms in detail. In Section 4, the reverse engineering process is described, while in Section 5 the rapid prototyping process is discussed. The C^0 continuity is discussed in Section 6. In Section 7, the LOD method is extended to meshing according to color/texture criteria. Section 8 summarizes the results and draws conclusions.

2. Related work

Multiresolution and mesh simplification methods have been covered quite intensively of late in areas such as data reduction, rendering, remodeling, progressive transmission and mesh compression. The geometry representation used is mainly unstructured or structured triangular and quadratic meshes. These meshes are simplified either by merging or splitting elements. The methods can be classified into two main approaches: (1) mesh simplification, which is a static level-of-detail generation approach, and (2) multiresolution representation, which is a dynamic approach. The mesh simplification method can be seen as a base for the dynamic multiresolution approach.

Mesh simplification methods were implemented by deleting/inserting vertices and then merging/splitting mesh elements. Different error norms were computed in order to estimate and control the error locally or globally. In general, with most existing methods, any level of reduction can be obtained, and interactive refinement of a selection is optional. In the 1995 and 1997 Siggraph courses [5,6] given by Schroeder and Heckbert, respectively, simplification methods were discussed: (a) the merging approach, where several polygons are merged into one polygon according to coplanarity criteria [7]; (b) the mesh decimation approach, where geometry and topology are analyzed locally, and only vertices that meet minimal distance or curvature criteria are removed [8]; (c) mesh optimization [3,4], which is achieved by evaluating an energy function over the mesh and minimizing the function by removing/moving vertices or collapsing/swapping edges.

Heckbert and Gerald [5] discuss the performances of several methods. The complexity of the methods varies from $O(nm)$ to $O(n \log(m))$, where n is the number of