Computers & Industrial Engineering 63 (2012) 1189–1200

Contents lists available at SciVerse ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

A framework for 3D model reconstruction in reverse engineering

Jun Wang [a,*], Dongxiao Gu [b], Zeyun Yu [c], Changbai Tan [a], Laishui Zhou [a]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] School of Management, Hefei University of Technology, Hefei 230009, China
[c] Department of Computer Science, University of Wisconsin, Milwaukee, WI 53211, USA

ARTICLE INFO

Article history:
Received 26 August 2011
Received in revised form 21 February 2012
Accepted 1 July 2012
Available online 7 September 2012

Keywords:
Model reconstruction
Mesh denoising
Mesh segmentation
Feature reconstruction
Reverse engineering

ABSTRACT

We present a framework for 3D model reconstruction, which has potential applications to a spectrum of engineering problems with impacts on rapid design and prototyping, shape analysis, and virtual reality. The framework, composed of four main components, provides a systematic solution to reconstruct geometric model from the surface mesh of an existing object. First, the input mesh is pre-processed to filter out noise. Second, the mesh is partitioned into segments to obtain individual geometric feature patches. Then, two integrated solutions, namely solid feature based strategy and surface feature based strategy, are exploited to reconstruct primitive features from the segmented feature patches. Finally, the modeling operations, such as solid boolean and surface trimming operations, are performed to "assemble" the primitive features into the final model. The concepts of "feature", "constraint" and "modeling history" are introduced into the entire reconstruction process so that the design intents are retrieved and exhibited in the final model with geometrical accuracy, topological consistency and flexible editability. A variety of industrial parts have been tested to illustrate the effectiveness and robustness of our framework.

1. Introduction

In many industries, such as the aerospace, automobile, and die and mold industries, plenty of efforts have been put on the design and manufacture of advanced products that deliver superior performance. The ability to rapidly design those products with improved characteristics is vital to success in the competitive environment of continuous change, and to respond quickly to the changing markets. However, conventionally, the product is designed on the shop floor instead of on the computer screen, and is represented by real physical prototypes, rather than virtual digital models. For example, style artists often work on physical mediums such as clay or wood rather than digital models to achieve a favorable shape design in the automobile industries (Huang and Menq, 2002). With the advance of CAD/CAM technology, creating geometric models of existing objects plays a substantial role in reverse engineering, especially when the prototype is created or modified on the shop floor and when the CAD model does not exist. Therefore, there are increasing demands to achieve 3D model reconstruction of existing objects in various industrial applications. Typically, the applications of model reconstruction consist of three categories: (1) the reproduction application; (2) the quality control application and (3) the redesign and modification application (Langbein, Marshall, and Martin, 2004). In the first two cases, the low level design intents are sufficient to their purposes, where only the exact shape information is needed. In the case of last one, the high level design intents, such as the geometric properties and relations, are required. Specifically, the high-level design intents refer to the information regarding features and constraints. Our framework aims to capture the design intents from existing objects and hence represent them in reconstructed models.

1.1. Previous works

Many model reconstruction methods have been proposed for converting scanning data to geometric models (Au and Yuen, 1999; Benko et al., 2001; Bernardini et al., 1999; Chivate and Jablokow, 1993, 1995; Franke, 1982; Hoppe et al., 1992; Park and Kim, 1996; Pottmann and Randrup, 1998; Pratt, 1987; Protopsaltis, 2009; Varady et al., 2007; Varady et al., 1997), which can be classified into two types: (1) surface-based methods and (2) feature-based methods. Comparatively, the surface-based methods have been studied more maturely. For instance, most of the state-of-the-art commercial reverse engineering systems such as CATIA, CopyCAD, Geomagic, Imageware, Rapidform and RE-SOFT adopt this surface-based strategy to reconstruct geometric models. The surface-based methods are typically suitable for products comprised of freeform surfaces, e.g., the surface parts of automobiles and aircrafts. However, they are not applicable to complicated industrial parts consisting of geometric features and constraints.

The feature-based strategy was proposed to carry out model reconstruction of industrial products. Werghi, Fisher, Ashbrook, and Robertson (1998), Werghi, Fisher, Robertson, and Ashbrook

* Corresponding author.
E-mail address: davis.wjun@gmail.com (J. Wang).

0360-8352/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cie.2012.07.009

(1999) and Fisher (2004) studied the constrained reconstruction of 3D geometric models of objects from range data and proposed a new technique of global shape optimization on the basis of feature positions and geometric constraints. They pioneered in giving such a large framework for the integration of geometric relationships in object reconstruction. The basic idea is to minimize a function containing a least-squares term and a penalty term associated with the constraints. This method uses a complex formulation of the constraint function, which heavily relies on the convexity of the constraint space and also needs accurate initial estimates of the solution. Benko, Kos, Varady, Andor, and Martin (2002), Kos, Martin, and Varady (2000) and Lukacs, Marshall, and Martin (1998) conducted the research of solid model reconstruction with boundary representation and constrained quadratic surface fitting in reverse engineering. Thompson, Owen St, and Germain (1999) worked on the REFAB project to reconstruct models of manufactured parts. The constraints and features are first introduced in REFAB so that high accuracy models are reconstructed efficiently. Because only simple features are used, this method is incapable of handling complicated parts. Ke et al. (2006) proposed feature-based reverse engineering strategies for modeling industrial components from point clouds to surfaces, in which the sectional feature based strategy and surface feature based strategy are exploited respectively. The main idea is to construct surface features and thereby perform surface modeling operations to generate the final model. However, it is non-trivial to impose the global constraints to surface features to generate a highly accurate and topologically consistent model. Ye et al. (2008) proposed a reverse engineering innovative design methodology (namely RID), which has introduced the definitions and construction of feature-based parametric solid models from scanned data. The RID methodology makes design and knowledge reuse possible for 3D digital design applications. The concept of surface feature reconstruction is incorporated into the methodology, while the solid features are not considered. Durupt, Remy, and Ducellier (2010) came up with a knowledge based reverse engineering (KBRE) methodology, which includes the functionality of managing and fitting manufacturing and functional features in mechanical products. The method categorizes and reconstructs features from manufacturing point of view, not from geometric perspective. Beccari, Farella, Liverani, Morigi, and Rucci (2010) presented a reverse engineering method for fast and interactive acquisition and reconstruction of a digital 3D model representing an existing physical object. This method uses a pen-based active stereo acquisition system to capture curve network of cubic splines and reconstruct a smooth surface using the Catmull–Clark subdivision technique. This method takes as an input the curve network of contours of 3D model, instead of the scanned point cloud. Consequently, minor features may be discarded and the reconstruction result is not accurate.

2. Overview of our framework

Our framework provides a systematic solution to reconstruct a 3D model from the surface mesh of an existing object. First, the input mesh is processed using the mesh smoothing technique, and mesh segmentation is performed on the mesh to extract individual geometric feature surfaces. Then, two types of feature reconstruction schemes are applied to the geometric feature surfaces to construct the primitive features. Finally, according to the topological and connectivity relationships of primitive features, a series of modeling operations are performed on those features to generate the final geometric model using the geometric modeling kernel: Open CASCADE (http://www.opencascade.org/, xxxx). Meanwhile, the history of model building operations is stored. Fig. 1 gives a systematic flowchart for model reconstruction from a surface mesh and an example of the fandisk model reconstruction. In summary, the main contributions of this paper are:

- An effective framework is proposed to produce the unique boundary representation of a complex 3D object. It is capable of automatically extracting geometric features and reconstructing CAD models from low quality mesh.
- An effective mesh denoising method is presented to filter out noises, capable of preserving smooth and sharp features.
- The combination of solid feature based and surface feature based strategies is proposed, allowing for reconstructions of all kinds of industrial products.
- Parametric features, constraints and modeling history are incorporated into the model reconstruction so that the original design intents are captured and embedded in reconstructed models. The strategy brings fast and flexible editing capabilities to models and hence facilitates model reuse and redesign for innovation applications.

3. Mesh processing

With the advance of scanning techniques, the 3D scanning device has become a powerful and popular tool to capture point clouds from an existing object. The surface mesh of the object is thereby generated from tessellation of the point clouds. During scanning, it is inevitable to introduce some noises to the acquired data, and consequently the surface mesh is noisy. Such noises usually result in errors to the subsequent model reconstruction. Therefore, removing the noises from the mesh, namely mesh denoising, is crucial prior to further processes. Over the last two decades, mesh denoising has been studied deeply and a number of methods have been proposed (Desbrun, Meyer, Schroder, and Barr, 1999; Fleishman, Drori, and Cohen-Or, 2003; Hildebrandt and Polthier, 2004; Jones, Durand, and Desbrun, 2003; Lange and Polthier, 2005; Ohtake, Belyaev, and Seidel, 2002; Sun, Rosin, Martin, and Langbein, 2007; Taubin, 1995, 2001; Zheng, Fu, Au, and Tai, 2010). Botsch et al. (2007) gave an insightful survey on general mesh smoothing and denoising. Using the Laplacian operator, Taubin (1995) proposed a mesh smoothing method by using an isotropic scheme to improve the smoothness of a surface mesh, while alleviating the shrinkage problem. Desbrun et al. (1999) extended Taubin's work to smooth irregular mesh by using geometric flows and re-scaling the mesh to preserve its volume. However, features are often blurred or filtered out in both methods. Ohtake et al. (2002) defined an error function over the mesh, the new position of each vertex is calculated through the minimization of the function. They also designed a diffusion-type smoothing method on the normal field. Jones et al. (2003) designed a non-iterative, feature-preserving smoothing algorithm by adopting local first-order predictors statistically defined on triangular surface meshes. Similarly, a bilateral filter is applied to the signed distances of neighborhood to the tangent plane on a vertex and the vertex is updated along its normal vector with the displacement obtained from the filter (Fleishman et al., 2003). The two bilateral methods work well in the presence of low noises but become ineffective with high level of noise. Hildebrandt and Polthier (2004) used mean curvature flows to remove noises while retaining features and volumes. Sun et al. (2007) designed a truncated function to filter the normal vector and update the vertex position, which is fast and effective to remove mesh noises. These approaches work well at low noise levels. When the noise level became reasonably high; however, it would oversharp or create features that do not exist in the original mesh.

We propose an efficient, feature-preserving mesh denoising approach based on anisotropic neighborhood searching and surface fitting techniques. First, a new filter is designed to operate on the normal vector fields. For each vertex, we choose as a seed face