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Towards locally and globally shape-aware reverse 3D modeling

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ABSTRACT

The process of re-creating CAD models from actual physical parts, formally known as digital shape reconstruction (DSR) is an integral part of product development, especially in re-design. While, the majority of current methods used in DSR are surface-based, our overarching goal is to obtain direct parameterization of 3D meshes, by avoiding the actual segmentation of the mesh into different surfaces. As a first step towards reverse modeling physical parts, we extract (1) locally prominent cross-sections (PCS) from triangular meshes, and (2) organize and cluster them into sweep components, which form the basic building blocks of the re-created CAD model. In this paper, we introduce two new algorithms derived from Locally Linear Embedding (LLE) (Roweis and Sauk, 2000 [3]) and Affinity Propagation (AP) (Frey and Dueck, 2007 [4]) for organizing and clustering PCS. The LLE algorithm analyzes the cross-sections (PCS) using their geometric properties to build a global manifold in an embedded space. The AP algorithm, then clusters the local cross sections by propagating affinities among them in the embedded space to form different sweep components. We demonstrate the robustness and efficiency of the algorithms through many examples including actual laser-scanned (point cloud) mechanical parts.

1. Introduction

Digital shape reconstruction (DSR) in Computer Aided Design (CAD) is a process which involves extraction of high level parametric information from low level mesh or point cloud data. With the help of various CAD modelers available today, this high level parametric information is converted into surface parameterized models that can be modified or analyzed for further improvement and development. The initial complex and important step in DSR is segmentation of the mesh model [1].

Two major approaches that have been developed in segmenting a mesh model include surface-based and volume-based techniques (commonly known as feature based). Fig. 1 shows the difference between the two approaches. Both these approaches involve segmenting a mesh model into either surfaces or volumes. Digital model reconstruction through current surface-based segmentation methods does not lend itself to intuitive and flexible manipulation in contrast to what a parameterized CAD solid model does (see Fig. 1). Parameterized CAD models are associated with high level shape definition parameters such as radius, angle, width, and geometric constraints, while surface-based representations have low-level shape parameters such as knots, weights, and control points which are counter-intuitive to manipulation, especially for designers [2]. For example, from a functional design point of view, a digitally reconstructed model of an aerospace engine blade cannot embody original hydrodynamic properties without the parametric representation. Moreover, reconstructing a solid by stitching surfaces usually results in an inaccurate and inconsistent CAD model, and is also time consuming and laborious. The evolution of CAD modelers from surface to volume based design has led the volume based approach to gain more importance since volumetric or feature segmentation represents the design intent more closely and accurately.

Our overarching goal is to obtain direct parameterization of 3D meshes, by avoiding the actual segmentation of the mesh into different surfaces. Fig. 3 shows the difference between the traditional reverse engineering pipeline and our approach. As a first step towards reverse modeling physical parts, we extract (1) locally prominent cross-sections (PCS) from triangular meshes, and (2) organize and cluster them into sweep components. These sweep components form the basic building blocks in recreating a CAD model of the original object with user interaction.

We refer to the extracted cross-sections that are closed as 'Full Prominent Cross-Sections' (FPCS) and those that are open as 'Partial Prominent Cross-Sections' (PPCS). Feature intersection is addressed by the introduction of PPCS created in the regions of sweep intersections (red colored PCS in center model of Fig. 2). An individual set consists of a large number of uniformly distributed PCS, each of which approximates a local sweep in the small region

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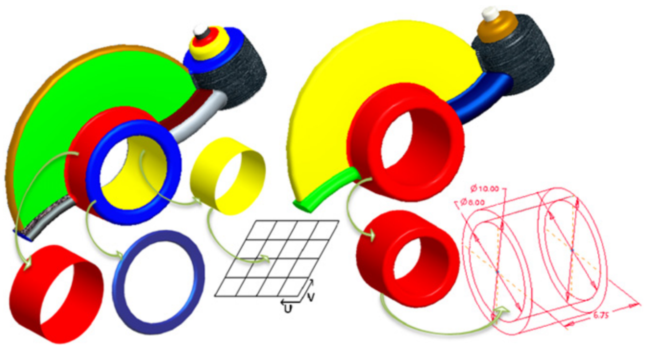

Fig. 1. Difference between surface–volume segmentation and subsequent parameterizations.

around that PCS. Fig. 5 shows a set of local cross-sections which collectively represents a single volumetric sweep segment. It is not feasible or necessary to cover each and every mesh facet with PCS as the amount of time and data will increase drastically for dense mesh models. Therefore, for the purpose of extraction we assume that for a small region around each PCS, the sweep cross-section is constant and represented by a single PCS.

In this paper, we introduce two new applications of the algorithms—Locally Linear Embedding (LLE) [3] and Affinity Propagation (AP) [4] for organizing and clustering PCS. The LLE algorithm analyzes the cross section (PCS) using their geometric properties to build a global manifold in an embedded space. The AP algorithm then clusters the local cross sections by propagating affinities among them in the embedded space to form different sweep components. The method may produce multiple but feasible sweep components corresponding to a particular portion of the original part. In such cases, user interaction is required to resolve the ambiguous interpretations. We also show the construction of a CAD model from the extracted sweep components using *CATIA*™.

We clearly distinguish that our intent is not to reconstruct the original object as designed in a complete sense. We characterize our capabilities as being able to handle those shapes with swept volumes where the "non-interacting" parts carry enough evidence together with the partial cross-sections. For example, when shell operations take out a large portion of the sweep, our method will not work.

1.1. Background

Our semi-automatic approach transforms the physical part into a set of generalized sweep components. A generalized sweep involves two components namely, the 2-dimensional profile(s) or cross-section(s) being swept and the 3-dimensional trajectory (trajectories) along which they are swept orthogonally. The different modeling operations typically used in creating CAD models in tools like *Pro/ENGINEER*™ are nothing but special cases of a generalized sweep. For example, an 'extrusion' is a sweep operation involving a 'constant' sketch swept along a 'linear' trajectory. The other cases are listed in Table 1. For any 2-dimensional cross-section swept along a trajectory (Fig. 4), the swept volume can be described as [5]:

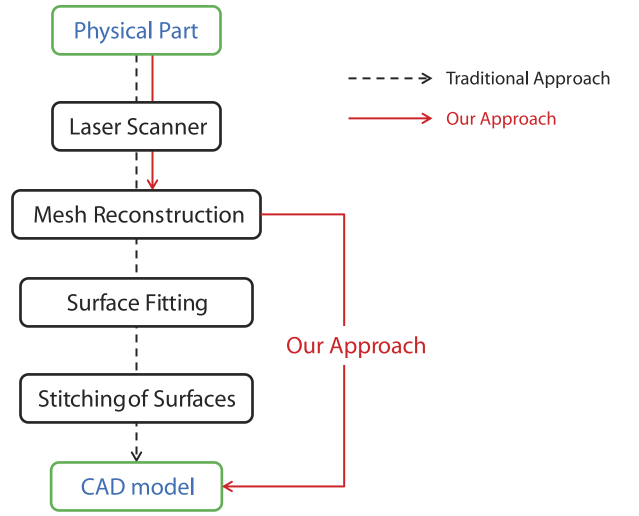

Fig. 3. Traditional reverse engineering pipeline versus our approach. We obtain the direct parameterization of CAD model by completely skipping the reconstruction of surfaces.

$$X(u, s) = T(s)\Gamma(u) + \Psi(s) \quad (1)$$

where $u = [u1, u2]^T$, $\Gamma(u)$ represents a section being swept (a surface parameterized in two variables $(u1, u2)$), $\Psi(s)$ is the swept path parameterized by the arc length s, $T(s)$ the transformation matrix and $X(u1, u2, s)$ characterizes the set of all points inside and on the boundary of the swept volume. The swept surface $\Gamma(u)$ is a 2-dimensional section, hence its boundary can be represented by a single parameter t. Thus Eq. (1) can be represented as:

$$X(t, s) = T(s)\Gamma(t) + \Psi(s) \quad (2)$$

$X(t, s)$ characterizes the set of all the points on the boundary of sweep. Given a set of local cross-sections representing a single sweep, we can compute the transformation $T(s)$ between any two consecutive sections. Each individual cross-section can be parameterized to compute $\Gamma(t)$. And finally, the trajectory equation $\Psi(s)$ can be determined by approximating a curve which is perpendicular to each cross-section and passes through their centroid.

In the following section, we introduce two new algorithms LLE and AP, used to build a global manifold and subsequently cluster them to obtain sets of PCS. To the best of our knowledge these ideas are new to the field of DSR or CAD model segmentation. These two algorithms can be adapted to segment any data set having a representation of local distances.

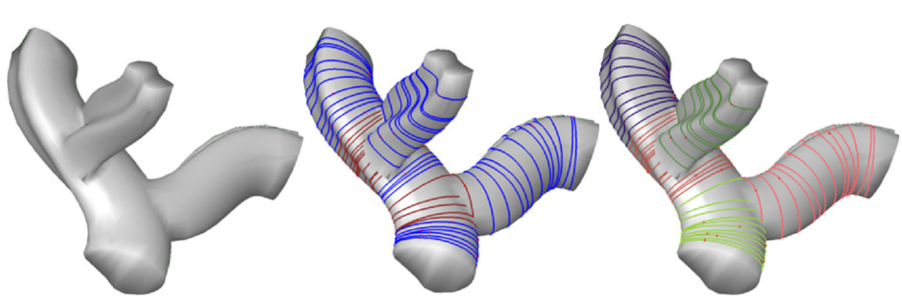

Fig. 2. Volumetric understanding: (From Left to Right) mesh model, PCS generation (full cross-sections are shaded in blue and partial cross-sections in brown), and sets of PCS representing different sweep segments obtained after clustering. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)