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Applying geometric constraints for perfecting CAD models in reverse engineering

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ABSTRACT

An important area of reverse engineering is to produce digital models of mechanical parts from measured data points. In this process inaccuracies may occur due to noise and the numerical nature of the algorithms, such as, aligning point clouds, mesh processing, segmentation and surface fitting. As a consequence, faces will not be precisely parallel or orthogonal, smooth connections may be of poor quality, axes of concentric cylinders may be slightly tilted, and so on. In this paper we present algorithms to eliminate these inaccuracies and create "perfected" B-rep models suitable for downstream CAD/CAM applications.

Using a segmented and classified set of smooth surface regions we enforce various constraints for automatically selected groups of surfaces. We extend a formerly published technology of Benkő et al. (2002). It is an essential element of our approach, however, that we do *not* know in advance the set of surfaces that will actually get involved in the final constrained fitting. We propose *local* methods to select and synchronize "likely" geometric constraints, detected between pairs of entities. We also propose *global* methods to determine constraints related to the whole object, although the best-fit coordinate systems, reference grids and symmetry planes will be determined only by surface entities qualified as relevant. Lots of examples illustrate how these constrained fitting algorithms improve the quality of reconstructed objects.

1. Introduction

Reverse engineering (digital shape reconstruction) is an expanding and challenging area of Computer Aided Geometric Design [2]. This technology is utilized in various applications where a given physical object is scanned in 3D, and a computer representation is needed in order to perform various computations. A wide range of applications emerges in engineering, medical sciences, and to preserve the cultural heritage of mankind [3].

For CAD models the process can be split into the following phases:

(1) 3D data acquisition (scanning), (2) filtering and merging point clouds, (3) creating triangular meshes, (4) simplifying and repairing meshes, (5) segmentation (partitioning into disjoint regions), (6) region classification, (7) fitting primary (functional) surfaces, (8) fitting connecting surfaces (e.g. fillets), (9) *perfecting surfaces* (including constrained fitting and surface fairing), (10) creating a B-rep model (i.e., stitching surfaces and building up a topological structure), (11) exporting to CAD/CAM systems.

In the majority of engineering applications, it is crucial that the reconstructed models satisfy various geometric constraints. The primary surfaces—and their associated directions and axes, if any—must obey various rules, such as being orthogonal, parallel, tangential, symmetric, concentric, and so on. If we approximate the segmented regions *separately*, one by one, we may obtain inaccurate surfaces and poor CAD models. This is due to the noise and incompleteness of

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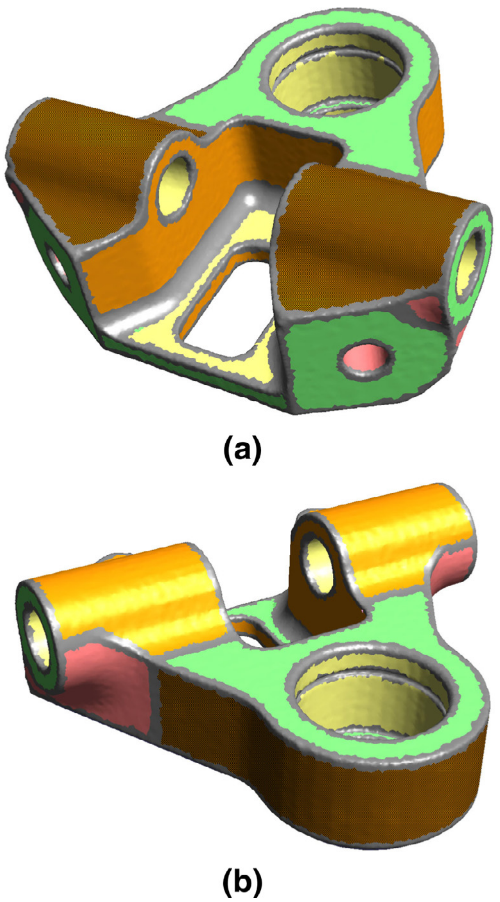

Fig. 1. Segmented object: (a) view 1; (b) view 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)..

measured data, and the numerical nature of the subsequent algorithmic phases, such as merging multiple data sets, decimating and repairing triangular meshes, segmentation, and least-squares fitting without constraints.

The goal of our research is to perfect CAD models created from measured data. We introduce techniques to automatically detect likely engineering constraints, and enforce these by performing *constrained fitting*. We work with the following assumptions.

(i) Our input is a segmented mesh containing a set of regions. In most cases, this means that the highly curved triangle-strips corresponding to fillets or sharp edges get removed, and thus a numerically stable set of *disjoint regions* is obtained that corresponds to the face structure of the final B-rep model—an example is shown in Fig. 1.

(ii) By means of classification, a surface type has already been assigned to each region providing the best local approximation to the underlying data points.

(iii) We deal with the most frequent engineering surfaces: planes, quadric surfaces (cylinders, cones, spheres), extruded and drafted surfaces (defined by a direction vector and a profile), rotational surfaces (defined by an axis and a profile), and the remaining surfaces considered as free-form. (Constraints for free-form surfaces and general sweeps are going to be subject of future research.)

Let us take the above simple CAD model and look at a few problems that motivate our work. This object has been measured in a general 3D workspace, so its base surfaces are not aligned to an optimal coordinate system. The planar surfaces at the bottom and top (green) are not perfectly parallel, neither perpendicular to the planar faces at the left and right sides. The horizontal cylindrical holes (yellow) are unlikely to share the same axis and radius. The two extruded surfaces (beige) on the top may have two slightly different profiles and directions of extrusion. The two vertical cylinders (yellow) in Fig. 1(b) will not be exactly concentric, their axis will not necessarily be contained in the plane of symmetry, and will not be perpendicular to the top planar face (green), and so on. Nothing guarantees that the reconstructed object will be symmetric.

Our proposed techniques are based on recognizing the most likely constraints using the initial parameters of individually fitted surfaces. We select groups of relevant surfaces that are likely to comprise a set of parallel/orthogonal entities, share common axes and directions, force profile curves to be identical or symmetric, and so on; then refit while maintaining these constraints. We also search for likely best-fit coordinate systems that align the majority of surface elements and refit accordingly. We locate relevant surface groups that are found fully or partially symmetric and enforce symmetry accordingly. We attempt to compute a global reference grid, where the dimensions match a well-defined grid-size, that likely corresponds to the original design intent, and snap the related elements. All these problems are converted into solving a large system of non-linear algebraic equations.

Handling constraints may seem relatively easy for a human engineer, when the constraint types and the set of relevant surfaces are explicitly specified. However, this is fairly difficult for a program, where even the group of surfaces is unknown for which the constraints needs to be set up. While the majority of commercial systems offers a wide range of operations to tweak surface parameters directly, here we search for *automatic* techniques, that can save a large amount of manual work and reduce errors. In this context users remain involved at two levels: (i) prescribe “likelihoods” by setting various tolerances (depending on the quality of measured data and the dimensions of the object), and (ii) check and approve perfected surface geometries, as constrained fitting is moving forward.

The paper is structured as follows. In Section 2 previous work is reviewed. In Section 3, the method of Benkő et al. [1] is revisited, as this constitutes the basis of the current work. Section 4 deals with *local* constraint detection and satisfaction. In Sections 5–7 algorithms are presented to compute *global* constraints that relate to the whole, or at least large parts of the object including best-fit coordinate systems, reference grids and symmetry planes. Test examples at the end of each section illustrate the results.

2. Related work

Discovering design intent and inherent structural properties is an important topic in many areas. Related publications