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A fast interactive reverse-engineering system

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ABSTRACT

A new method of reverse engineering for fast, simple and interactive acquisition and reconstruction of a virtual three-dimensional (3D) model is presented. We propose an active stereo acquisition system, which makes use of two infrared cameras and a wireless active-pen device, supported by a reconstruction method based on subdivision surfaces. In the 3D interactive hand sketching process the user draws and refines the 3D style-curves, which characterize the shape to be constructed, by simply dragging the active-pen device; then the system automatically produces a low-resolution mesh that is naturally refined through subdivision surfaces. Several examples demonstrate the ability of the proposed advanced design methodology to produce complex 3D geometric models by the interactive and iterative process that provides the user with a real-time visual feedback on the ongoing work.

1. Introduction

In the field of computer-aided design (CAD), reverse engineering has become an effective method to create a three-dimensional (3D) virtual model of a physical object for later use in software for computer-aided design and manufacturing. Reverse engineering has many applications in different fields, such as medical imaging, entertainment, cultural heritage, web commerce, collaborative design and obviously engineering; all these applications can take advantage in different ways from the reconstructed 3D virtual model. Conventional reverse engineering involves two main steps (see Fig. 1(a)): the measurement of the physical object and its reconstruction as a 3D virtual object. The physical object can be measured using 3D scanning technologies such as coordinate measuring machines or computed tomography scanners, which provide outputs in the form of an unstructured point cloud, i.e. a large set of vertices in a 3D coordinate system, which lacks topological information and therefore is generally not directly usable in most 3D applications. The point cloud is then usually converted to a mesh model, NURBS (non-uniform rational B-spline) surface model, or CAD model through a process commonly referred to as 3D reconstruction so that it can be used for computer-aided engineering and computer-aided manufacturing. This second step of reconstruction of the virtual 3D object from the dense point cloud is an inverse problem and generally does not admit a unique solution. Most proposed approaches to reconstruction from unstructured data points build polygon meshes that interpolate or approximate the input points. The fundamental difficulties of reconstruction arise from the lack of topological information in the data and also from the noise and inaccuracies of the measuring process, the presence of obstructions and holes, and consequently additional assumptions and requirements on the input data are generally needed to make the problem tractable. As a result, most reconstructed models need to be post-processed for simplification and optimization, introducing another step in the reverse-engineering process.

The steps of measuring and reconstruction could be achieved by using different techniques and devices, and all of them have strengths and weaknesses. Regarding the alternative 3D scanning methods, we can outline the following quality measures: accuracy and resolution, environmental sensitivity, repeatability, speed, and cost. A reconstruction process is usually required to be automatic, sensible to the object topology, time and space efficient, and robust (with respect to noisy data). All current reverse-engineering solutions suffer from some common limitations. For example, the overwhelming number of points acquired and the lack of topological information in this data, combined with the presence of noise and inaccuracies, usually require complex and time-consuming solutions. Moreover, the strict separation of the two fundamental steps of measuring and reconstruction makes this process a non-iterative and non-interactive process.

In this paper, we introduce a new method of reverse engineering for fast, simple and interactive acquisition and reconstruction of a virtual 3D model representing an existing physical object

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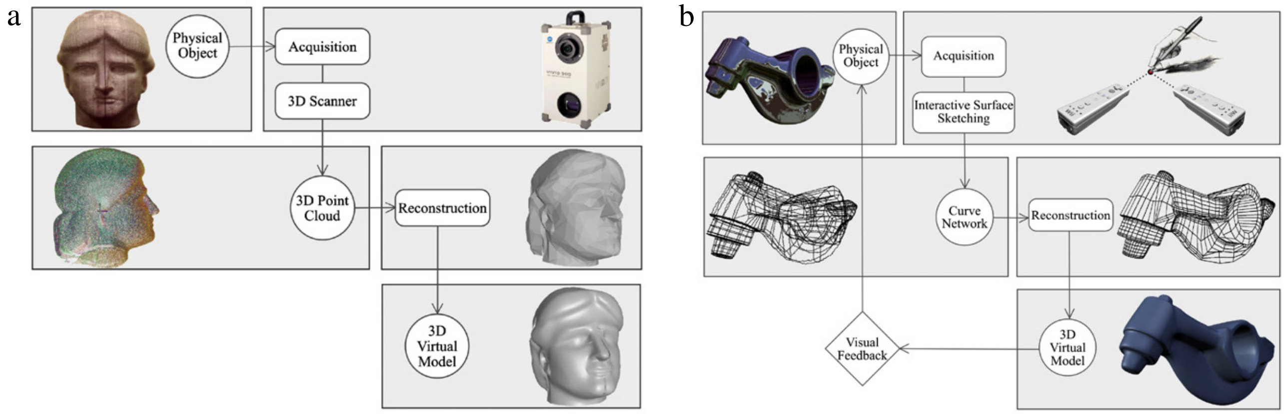

Fig. 1. (a) Traditional reverse-engineering pipeline, (b) fast and interactive reverse-engineering pipeline.

which exploits a pen-based active stereo acquisition system supported by a reconstruction and visualization layer based on subdivision surfaces.

We named our approach a fast interactive reverse-engineering system (FIRES). In our context, we consider the term reverse engineering in the broadest sense, where the operator uses physical objects as a 3D template to start his/her own design. Therefore, the reconstruction of an exact digital replica of the physical object is not our goal, and, consequently, we do not pursue the goal of an extreme accuracy. Instead, our target is to capture and reproduce the style features which characterize the original object design, and eventually let the user add new features following his/her own design intent.

The objective in FIRES is twofold. First, we designed and developed a low-cost, wireless pen-like device able to provide an intuitive and easy 3D input/editing; moreover, we developed a set of algorithms that, exploiting low-cost technologies, provides a real-time acquisition and editing of 3D shapes available alongside the CAD system.

In the field of reverse engineering, regarding 3D modelling and interaction devices, there is a significant demand for flexibility and effectiveness with respect to classical bidimensional devices (e.g. a mouse). Thus, the former goal is to develop a pen-like device with the capability of drawing and selecting points and curves, which introduces a natural way to draw and edit the style-lines of a physical object. These style-lines are traced by simply dragging the pen in space, and they define the most characteristic curves of the shape to be reconstructed. This process generates a low-resolution smart mesh, which is naturally well suited to be represented by subdivision surfaces. Three different geometric models of the reconstructed object can be provided by FIRES: the curve network in spline form, a polygonal mesh refined as necessary, and a smooth surface represented as subdivision surface. This aims to anticipate the current trend in the CAD field to integrate subdivision surfaces as geometric primitives and provides more flexibility in the integration in the CAD system.

Although the resulting 3D model does not have the accuracy of classical reverse-engineering systems, our approach allows us to significantly shorten the acquisition and integration time of the real model directly into the virtual environment up to an interactive feedback. The reconstruction time is even shortened by using more flexible geometric primitives, such as subdivision surfaces.

In FIRES we introduced the following novel contributions.

- The design of a specific, innovative, low-cost hardware device which is able to acquire in real time 3D control curves by drawing them onto the shape.
- The development of an innovative reconstruction procedure, which is able to produce a unique smooth representation of an arbitrary topology 3D object, starting from an irregular 3D curve network. This is unlike the conventional sketching systems which in general represent a surface only as a collection of reconstructed patches which require further work to be joined together to satisfy continuity constraints.
- Fast editing capabilities to support both the acquisition of physical objects and the editing of non-existing parts of them, which can be easily integrated in a CAD working session in real time. In contrast, conventional reverse-engineering systems require long reconstruction times before the user can interact with the reconstructed virtual model.

This paper is organized as follows. The remainder of this section presents some related works. Section 2 is an overview on FIRES whose work pipeline is illustrated in Fig. 1(b). The data structure layer of FIRES is presented in Section 3. Then, following the main stages shown in Fig. 1(b), we describe in Section 4 the acquisition phase, in Section 5 the interactive surface sketching methodology, and in Section 6 the surface reconstruction method adopted in FIRES. Examples in Section 7 illustrate the performance of the reconstruction method when applied to a few object reconstructions.

1.1. Related work

Reverse engineering (RE) is the process of measuring an object and then generating a CAD model of it which captures the object's physical features. While conventional RE methodology does not reflect the design intent, recently feature-based RE has been developed [1,2], to reconstruct specific analytic features such as planes, quadric shapes, and blends. In [3] a reverse-engineering innovative design methodology called reverse innovative design (RID) has been introduced to integrate the design intent and knowledge with the shape editing. Both FIRES and RID, proposed in [3], share the common objective of the significative time reduction in modelling and simulation, starting from a 3D real object. But FIRES arises from the idea that a huge amount of data is redundant and time consuming for a fast and interactive digitization and aims to short cut the classic steps compacting them into a single real-time stage. This implies significant benefits in terms of speed, but it is not competitive in terms of precision.

Computer modelling of 3D geometry using alternative three-dimensional user interfaces (3D UIs) and interaction techniques has received considerable attention in recent years. While a number of techniques involving 3D UIs, 3D devices, haptic devices, and VR systems have been proposed, the usability of 3D UIs in many real-world applications is still surprisingly low. For example, the