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Reverse innovative design — an integrated product design methodology

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Abstract

Today's product designer is being asked to develop high quality, innovative products at an ever increasing pace. To meet this need, an intensive search is underway for advanced design methodologies that facilitate the acquisition of design knowledge and creative ideas for later reuse. Additionally, designers are embracing a wide range of 3D digital design applications, such as 3D digitization, 3D CAD and CAID, reverse engineering (RE), CAE analysis and rapid prototyping (RP). In this paper, we propose a reverse engineering innovative design methodology called Reverse Innovative Design (RID). The RID methodology facilitates design and knowledge reuse by leveraging 3D digital design applications. The core of our RID methodology is the definition and construction of feature-based parametric solid models from scanned data. The solid model is constructed with feature data to allow for design modification and iteration. Such a construction is well suited for downstream analysis and rapid prototyping. In this paper, we will review the commercial availability and technological developments of some relevant 3D digital design applications. We will then introduce three RE modelling strategies: an autosurfacing strategy for organic shapes; a solid modelling strategy with feature recognition and surface fitting for analytical models; and a curve-based modelling strategy for accurate reverse modelling. Freeform shapes are appearing with more frequency in product development. Since their "natural" parameters are hard to define and extract, we propose construction of a feature skeleton based upon industrial or regional standards or by user interaction. Global and local product definition parameters are then linked to the feature skeleton. Design modification is performed by solving a constrained optimization problem. A RID platform has been developed and the main RE strategies and core algorithms have been integrated into SolidWorks as an add-in product called ScanTo3D. We will use this system to demonstrate our RID methodology on a collection of innovative consumer product design examples.

Keywords: 3D CAD; CAID; Reverse engineering; Product design methodology; Reverse innovative design; Feature-based modelling; Parametric modelling; Product definition parameters; Local shape deformation

1. Introduction

Design is a purposeful process involving creative thinking and problem solving. Design and knowledge have a very strong association: recollection and application of knowledge can be considered as a straightforward and practical design process [1–3]. Emerging new techniques, devices and the globalization of the product market are pushing creativity to its limit. Today's market is characterized by faster time-to-market, and greater demands for fresh and distinctive products. Facing intense market challenges, advanced design methodologies are being actively sought to reduce the time required for knowledge acquisition in design activities, and to leverage creativity.

It is estimated that designers spend about 60% of their time searching for information. This process is rated as the most frustrating aspect of an engineer's design activities [4]. It is also conservatively estimated that more than 75% of engineering design activity comprises case-based design — reuse of previous design knowledge to address a new design problem [4]. However, physical models and associated knowledge, which are increased considerably in complexity and quantity during the design process, are often not reused. This results in significant time and capital losses. Hence, design and associated knowledge reuse is the key to reducing new product development costs.

The use of 3D CAD (Computer Aided Design) tools is a prominent factor in shortening time-to-market and reducing

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product development costs. With the wide adoption of 3D CAD technology [5], product development has moved from physical to digital mockup, and from 2D to 3D design in the last few decades. 3D CAD has become part of a completely digital development process that includes design, modelling, simulation and tooling [6,7]. As a result, more and more designs exist in 3D digital form and are maintained in product databases. For new designs, if a digital form of similar product model is readily available in the database, 3D searching techniques [4,8,9] can be used to locate product models with similar shapes and design intent. In these cases, a new design can be accelerated by the reuse, in whole or part, of previous designs. 3D searching and reuse techniques have been extensively researched [10,11]. Although there already are some commercially available 3D search engines [12], 3D searching and reuse remains a very active topic of research in the design and media retrieval areas. On the other hand, with the rapid advancement of 3D data acquisition devices, Reverse Engineering (RE) technology has gained wide acceptance in the design community. This is especially true in the CAID (Computer Aided Industrial Design) community where physical models such as clay models are built and digitized. Unlike solid modelling CAD software packages which focus on making watertight solids, RE software packages typically output surface models.

Many commercial 3D CAD software packages are feature based with parametric definitions of the features. A definition of a *feature* is given by the FEMEX (FEature Modeling EXperts) work group, see, e.g. [13]. A feature is defined as a representation of the shape aspects of a product that can be mapped to a generic shape and functionally significant for some product life-cycle phase [14]. In practical terms, a feature can be viewed as the basic unit of product information that can represent a specific region. The term product can be a real, physical object or it can be a process. The term region describes a spatial or geometrical portion of a physical object or a process-orientated portion of a process [15]. In this paper, we use the term *feature* to represent design intent and design knowledge. High-level shape definition parameters such as radius, length, angles and width are presented to the designers, and constraints between geometrical entities such as dimension equality, parallelism, perpendicularity, co-linearity and concentricity are imposed. By changing these intuitive parameters and editing the constraints, different configurations can be created for the same model, and a product family can be obtained. Usually, a feature tree is formed to record the history of the design process, and the feature creation sequence can be replayed.

In RE software packages, however, surfaces (usually freeform surfaces) are created. While freeform surfaces have flexibility and allow the manipulations typically required in the conceptual design phase, they lacked the ability to express design intent or knowledge in a detailed and explicit manner. Although low-level shape parameters such as weights, knots, and control points [16] are available to adjust the freeform surfaces, they are counter-intuitive to designers. Many shape deformation methods have been developed in the last decade to increase the intuitiveness of the freeform shape deformation, and to increase the designers' ability to control the shape changes through mesh and surface deformation.

This paper presents a new product design methodology called Reverse Innovative Design (RID) which combines the benefits of these two worlds, namely the design intent and knowledge represented by features with their associated definition parameters; and the flexibility of shape deformation. Features with high-level definition parameters are directly created from scanned data in a 3D CAD system. A new design can be obtained by changing these high-level definition parameters, while retaining aspects of the original design. Starting from a digitized model of an existing product or conceptual clay model, a clean mesh will be obtained by preprocessing of a point cloud data (e.g. registration, sampling, noise data removal, global and local smoothing), meshing and mesh preprocessing (e.g. sampling, smoothing, topology repair and hole filling). From the cleaned mesh, a feature-based parametric solid model will be constructed with natural definition parameters by the extraction of analytically shaped features. For freeform product models, product definition parameters will be obtained based on the feature skeletons extracted from the mesh. The natural definition parameters of the features and the product definition parameters will be used for design of new products and product families.

Our RID provides three RE modelling strategies for different use case scenarios:

(1) For organic shapes, C^1 or C^2 solid models are automatically generated from the mesh model. The solid model can be used in the application scenarios such as model references, data transmission, high-quality graphics presentation and rapid prototyping.

(2) For more analytical shapes, the mesh model is segmented into functional regions called submeshes. Feature recognition techniques are exploited to build analytically shaped features in a 3D CAD package, resulting in high-level shape characteristics (e.g. cylindrical, spherical, conical, extruded or revolved surfaces) and natural shape parameters (e.g. radius, length, height and angle). Submeshes that are not analytical are fitted by B-spline surfaces. All reconstructed surfaces will be extended, trimmed and sewn into a solid (if possible) in the 3D CAD software.

(3) Should a more accurate model be required, a curve-based modelling strategy can be adopted. 2D or 3D sketches can be generated by inferring from the mesh model, and curves such as section curves, boundary curves, and feature lines can be generated from the digitized model. From these curves, lofted surfaces (with one or two directional curve nets) [17] can be generated directly within the 3D CAD package.

Freeform product design has been the main focus of conventional RE. Since their "natural" parameters are hard to be defined and extracted, in our RID we propose dealing with freeform product models by extracting global and local product definition parameters that are defined by international, domestic or industrial de-facto standards; or by user-defined key parameters. Designers can produce new design variations by editing the product definition parameters.