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From reverse engineering to shape engineering in mechanical design

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ABSTRACT

Reverse engineering and shape reconstruction play an important role in design and manufacturing through the increased use of shape acquisition and processing technologies in the product development process. The application of shape theories to geometric modelling and variability characterization are paving the way to shape engineering and more generic methods for reverse engineering.

This paper investigates the fundamentals of shape representation, shape processing and mining at a conceptual, geometric and computational level to address geometric reverse engineering issues in mechanical design. New developed concepts based on discrete curvatures and their applications are presented. Challenges and future researches are also highlighted.

1. Introduction

Nowadays, reverse engineering is recognized as an important issue in the product design process which highlights inverse methods, deduction and discovery in design. In mechanical engineering, reverse engineering has evolved from capturing technical product data, and initiating manual redesign procedure while enabling efficient concurrency benchmarking to a more elaborated process based on advanced computational models and modern digitizing technologies.

The reverse engineering of mechanical products is generally addressed in both the practice and the literature from a geometric or shape perspective. Geometric reverse engineering relies on a set of generic methods inherited from the geometric modelling and processing fields. Those methods encompass mesh segmentation, surface reconstruction, and feature recognition. Moreover, geometric reverse engineering is nowadays supported by a digital thread from the raw acquired point cloud data to parametric feature-based CAD models. In this context, it envisions a more global geometric reverse engineering process with a life cycle perspective (Fig. 1).

It enables also an improved reverse engineering process through knowledge-based techniques to make more explicit and sharable the knowledge embedded in the digital flow, and recently, it draws the attention to the convergence of reverse engineering, metrology, and software for additive manufacturing-related applications [1].

Lying at the interface of mechanical engineering, modern geometry, computer science, and statistics, shape engineering is concerned with the study of geometric properties of mechanical parts and assemblies. Its goal is to establish a theoretical foundation for the modelling and processing of product's shape and variability, and to develop methods for geometric reasoning to infer knowledge and enable decision making in the product development process [2].

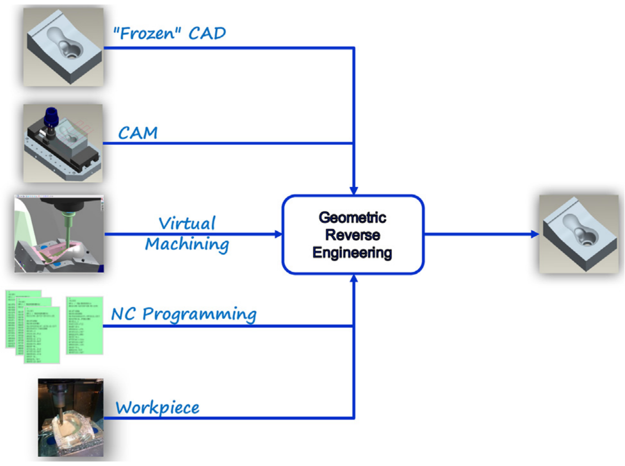

Fig. 1. The global context of geometric reverse engineering.

This paper investigates the fundamentals of shape representation, shape processing and mining at a conceptual, geometric and computational level to address geometric reverse engineering issues in mechanical design. New developed concepts based on discrete curvatures and their applications are presented. Challenges and future researches are also highlighted.

2. Reverse engineering vs. geometric reverse engineering

Although reverse engineering theories and methods, traced back to the 1980s, were predominant in the areas of software, hardware and biological systems, reverse engineering techniques

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are applied in different areas [3–6], ranging from mechanical engineering, civil engineering, architecture, cultural heritage, to dentistry and medicine.

2.1. Reverse engineering

Reverse engineering was originally defined as "the process of developing a set of specifications for a complex hardware system by an orderly examination of specimens of that system" [7]. Chikofsky and Cross [8] defined reverse engineering as "the process of analysing a subject system to identify the systems components and their relationships, and to create representations of the system in another form or at a higher level of abstraction".

Reverse engineering is generally addressed in the literature from different perspectives that include system benchmarking and recovery, and inverse problem modelling to infer a model and its parameters from experimental data [9].

In mechanical design, reverse engineering can be defined as the process that "initiates the redesign process wherein a product is predicted, observed, disassembled, analyzed, tested, 'experienced', and documented in terms of its functionality, form, physical principles, manufacturability, and assemblability" [10]. It has been considered a method to understand how a product works [11], and the process of duplicating an object to obtain a surrogate model or a clone to enhance its performance, and to capture and apply the embedded knowledge to new design.

2.2. Geometric reverse engineering

The consideration of the geometrical aspect of the product has led to a tremendous growth in research on what is called, variously, geometric reverse engineering or reverse geometric modelling [12]. The extraction of geometry from an existing product to reconstruct a 3D CAD model is the most used approach for geometric reverse engineering. Though there exist multiple descriptions of the geometric reverse engineering process, they can all be condensed to three main steps: product digitization, shape reconstruction, and 3D CAD modelling. This process can be iterative in nature (Fig. 2).

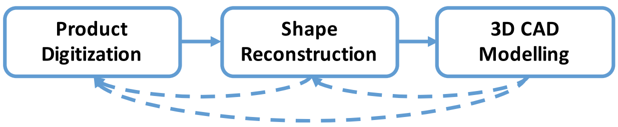

Fig. 2. Basic phases of geometric reverse engineering.

Product digitization refers in general to the phase of digitizing a physical product using measurement and scanning devices. It can be extended to include all other processes that can define a virtual product or its signature such as mechanical simulation, manufacturing process simulation and shape and topology optimization. Thus, geometric reverse engineering focuses not only on the reconstruction of the shape from measurement, but also on the integration of materials properties and manufacturing processes and their inherent variability.

The step of shape reconstruction is to determine a surface that approximates an unknown shape from samples. This problem is ill-defined since many surfaces approximating the samples can be retrieved. Moreover, the point set can be characterized with variable density as well as noise and outliers due to the acquisition process. The main challenge here is to guarantee that the topology of the original surface is preserved, while sharp features and surface boundaries are reproduced accurately in the reconstructed surface. The research literature is very rich and various techniques have been developed. The earliest techniques used NURBS or B-Splines to fit and stitch together local surface patches but showed their limits when dealing with complex physical objects, large data, sparsity and noise. Moreover, they are not applicable when physical properties like material or density of the object need to be considered.

3D CAD modelling is the final step to create a geometric (solid) product model using a Boundary Representation (B-Rep) or a feature-based parametric representation to embed design intents through geometric features, parameters and constraints. Feature-based parametric models are often required for model query and interrogation or design modification. Moreover, they enable the development of Knowledge-Based Reverse Engineering (KBRE) methodologies to include more a priori information to overcome noisy or missing data and to extract more design and manufacturing data [13,14].

3. Shape framework for geometric reverse engineering

The study of shape has a long and rich history. It has been highlighted in different areas such as philosophy, psychology, mathematics, and engineering for understanding the mechanisms of perception, to emulate the human visual system, and to address geometric and structural data of natural and man-made objects.

3.1. Shape conceptualization

According to the Merriam-Webster Dictionary a shape is "the visible makeup characteristic of a particular item or kind of item," "a spatial form or contour," or "a standard or universally recognized spatial form." Thus, the geometrical properties of shape have generated the most interest from the researchers since the pioneering work of D'Arcy Thompson and Kendall [15]. An intuitive definition of shape given by Kendall is: "shape is all the geometrical information that remains when location, scale, and rotational effects are filtered out from an object." Hence, this definition allows for a similarity measure among shapes, which is the fundamental of Statistical Shape Analysis (SSA) [16]. Moreover, SSA methods establish, from a training set, the pattern and the parameters of variation in the shapes and their spatial relationships. Thus, an efficient parameterization of this variability can be established which provides a compact representation of shapes. SSA methods have been successfully applied to Geometrical Product Specifications (GPS) thanks to Skin Model Shapes paradigm [17].

3.2. Shape representation and description

A shape model is a computational structure that captures the spatial aspects of the product. Shape representation can be defined as a mapping from a computer structure to a well-defined mathematical model which defines the real or physical product in terms of computable mathematical properties [18]. These properties for shape representation include shape type (discrete or continuous), structural expression (point-based, surface/shell-based or volume-based), and the representation scheme (enumerative, cell complex, functional or constructive).

Since a cloud of points does not infer too much information, a polyhedral or triangular mesh is constructed in order to organize the points and reconstruct the topology of the product. Mesh reconstruction algorithms build a first order approximation of the shape and rely on combinatorial structures or implicit methods. A benchmark for evaluation of mesh reconstruction techniques shows that reliable topological and geometrical guarantees are raised by sampling strategy, density, noise, outliers and sharp features [19]. Moreover, the computation of point-set orientation and differential geometry parameters are often required.

While shape representation contains enough information to reconstruct the product, shape description more likely contains enough information to identify, analyze, understand, and recognize shapes [20]. Through shape descriptors, a more compact and concise representation is enabled for shape processing, interrogation and mining.

Various descriptors have been reported in the literature such as shape signature, Fourier descriptors, medial axis, curvature, etc. [21]. Curvature is one of the most important differential character