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The skin model, a comprehensive geometric model for engineering design

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ABSTRACT

The modelling of product shapes and dimensions is now largely supported by geometric modelling tools. However, the underlying geometrical variations cannot be addressed efficiently when covering the overall product life cycle. The fundamental concept of skin model has been developed as an alternative to the nominal model and covers geometric deviations that are expected, predicted or already observed in real manufacturing processes.

This paper investigates the fundamentals of the skin model at a conceptual, geometric and computational level. Representation and simulation issues for product design are presented. Finally, applications and perspectives are highlighted.

1. Introduction

Nowadays, the use of Information Technology (IT) for design and manufacturing has increased mainly among aerospace and automotive industries, owing in a large part to the availability of advanced Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), Computer-Aided Manufacturing (CAM) systems and enhanced computing facilities [1,2]. Virtual prototyping and virtual usage before real production is increasing through digital manufacturing enhanced by virtual reality (VR) technologies [3]. The widespread availability of sensors, networks, computers and the fastest growing sector of reverse engineering and virtual/augmented reality is revolutionizing product development [4,5]. Geometric modelling, at the heart of the product development cycle, becomes ubiquitous and offers essential and different tools for the digital product development process.

Although the product form or shape have been extensively investigated considering the nominal geometry, initially specified with ideal shape and nominal dimensions, inevitable limitations can be observed, especially when dealing with accurate solid models of physical products. Despite substantial research efforts in geometric modelling, finite-element methods, geometric tolerancing and computational metrology, the efficient consideration of real-life situations of product geometric variations remains an open problem. Computer Aided Tolerancing (CAT) systems provide simulation tools for modelling the effects of tolerances on digital assembly simulation. Integration of manufacturing simulations and physical modelling into tolerance analysis [6] lead to more accurate methods but still lack of form deviations considerations.

The key point in overcoming the problems mentioned above is the consideration of new paradigms for geometric product modelling that supersede the actual CAD or nominal model.

The skin model has been developed to enrich the nominal idealized geometry considering physical shapes. The concept stemmed from the theoretical foundations of Geometrical Product Specification (GPS) [7] and the two acknowledged axioms of manufacturing imprecision and measurement uncertainty [8].

The representation of the skin model has been investigated only recently. A discrete shape approach proposed by Zhang et al. [9,10] paved the way for skin model representation and simulation. Their approach enabled to model form, orientation and position deviations employing second order shapes and different methods for obtaining randomly deviated geometry. Multiple views and different instances of skin models are also developed within the context of Statistical Shape Analysis. The concept of mean skin model is introduced as well as a new parameterization of skin model shapes. In the continuity of this work, Schleich et al. [11] proposed a comprehensive framework for skin model simulation. The skin model considers geometric deviations that are expected, predicted or already observed in real manufacturing processes. The process of skin model simulation is split into two phases. In the early design stages geometric deviations are not yet observed but should be incorporated. Therefore, predictive assumptions on systematic and random deviations should be made. This stage is defined as the ‘‘Prediction Stage’’. During later design stages, manufacturing process simulations and prototypes of the part may be available. Thus, a skin model should take the given virtual or physical observations into consideration and simulate possible outcomes based on existing samples. This stage is called the ‘‘Observation Stage’’.

This paper investigates the fundamentals of the skin model at a conceptual and at a representation level. Paradigms for skin model through shape modelling and Requicha’s seminal work, which shaped the CAD domain, are presented in Section 2. Skin model representation and novel concepts for Statistical Shape Analysis are discussed in Section 3. An illustrative example is provided in Section 4. Finally, conclusions and perspectives are highlighted.

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2. Mathematical conceptualization of the skin model

2.1. Skin model in the context of shape modelling

Alongside with the development of CAD systems, the physical shape of manufactured product is regarded from different perspectives such as design, manufacturing and simulation. A formal definition of shape can be borrowed from Kendall's definition [12]: "Shape is all the geometrical information that remains when location, scale, and rotational effects are filtered out from an object."

It is also interesting to point out Requicha's works on the fundamentals of shape modelling for CAD systems and tolerancing. Requicha [13] introduces three levels of abstraction. The first level clarifies the universe to be modelled (the physical universe); the second level is used to analyse the problem from a mathematical point of view (the mathematical model); the third allows to understand the various issues of discretizing the elements of the mathematical universe (the representation or computational model).

In the same seminal paper, Requicha presents the properties of a solid model (mathematical level). These properties are: rigidity, homogeneous three dimensionality, finiteness, closure, finite describability, and boundary determinism. The related models are geometrical models with perfect boundary surfaces, and they are used daily in CAD systems to represent parts and assemblies (hereinafter referred to as nominal models).

Nominal model allows ensuring complex mechanical modelling and simulation and is ubiquitous throughout the product lifecycle. Nevertheless, a conceptual gap still exists between the nominal model and the physical workpiece (physical level) because geometrical deviations are not well considered. In [14], Requicha presents a theory of tolerancing, but he does not link the model of the part used to define the specification with shape modelling. The model of the part proposed in this paper, which includes geometrical deviations, is called skin model.

The premise of skin model has been presented several years ago by Ballu and Mathieu [15] using the concept of real surface of the part. At that time, the 'physical surface' of the part (physical level) and its model (mathematical level) were not clearly distinguished. Ballu and Mathieu proposed in 1995 to ISO TC 213 (Technical Committee 213: Dimensional and geometrical product specifications and verification) to introduce several concepts for GPS (Geometrical Product Specification), among which the concept of skin model. The skin model (or non-ideal surface model) has been defined in ISO 17450-1 [7] as "a model of the physical interface of the workpiece with its environment". From that time, the skin model is distinguished from the physical surface. With regard to Requicha's solid model properties, the key difference is that the describability of the skin model is infinite.

2.2. Infinite describability

A CAD model is defined by a finite number of parameters: point's coordinates, angles, lengths, control points of NURBS surfaces, etc. As expressed by Requicha, the CAD model has the property of finite describability. On the contrary, the skin model is defined by an infinite number of parameters.

Why do we need infinite description? To be able to consider all kinds of geometrical variations, the description has to be infinite. Otherwise, it is impossible to completely capture all these variations, and it is not possible to define accurately the shape by one or several mathematical equations. The skin model includes geometric defects such as orientation and position deviations, dimensional and texture defects that cannot be completely described.

How to represent the skin model? Infinite describability implies that the skin model cannot be represented in computers or by any other media. There is no corresponding representation model as described by Requicha. The skin model is purely conceptual and one can only imagine it. Obviously, finite models can be used to represent particular skin models, to produce a shape, to simulate assemblies or to represent them in a computer system. In Fig. 1, skin model is represented only for an illustrative purpose.

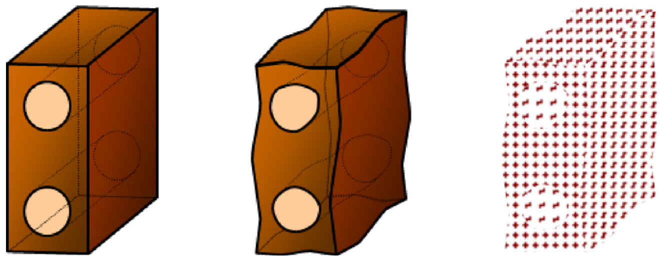

Fig. 1. Illustration of nominal model, continuous and discrete skin model.

Is it really important to have an infinite describability? We are not used to consider infinite models in mechanical engineering. Nevertheless, it is the only way to consider all the possible variations. The infinite describability of the skin model is not a problem from a theoretical point of view, as it is only a conceptualization of the workpiece, which is important to completely understand the concepts of geometrical tolerancing and the influence of geometrical defects on assemblies.

2.3. Continuous vs. discrete model

In general, the skin model is imagined as a continuous surface, but shape defects are considered at different scales of observation: macro, micro, and nano scales. At an atomic scale, a discrete model could be more realistic, and even from metrology point of view, there is a discrimination threshold inducing discretization of the measurement [16]. Nevertheless, the problem whether the model is continuous or discrete is overcome when the model is sufficiently precise to take into account all kinds of geometrical variations. When dealing with the skin model as a discrete model, the describability is finite, leading to a huge number of parameters. Thereby, the representation in a computer is unreasonable. Nevertheless, for quantitative analysis, and in particular for computational representations, a discrete model is easier to manipulate. For qualitative analysis of the skin model, in order to express geometrical specifications, or to define a verification operator in metrology, a continuous model is much easier to use and comprehend.

2.4. Mathematical classification

From a topological point of view [17], the skin model is imagined as any surface, closed (connected and without boundary) and orientable (without self-intersection). Such a surface is homeomorphic either to a sphere or a finite connected sum of tori. The number of tori (zero for a sphere) is the genus of the surface and corresponds to the number of through holes of the part. At this stage, the genus of the surface is the only way to distinguish different skin models. Indeed, the faces of the skin model are not bounded because the edges are not rough; they are rounded with fuzzy boundary and cannot be precisely defined.

Curvatures are also useful to describe and classify surfaces [18]. Curvature is a shape invariant parameter and has been classically used as a shape descriptor (both continuous and discrete mathematical models). There are many curvature-based descriptors, such as the principal curvatures, Gaussian curvature, and mean curvature [19].

2.5. Synthesis

Above all, the skin model is not unique; it is a closed, orientable surface with an infinite describability. It permits to consider all kind of geometrical defects of workpieces. This is the only model