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From solid modelling to skin model shapes: Shifting paradigms in computer-aided tolerancing

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ABSTRACT

Product design requires the consideration of geometric models and representations that reflect shape deviations and support tolerance management issues. Computer-Aided Tolerancing (CAT) systems have been developed as simulation tools for modelling the effects of tolerances on digital product simulation. However, geometric variations cannot be addressed efficiently with regard to form deviations. This paper investigates the concepts of Skin Model Shapes, which provide a finite describability and the digital representation of the Skin Model concept, and their unified discrete geometry representation. New contributions to tolerance representation and analysis are presented. Applications and perspectives for CAT systems are highlighted as well.

1. Introduction

Product modelling and solid modelling have been active research topics since the early 80s. Product modelling has emerged as a comprehensive concept for managing geometric data and semantic information during the product lifecycle [1,2]. The advent of solid modelling has contributed significantly to the use of Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and Computer-Aided Manufacturing (CAM) systems to support the digital product development process.

Even though solid models enable 3D product models to replace traditional 2D engineering drawings as the product's master representation and primary product definition data, engineering drawings are still used to convey semantic and ambiguous geometric and non-geometric information. New researches on Model-based Definition (MBD) use 3D models supplemented with tolerancing annotations by integrating drawing information directly onto a 3D product model to define product geometry and product specifications for interoperability of Product and Manufacturing Information (PMI) [3,4].

Tolerancing has become a major concern for product's functioning, the manufacturing process, and assembly. It has been a permanent and serious issue in the long history of CIRP [5]. Early researches on tolerancing mostly focus on unidirectional or bidirectional dimension chain and its tolerance allocation. Farmer and Gladman [6] analyzed how computer-based tolerancing has to adapt to the functional requirements. Fainguelernt, Weil and Bourdet depicted the role of Computer-Aided Tolerancing (CAT) systems for Process Planning [7]. Wirtz, Gächter and Wipf proposed the Vectorial Tolerancing Quality Control Loop (VT-QCL) and its computerized structure to manage geometric variations for CAD-CAM with an integrated measuring system [8].

With the continuous improvement of manufacturing processes, the geometric variations of the part and the assembly clearance between the parts have become important factors that affect product performance. Although these variations are addressed through established theories of geometric tolerancing and Geometrical Product Specifications (GPS) ISO standards, the representation of geometric deviations within CAD solid models still relies on symbolic languages and non-geometric data. Moreover, 3D product modelling and representation is mainly influenced by the consideration of idealized nominal geometry.

The Skin Model concept which stemmed from the theoretical foundations of Geometrical Product Specification and Verification has been developed to enrich the nominal geometry considering realistic physical shapes [9]. However, the digital representation of the Skin Model has been investigated only recently [10]. In a previous work [11], we investigated the fundamentals of the Skin Model, through shape and solid modelling, at a conceptual level as a new comprehensive geometric product model that supersedes the nominal solid model.

This paper investigates the concept of Skin Model Shapes that has been developed to address digital representation of "non-ideal" parts and extended to mechanical assemblies. The evolution of researches on tolerancing and the development of CAT systems are presented in Section 2. Skin Model Shapes for Computer-Aided Tolerancing are discussed in Section 3. An illustrative example of tolerance analysis based on Skin Model Shapes is provided in Section 4. Finally, conclusions and perspectives are drawn.

2. The evolution of research on Computer-Aided Tolerancing

Nowadays, the efficient execution of product development, manufacturing, and inspection activities relies inevitably on the

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extensive use of computer-aided tools for the modelling and analysis of parts, assemblies, and products as well as the simulation of manufacturing and inspection processes. However, geometric part deviations are rarely completely considered by most of these tools, even though they strongly affect the function, quality and cost of mechanical products.

In order to enable the consideration of geometric deviations already during the design of physical artefacts, CAT tools have been developed. These tools are to support the various tasks in geometric variations management, such as tolerance specification, tolerance synthesis, and tolerance analysis. In this context, particularly computer-aided tolerance analysis has gained much research attention during the last decades, since the prediction of the effects of geometric deviations on the product quality without building physical prototypes is a key issue in the design and manufacturing of high quality products at moderate costs. The available tools for computer aided tolerance analysis ground on mathematical models for the representation and analysis of geometric deviations, where it can be found, that a wide variety of models for the expression and representation of geometric deviations, geometric tolerances, and geometric requirements have been developed during the last decades.

2.1. Survey of research on tolerancing

The modelling of geometric deviations as a basis for the evaluation of their effects on the product quality is a key issue in tolerancing research. Many models have been presented including 1D or 2D tolerance stack-ups, homogeneous matrix transforms, Vectorial Tolerancing, the concept of Technologically and Topologically Related Surfaces (TTRS), the Small Displacement Torsor (SDT), the Direct Linearization Method, Deviation Domains, Tolerance Maps (T-Map), specification hull techniques, and modal decomposition, where a comprehensive overview can be found in [12,13]. Furthermore, the applicability of many deviation representation schemes for the tolerance analysis of mechanical assemblies has been extensively discussed, where it can be found, that main drawbacks of these representation schemes are the lack of form deviation considerations and the missing conformance with tolerancing standards [13–15].

The first shortcoming is illustrated in Fig. 1, where it can be seen, that most representation schemes for geometric deviations disregard form deviations. As a consequence, part feature deviations are simplified to rotational and translational imperfections, which has tremendous effects on the part representation as well as on tolerance analysis results at the assembly level. Furthermore, tolerance analysis models hardly allow a coherent and complete geometric variations management process, because they either imply uncertainties or do not allow the consideration of manufacturing and metrology aspects.

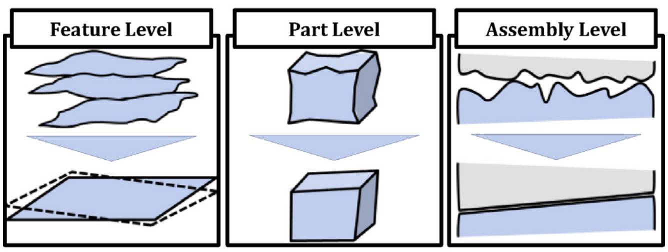

Fig. 1. Simplifications of most deviation representations for CAT.

2.2. Computer-aided tolerancing systems

Requicha's seminal work on solid modelling and tolerancing [16,17] sketched a formal description of product modelling considering geometric deviations. The variation of the position and orientation of the parts within an assembly is described through the concept of nominal assembly, while variational assembly covers part's variability and tolerances.

Early researches in tolerance-based solid modelling lead to the development of tolerance representation techniques directly integrated into the data structure of CAD systems. Those systems benefit from object-oriented environment in which specifications of each part, such as tolerances, functional requirements, the cost function or machining process, have been treated as classes with their attributes [18]. Other tolerance representation techniques, which are not directly integrated in solid modellers, have been developed to ensure a better integration of tolerancing data and related knowledge with CAD and Product Lifecycle Management (PLM) systems [19], at different design stages [20], with more expressiveness [21], improving the visualization of the simulation results [22], and supporting the semantic interoperability in assembly design [23]. At present, mainstream CAD softwares allow adding annotations on the three-dimensional model of a part. However, the tolerance specification is only attached to the ideal surface as additional information and cannot reflect the geometric deviations of the part. The FT&A workbench of CATIA® (by Dassault Systemes) provides semantics analysis functions to check the consistency between the tolerance specification and associated geometric features. The DimXpert module of SolidWorks® (by Dassault Systemes) can automatically generate the tolerance specification for individual parts, taking into account under-constrained and over-constrained situations. The other tolerance analysis software such as 3DCS® (by Dimensional Systems), eMTolMate® (by TecnoMatix/UGS/SiemensPLM), MECAmaster (by MECAmaster SARL), CETOL 6σ® (by Sigmetrix), and VisVSA® (by UGS/SiemensPLM) can calculate assembly deviations by variations of geometric parameters or Monte Carlo simulation, but cannot effectively optimize the tolerance intervals of multiple assembly dimension chains [24].

2.3. Discussion

Today, tolerance information is created as a part of the design process with support by CAD. The efficient use of commercial CAT systems depends on the expertise of the user in building a valid model that conforms to standards, ensures functional requirements, and leads to accurate and reliable results.

CAT systems are evolving along with the advancing technologies of digital product development processes, therefore ensuring a better integration with PLM systems and incorporating more semantics. Although conformance to ISO and ASME standards can be partly achieved by these systems, many issues are still to be investigated in depth, such as 3D tolerance zones, form tolerances, material condition modifiers, datum precedence, and closed form solutions through Monte Carlo simulations [25]. Moreover, in our knowledge, there is no agreed benchmark set for the evaluation and the comparison of existing CAT systems.

3. Skin model shapes for computer-aided tolerancing

3.1. The concept of Skin Model Shapes

As a response to the need for a coherent and complete language to be used in the geometric variations management process, GeoSpelling has been developed and adopted in the standards for the geometric product specification and verification (ISO 17450-1:2005 [26]). It defines a geometric specification as a condition on a characteristic, which is defined on one or multiple geometric features. These ideal or non-ideal features are obtained by various GeoSpelling operations, such as partition and extraction, from the Skin Model, which is a model of the physical interface between a workpiece and its environment comprising geometric deviations introduced by manufacturing and assembly. The idea behind the Skin Model is the clear differentiation between the part surface in the real world and its model in the abstract world. However, since an infinite description is required in order to consider all geometric deviations from a macro to a micro scale, there exists no possibility for the identification and the simulation of the Skin Model. In contrast to