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Approaches for the assembly simulation of skin model shapes☆

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HIGHLIGHTS

- Skin Model Shapes are digital part representatives comprising geometric deviations.
- Approaches for the relative positioning of point-based Skin Model Shapes are proposed.
- The approaches ground on algorithms from computational geometry and computer graphics.
- Applications for the assembly simulation in tolerancing are given.

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ABSTRACT

Even though they are weakly noticed, geometric part deviations accompany our everyday life. These geometric deviations affect the assemblability and functional compliance of products, since small part variations accumulate through large-scale assemblies and lead to malfunction as well as decreased product reliability and safety. However, the consideration of part deviations in the virtual modelling of mechanical assemblies is an ongoing challenge in computer-aided tolerancing research. This is because the resulting assembly configurations for variant parts are far more complicated than for nominal assemblies. In this contribution, two approaches for the relative positioning of point based models are highlighted and adapted to the assembly simulation of Skin Model Shapes, which are specific workpiece representatives considering geometric deviations. The first approach employs constrained registration techniques to determine the position of variant parts in an assembly considering multiple assembly steps simultaneously, whereas the second utilizes the difference surface to solve the positioning problem sequentially. The application of these approaches to computer-aided tolerancing is demonstrated, though their applicability reaches various fields of industrial geometry.

1. Introduction

Geometric deviations are inevitably observed on every manufactured workpiece [1] and affect the quality and function of mechanical products. In order to enable part interchangeability and manufacturing process independence in serial production though the presence of these deviations, geometric dimensioning and tolerancing (GD&T) has evolved as an important task in the design of physical artefacts [2]. This task comprises i.a. the definition of nominal geometric part specifications as well as their allowable limits from a functional and manufacturing point of view with the aim to ensure assembly and functional requirements [3,4].

GD&T practice has led to the need for international standards, which are to offer a toolbox for the specification and non-ambiguous interpretation of tolerancing information throughout the product life-cycle [5]. The lately revision of these standards (ISO 17450-1:2011) offers a definition of a geometric specification as a *condition on a characteristic, which is defined from geometric features* [6,7]. These features are created from the Skin Model, being a model of the physical interface between a part and its environment, by different operations, such as extraction or partition [7,8]. The aim of this basic concept is to differentiate between the physical workpiece and its model in the abstract world [8].

However, the advent of solid modelling has led to the increased use of computer-aided design (CAD), computer-aided manufacturing (CAM), as well as computer-aided tolerancing (CAT) tools in digital product development, where the latter aim at supporting the GD&T activities mainly by simulating the effects of geometric part deviations on the product requirements without the need for physical prototypes [8]. This requires the modelling and

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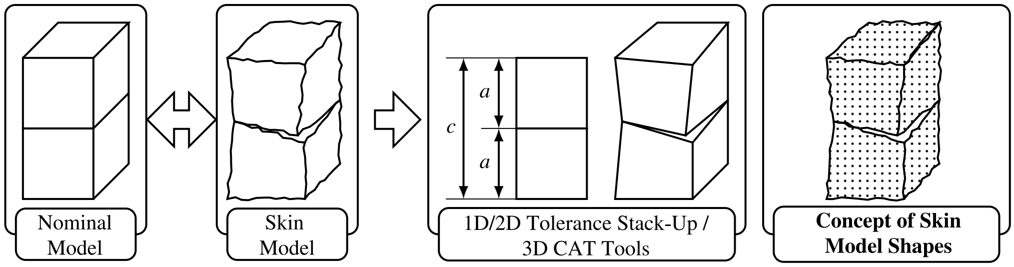

Fig. 1. Digital representation of physical artefacts for computer-aided tolerancing.

representation of geometric deviations and tolerances in such CAT tools, which is a key issue in computer-aided tolerancing research [9,10]. Despite the vast research interest in this topic, most of the existing approaches, from 1D/2D tolerance stack-ups to assembly modelling approaches for variational geometry, imply severe assumptions, since they reduce geometric deviations to translational and rotational part feature defects, and therefore lack of form deviation considerations [9–14]. This has tremendous effects on the digital feature, part, and assembly representation and leads to inadequate tolerancing decisions. Furthermore, most of these approaches are not conform to the standards for geometric product specification and verification (GPS) [15], which endorses ambiguities and misinterpretations.

In order to overcome these shortcomings of existing models for the computer-aided tolerance analysis, the concept of Skin Model Shapes has been developed, which are specific realizations of the Skin Model comprising geometric deviations brought in by manufacturing and assembly processes [16,17]. In this regard, the concept of Skin Model Shapes is a finite model in contrast to the Skin Model, which requires an infinite description to allow the consideration of all different kinds of geometric deviations from a macro to a micro scale. Though the concept of Skin Model Shapes is not linked to a specific geometry representation scheme, a discrete geometry framework for the Skin Model Shape simulation has been developed, which employs discrete geometry representations, such as point clouds and surface meshes, and aims at generating these shapes in early as well as later design stages [8,17–19]. These discrete geometry representations allow an integrated computer-aided GD&T process, since they are available throughout the product life-cycle from design, where they can be obtained from the CAD model by tessellation techniques, to manufacturing, inspection, and reverse engineering, where they are gathered from tactile or optical measurement systems [20]. Furthermore, surface models comprising discrete geometry elements, such as triangles and points, enjoy increasing attention in the computer graphics and the CAD community [21]. Fig. 1 illustrates the Nominal Model, the Skin Model, and the different digital representations of physical artefacts for computer-aided tolerancing.

The application of Skin Model Shapes to the computer-aided tolerance analysis requires models for simulating their relative positioning and assembly considering different kinds of geometric part deviations. In this context, the term "relative positioning" describes the positioning of a digital part representative relative to other part representatives in an assembly [22]. The need for such models gives rise for this contribution, where the presented approaches have a strong geometric component and are therefore closely linked to the subject of *Industrial Geometry* [23].

1.1. Related work

Various models for the assembly simulation in computer-aided tolerancing tools have been proposed, from simple 1D and 2D tolerance stack-ups [24,25] to vectorial tolerancing and the DLM method [26,27] and to approaches for the assembly constraint modelling and solving for variational part geometry [22,28,29]. A rich overview of these methods is for example given in [9,10], where it can be found, that these approaches differ in the formulation and derivation of assembly constraints and the proposed solution techniques. However, a main similarity is that they hardly allow the consideration of form deviations and are not capable of dealing with discrete geometry part representatives.

In contrast to that, local registration techniques, such as the Iterative Closest Point (ICP) framework [30] and adoptions of it [31], are widely used for the registration of 3D data point clouds to model shapes. Furthermore, alternative concepts, such as constrained registration approaches, have been developed to match broken objects [32] and to fit point clouds to surfaces in the presence of obstacles [33,34]. In these works, the constraint modelling is mainly based on local vertex normal distance computations, whereas Pierce and Rosen [35] convert the constrained optimization to an unconstrained optimization problem employing penalty functions. A similar approach for the relative positioning of surface meshes is presented in [36–38], where the objective function for the optimization is defined as the sum of projected point-to-point distances and the non-penetration requirement is checked by collision detection algorithms, which also trigger penalty terms in the objective function. Furthermore, an approach for the contact simulation of Skin Model Shapes employing constrained registration methods has been proposed in [39]. However, these registration-based approaches for the matching and relative positioning of point clouds seldom allow the consideration of assembly process characteristics, such as multiple assembly steps with different assembly directions, assembly forces, gravitational forces, or assembly constraints. This hinders their application to computer-aided tolerance analysis.

Unlike these methods, Samper et al. [40] present an approach for the assembly modelling, which is based on the difference surface computation of mating surfaces by modal analysis. Due to this modal surface decomposition for the difference surface computation employing the finite-element analysis (FEA), each two mating features have to share the same discretization, which is a strong drawback in many situations. Though, the algorithm allows the computation of the "deterministic" contact points between each two discretized variant part representations.

1.2. Main contributions and overview

In the following, two classes of approaches for the relative positioning of discrete geometry Skin Model Shapes for the application in computer-aided tolerance analysis are introduced, discussed, and compared, namely adapted registration techniques and an algorithm based on the feature difference surface. The main contributions can be found in the development of two approaches for the assembly simulation of point-cloud based Skin Model Shapes employing algorithms from registration, computational geometry, and computer graphics. These approaches are introduced and discussed, as well as applied to two case studies in the field of