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Status and Prospects of Skin Model Shapes for Geometric Variations Management

Benjamin Schleich[a,*], Nabil Anwer[b], Luc Mathieu[b], Sandro Wartzack[a]

[a]*Chair of Engineering Design KTmfk, Friedrich-Alexander-University Erlangen-Nürnberg, Martensstraße 9, 91058 Erlangen, Germany*
[b]*LURPA, ENS Cachan, Univ Paris Sud, Université Paris-Saclay, 61 Avenue du Président Wilson, 94235, Cachan, France*

[*] Corresponding author. Tel.: +49-(0)9131-85-23220; fax: +49-(0)9131-85-23222. *E-mail address:* schleich@mfk.fau.de

Abstract

Geometric part deviations, which are inevitably observed on every manufactured workpiece, have distinct effects on the assemblability as well as on the function and quality of physical artefacts. As a consequence, geometric variations management is an important issue for manufacturing companies. However, assessing the effects of form deviations already in virtual product realization remains an important challenge. This paper illustrates and summarizes the current status and development trends of the Skin Model Shape paradigm, which provides an operationalization and a digital representation of the Skin Model concept for modelling product shape variability and hence may serve as a comprehensive model for computer-aided variations management.
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Keywords: Computer-Aided Tolerancing; Skin Model Shapes; Geometric Variations Management; Virtual Product Realization.

1. Introduction

In times of fierce international competition and high requirements on the quality of mechanical products, there exists a necessity for companies to manage geometric variations along the whole product life-cycle as they distinctly affect the function and quality of mechanical assemblies [1]. In order to perform this within time and costs, computer-aided tolerancing tools support product and process development by enabling the early prediction of the effects of geometric part deviations on assembly characteristics without the need for cost and time expensive physical mock-ups. However, these established tools and their underlying mathematical approaches for the representation of geometric deviations, geometric specifications, and geometric requirements imply severe shortcomings regarding the consideration of form deviations and lack of a full conformance to international standards for the geometrical product specification and verification (GPS). With the aim to overcome these drawbacks, the concept of Skin Model Shapes has been developed, which is based on the Skin Model as a core concept of modern GPS standards and employs discrete geometry representation schemes for the representation of part geometry considering all different kinds of geometric deviations.

The aim of this paper is to present the current status as well as prospects and development trends regarding this model, where the main contribution lies in the comprehensive summary of the current development status. In this context, particularly the usefulness of Skin Model Shapes for the tolerance analysis is highlighted. The paper is structured as follows. In the next section, a brief state of the art regarding the virtual representation of geometric deviations and tolerances for computer-aided tolerance analysis with a focus on the consideration of form deviation modelling is given. Thereafter, the evolution as well as the fundamentals of the concept of Skin Model Shapes are presented. Following this, the current development status regarding the tolerance analysis based on this novel concept is highlighted and the results for an illustrative case study are discussed. Subsequently, future prospects and development trends are illustrated. Finally, a conclusion and an outlook are given.

2. Related Work

The modelling of product geometry employing computer models has gained vast attention during the last decades and the functionalities of modern computer-aided design tools have steadily increased. However, the underlying mathematical models for the representation of part geometry in these tools are suitable for modelling nominal part geometry, but imply shortcomings regarding the representation of form deviations, which are inevitably observed on every manufactured part. This

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also holds for most of the established approaches for the tolerance analysis such as the Small Displacement Torsor (SDT) [2], solid offsets [3], vector loops [4] and based thereon the direct linearization method [5], Deviation Domains [6], Polytopes [7], and T-Maps® [8], where their main shortcomings are the insufficient consideration of form deviations and the lacking conformance to international standards for the GPS [1,9].

However, the researches on form deviations modelling have adapted two main approaches. The so-called decomposition or separation methods use signal processing theories and spectral methods such as Direct Cosine Transfom, Discrete Fourier Transform, and Discrete Modal Decomposition to represent form deviations and errors as the first variation modes [10–12]. Despite their broad usefulness, they are limited to simple shapes such as planes and cylinders. Taubin [13], Vallet and Lévy [14] addressed spectral decomposition methods for general topological manifolds and used the Laplace-Beltrami Operator to solve the problem. This approach is also well adapted to discrete shapes and mesh-based representations. The other approaches for form deviations modelling use a deformation of morphing models to represent form deviations and errors [15]. The deformation can follow a physical law (elastic deformation, mass-spring, particle systems,...) or geometric considerations. Mesh deformation or morphing methods have been developed for non-rigid part tolerance analysis using free form deformation approaches [15] and FEA methods [16,17]. Other researches highlighted the non-deterministic or stochastic nature of form errors and deviations from the consideration of manufacturing processes and measurement characteristics [18]. Variability Analysis and reduction techniques such as Principal Component Analysis (PCA) have also been used to establish analytical models that highlight form deviations [19–22]. More recently, Statistical Shape Analysis techniques have been used to represent different kinds of geometric deviations from the observation and measurement of manufacturing processes and from simulation [23–25].

3. The Concept of Skin Model Shapes

As a response to the shortcomings of established models for the computer-aided modelling and representation of part geometry considering geometric deviations, the concept of Skin Model Shapes has been developed [25,26]. It is based on the Skin Model, which is a fundamental concept of modern standards for the geometrical product specification and verification and can be regarded as a model of the physical interface between a part and its environment [27]. The Skin Model concept was developed by Ballu and Mathieu [28] and is a purely conceptual, infinite model in order to allow the consideration of all kinds of geometric deviations and to enable the unambiguous definition of geometrical specifications.

As the Skin Model is an infinite model in order to allow the consideration of all different kinds of geometric deviations, it can neither be identified nor simulated. In contrast to that, Skin Model Shapes are specific outcomes of the Skin Model employing discrete geometry representation schemes, such as point clouds and surface meshes, which can hence serve as part representatives in simulations and virtual mock-ups. The difference between the nominal model, the Skin Model, and the concept of Skin Model Shapes can be seen from Fig. 1.

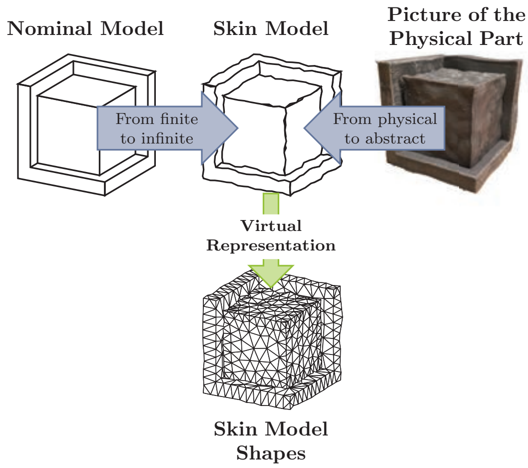

Fig. 1. The Skin Model and the Concept of Skin Model Shapes.

4. The Current Status of the Skin Model Shape Paradigm for Tolerance Analysis

The concept of Skin Model Shapes is a quite novel approach for the representation of part geometry considering geometric deviations. As it enables the representation of parts and assemblies considering deviations at different levels, such as macro, micro, or nano, it can be used for many applications in the context of virtual product realisation. However, as tolerance analysis is a key tool for supporting the tolerancing activities in design [26], the focus of ongoing research works is to enable the tolerance analysis based on Skin Model Shapes. In the following, the main procedure for the tolerance analysis based on Skin Model Shapes is highlighted and every stage of this procedure is detailed. The case study comprises three parts as can be seen from Fig. 2, where a beam is positioned on a base part according to a 3-2-1 positioning scheme [29] (three-point move in negative z-direction, two-point move in negative x-direction, and one-point move in positive y-direction), and a pin is assembled to the beam with "best-fit" condition. The single parts are specified by geometric tolerances and dimensional tolerances with material modifier as can be seen from Fig. 2 and the functional key characteristic of the assembly is the position deviation *pos* of the pin with reference to the datum system spanned by the base part. Worst-case and statistical tolerance analyses for the case study have been performed with and without consideration of form tolerances, respectively. For the worst-case analyses, the parts conform to the (maximum) specified tolerances but are randomly assembled, whereas Gaussian input probability densities for the tolerances as can be seen from Fig. 3 have been assumed for the statistical analyses. The procedure of the tolerance analysis based on Skin Model Shapes as well as the results of the analyses are highlighted and discussed in the following sections.

4.1. Procedure for the Tolerance Analysis based on Skin Model Shapes

The tolerance analysis based on Skin Model Shapes can roughly be divided in a pre-processing, a processing, and a post-processing stage [30] (see Fig. 4). In the pre-processing

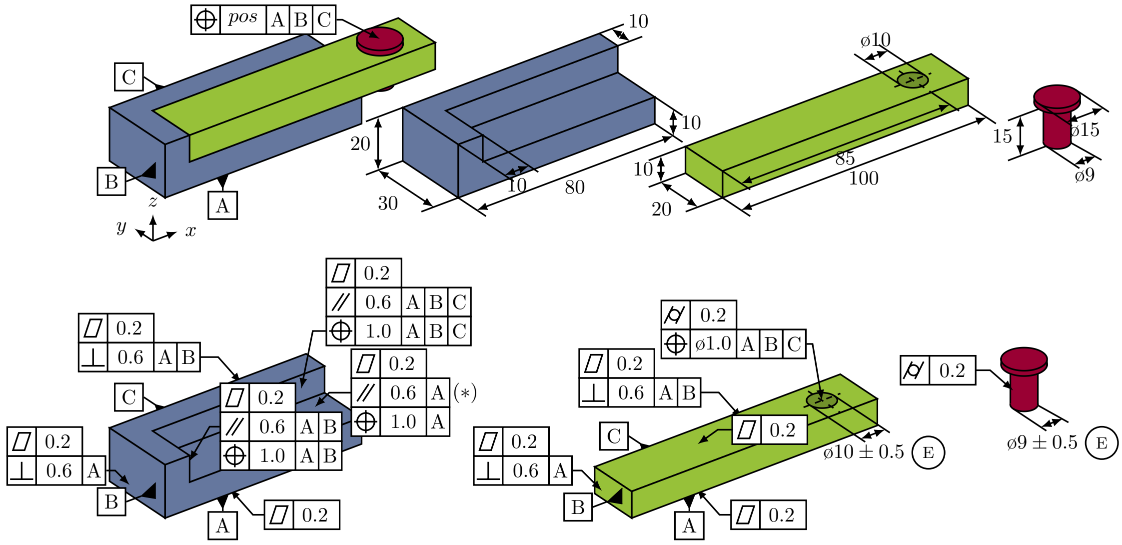

Fig. 2. Case Study: Functional Key Characteristic of the Assembly (top left), Part Measures (top right), and specified Geometric Tolerances (bottom).

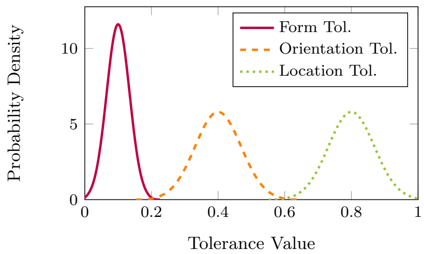

Fig. 3. Input Probability Densities for the different Tolerances.

stage, Skin Model Shapes of single parts are generated, which are then processed to compute the assembly positions and the motion behaviour in the processing stage. Finally, in the post-processing stage, the assemblies are evaluated regarding the contact quality, the functional key characteristics are measured from the resulting assemblies, and the results are visualised and interpreted. In the following, the current development status in each of these stages is highlighted and the results for the analysis of the case study are discussed.

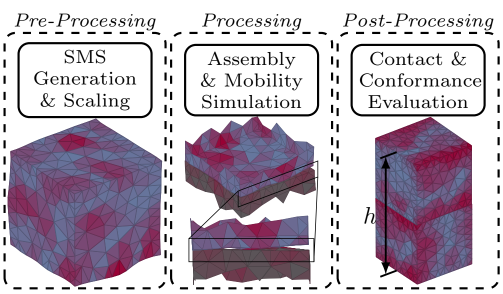

Fig. 4. Procedure of the Tolerance Analysis based on Skin Model Shapes.

4.2. Pre-Processing: Generation and Scaling of Skin Model Shapes

In order to perform a tolerance analysis, firstly Skin Model Shapes have to be generated. In early stages of virtual product realisation, this is performed based on predictions about the expected part deviations. In this regard, systematic part deviations can be modelled e. g. using second order shapes (quadrics) [25] or Fourier series [31]. Moreover, random geometric deviations, which are added to the systematic part deviations, can be simulated by Gaussian random fields [25,32] or similar approaches. In contrast to that, at least few observations of parts with geometric deviations are available in later design stages, for example as a result of manufacturing process simulations or part prototypes. These few observations can be used to extract the systematic as well as random geometric deviations by statistical shape analysis or other decomposition methods, such as natural mode decomposition, and to finally obtain a large set of Skin Model Shapes by sampling on the extracted modes.

As the aforementioned approaches for the generation of Skin Model Shapes not necessarily lead to part representatives, which conform to specified tolerances, the obtained Skin Model Shapes have to be "scaled" [33] (see Fig. 5). This is performed using algorithms from computational metrology [34,35] for the evaluation of geometric tolerances from point clouds, which are adapted to allow the manipulation of these point clouds, so that they conform to pre-defined tolerance specifications [33]. In this context, the concept of Skin Model Shapes allows the processing of points according to GPS standards [36].

In order to illustrate the results of the part scaling, the parallelism tolerance of the base part ($*$) in Fig. 2 is considered. Fig. 6 shows the introduced orientation defects around the x- and y-axis as components of the Small Displacement Torsor [2] r_x and r_y for the toleranced plane feature according to Fig. 2. It can be seen, that a regular rhombus is obtained for the worst-

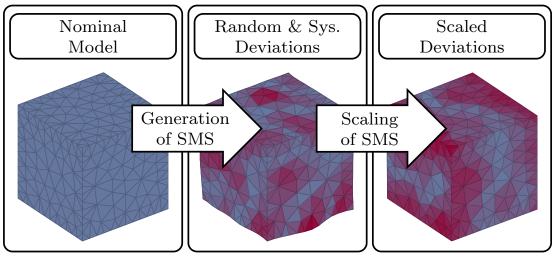

Fig. 5. Generation and Scaling of Skin Model Shapes.

case where the form deviations of the feature are nil, whereas an irregular rhombus results when form deviations are considered. This is because the parallelism tolerance zone comprises the form deviations according to GPS standards. Thus, the allowed orientation defects (i. e. feature rotations) are decreased by the form deviations of the plane feature. Furthermore, irregular rhombi are obtained when considering Gaussian input probabilities for the tolerances for the analysis with as well as without form tolerance considerations, respectively. Again, it can be seen, that the obtained rhombus for the case where form deviations are considered is slightly smaller than for the case where the form deviations are nil, since the form deviations decrease the allowed orientation defects.

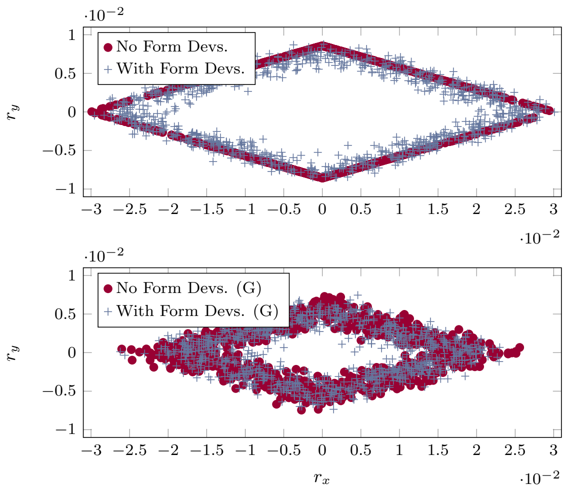

Fig. 6. Introduced Orientation Defects for the Parallelism Tolerance (∗) with and without consideration of Form Tolerances. Top shows the Worst-Case Computation, Bottom the Analysis with Gaussian Input Densities.

4.3. Processing: Assembly and Mobility Simulation

As the Skin Model Shapes have been generated and scaled, they have to be assembled according to the positioning scheme. In order to perform this, two approaches have been developed, where the first one employs the difference surface between two mating parts to calculate the contact points in a specified assembly direction, whereas the relative positioning problem is formulated as a constrained registration problem and solved using mathematical optimization in the second approach [30,37]. The relative positioning approach based on the difference surface identifies the contact points between two parts from their difference surface (see Fig. 7) and enables the assembly simulation for a 3-2-1 positioning scheme by iteratively repeating the single assembly steps [37]. In contrast to that, the constrained registration approach uses mathematical optimization methods to minimize the sum of projected distances between the set of points in the moving part and their correspondences in the mating part (see Fig. 8), such that these projected distances do not take negative values. This approach is well suited for the assembly simulation of best-fit conditions, as for example loose fits [37]. In the studied example, the 3-2-1 positioning of the beam onto the base part is simulated using the difference surface approach, whereas the assembly of the pin in the beam is performed employing the constrained registration approach. A resulting assembly of the case study considering form tolerances can be seen from Fig. 9.

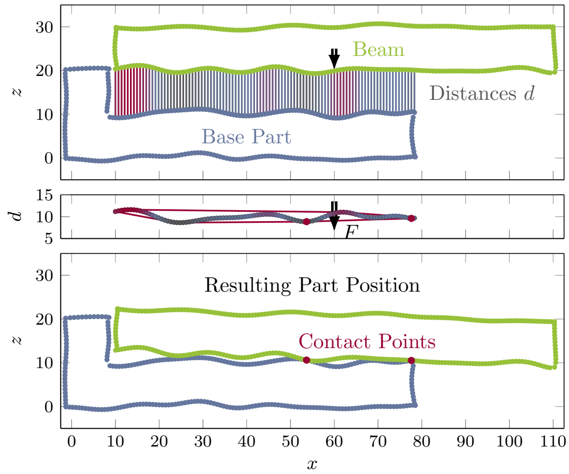

Fig. 7. Relative Positioning of the Beam on the Base Part employing the Difference Surface Approach: The Difference Surface is obtained by mapping the Part Distances d along the Assembly Direction (negative z-direction in the global coordinate system according to Fig. 2) onto the Point Coordinates. Its Convex Hull is then intersected with the Assembly Vector F to identify the Contact Points.

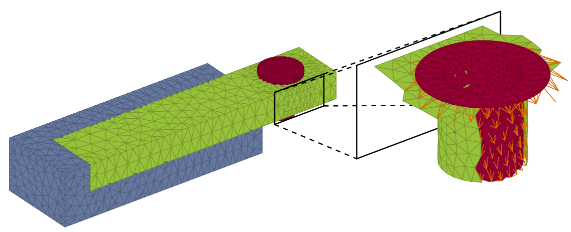

Fig. 8. Correspondences of the Pin in the Beam (Non-Interference) for the Relative Positioning using the Constrained Registration Approach.

The proposed approaches for the assembly simulation of Skin Model Shapes can be applied for the tolerance analysis of static assemblies, but can also be used for the motion tolerancing by quasi-statically repeating the assembly simulation with varying initial part positions. Furthermore, purpose-developed approaches for the contact simulation [38] or the tooth contact analysis [32] have been developed and can be used for the tolerance analysis of mechanism employing Skin Model Shapes.

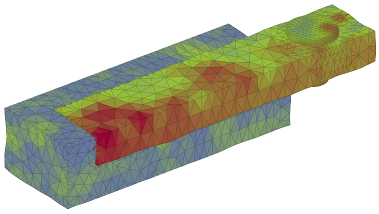

Fig. 9. Resulting Assembly of the Case Study with magnified Form Deviations.

4.4. Post-Processing: Comparison for Conformance and Contact Quality Evaluation

Similarly to the evaluation of geometric deviations on the part level, the evaluation of functional key characteristics from the simulated assemblies is performed using approaches from computational geometry. In this context, the Skin Model Shape paradigm enables the facile measurement of geometric assembly characteristics as well as of physically relevant measures, such as minimal gaps or maximal distances. Furthermore, the contact quality between the assembled parts can be evaluated using point projection methods to obtain the projected distances between the parts, which are then analysed [37].

The resulting kernel density estimates of the functional key characteristic *pos* for the case study can be seen from Fig. 10, where it can be found that the consideration of form deviations leads to a slightly increased position deviation *pos* in both the worst-case as well as the statistical analysis. This is because the form deviations, in fact, lead to decreased orientation defects on the part level (see Fig. 6), but to increased orientation defects on the assembly level due to irregular contact points between the parts. This can also be seen from Fig. 11, where the positions of a selected node on the bottom surface of the pin are shown. The consideration of form deviations leads to a wider range of position deviations due to increased orientation defects of the pin with reference to the base part. The two clusters of points for the worst-case analysis without form deviations (Fig. 11, top left) result from the two possible results of the part scaling for the position tolerances of the base part and the beam (i. e. minimum part length vs. maximal part length).

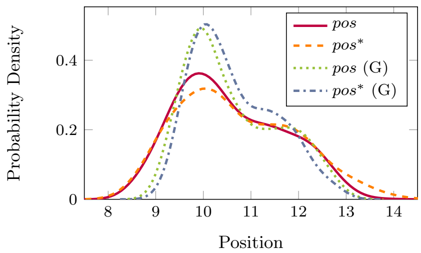

Fig. 10. Probability Densities of the Pin Position *pos* according to Fig. 2 with (*) and without Form Tolerances. (G) indicates the statistical Tolerance Analysis with Gaussian Input Probability Densities.

5. Development Trends and Future Prospects

The concept of Skin Model Shapes origins from the Skin Model as a fundamental concept in modern GPS standards.

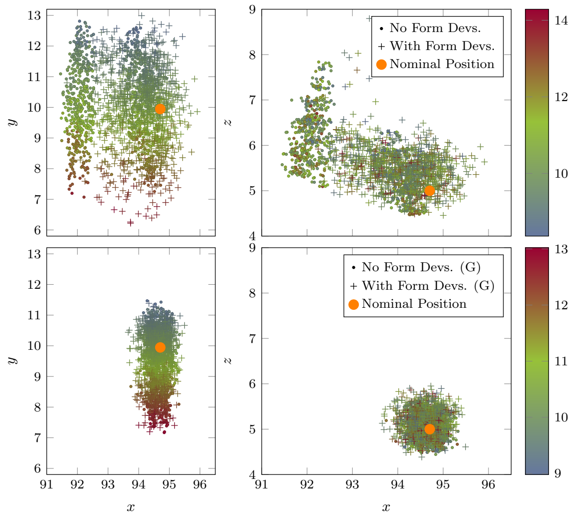

Fig. 11. Coordinates of a selected Node on the bottom of the Pin in the global coordinate system (see Fig. 2). Top shows the Results of the Worst-Case and bottom of the Statistical Tolerance Analysis, Colours indicate the Position Deviation *pos* of the respective Sample.

Consequently, the previous research works were dedicated to modelling and visualizing geometric deviations employing point-based models, and focused on establishing a tolerance analysis theory employing this novel concept in order to enable the assessment of various kinds of geometric deviations on assembly and functional requirements in conformance to international standards. However, in this context, some issues need to be investigated more in detail, such as the improved contact quality evaluation, the tolerance analysis of complex and compliant parts as well as over-constrained mechanism, the consideration of thermo-mechanical strains and deformations, and improved computational methods for the worst-case and statistical evaluation of the algorithms used in pre-processing and processing stages. Moreover, approaches for the sensitivity analysis considering form tolerances are to be developed, where moment-independent sensitivity indices [39] seem best suited for capturing the effects of different types of tolerances on functional key characteristics.

Beside this, novel manufacturing processes, particularly processes of additive manufacturing, hold challenges for all activities of geometric variations management, such as the tolerance specification, analysis, and verification [40]. In this regard, the concept of Skin Model Shapes offers vast potential for the computer-aided support of these activities by providing a versatile modelling platform.

Beyond that, the concept of Skin Model Shapes may serve as a basic model for engineering design considering not only geometric but also other kinds of deviations, such as varying material properties and wear, in the future.

6. Conclusion and Outlook

The management of geometric deviations along the product life-cycle is of high importance for modern companies. Thus, tolerance analysis is a key tool in virtual product realization, as it allows the early assessment of the effects of geometric deviations on the product quality. In this regard, the concept of Skin Model Shapes is a novel approach for the computer-aided representation of product geometry considering all kinds of geometric deviations.

The aim of this paper was to present the current status of the Skin Model Shape paradigm for tolerance analysis and to highlight future prospects and development trends. In this context, it can be found, that the tolerance analysis based on Skin Model Shapes can be divided in three stages, where different algorithms from computational geometry have been developed for each of these stages. They allow the generation and scaling of Skin Model Shapes, which conform to specified geometric tolerances, the simulation of their assembly, and the measurement of key characteristics from these assemblies. Based on the obtained results, it can be found, that the consideration of form tolerances leads to a more realistic prediction of functional key characteristics.

However, future research works are required in order to advance this concept for tolerance analysis and other computer-aided engineering applications. This will finally allow the holistic virtual representation of product behaviour considering deviations from different domains.

References

[1] Mathieu, L., Ballu, A.. A model for a coherent and complete tolerancing process. In: Davidson, J., editor. Models for Computer Aided Tolerancing in Design and Manufacturing. Springer Netherlands. 2007, p. 35-44.

[2] Bourdet, P., Mathieu, L., Lartigue, C., Ballu, A.. The concept of the small displacement torsor in metrology. In: Ciarlini, P., Cox, M.G., Pavese, F., Richter, D., editors. Advanced Mathematical Tools in Metrology II. World Scientific Publishing Company; 1996, p. 110-122.

[3] Requicha, A.A.G.. Toward a theory of geometric tolerancing. Int. J. Rob. Res. 1983;2(45):45-60.

[4] Gao, J., Chase, K., Magleby, S.. Generalized 3-d tolerance analysis of mechanical assemblies with small kinematic adjustments. IIE Transactions 1998;30(4):367-377.

[5] Wittwer, J.W., Chase, K.W., Howell, L.L.. The direct linearization method applied to position error in kinematic linkages. Mech. Mach. Theory 2004;39(7):681 - 693.

[6] Giordano, M., Samper, S., Petit, J.. Tolerance analysis and synthesis by means of deviation domains, axi-symmetric cases. In: Davidson, J., editor. Models for Computer Aided Tolerancing in Design and Manufacturing. Springer Netherlands. 2007, p. 85-94.

[7] Homri, L., Teissandier, D., Ballu, A.. Tolerance analysis by polytopes: Taking into account degrees of freedom with cap half-spaces. Comput.-Aided Des. 2015;62:112 - 130.

[8] Ameta, G., Samper, S., Giordano, M.. Comparison of spatial math models for tolerance analysis: Tolerance-maps, deviation domain, and ttrs. J. Comput. Inf. Sci. Eng. 2011;11(2):021004-021004.

[9] Hong, Y., Chang, T.. A comprehensive review of tolerancing research. Int. J. Prod. Res. 2002;40(11):2425–2459.

[10] Huang, W., Ceglarek, D.. Mode-based decomposition of part form error by discrete-cosine-transform with implementation to assembly and stamping system with compliant parts. CIRP Ann. 2002;51(1):21 - 26.

[11] Huang, W., Liu, J., Chalivendra, V., Ceglarek, D., Kong, Z., Zhou, Y.. Statistical modal analysis for variation characterization and application in manufacturing quality control. IIE Transactions 2014;46(5):497-511.

[12] Samper, S., Formosa, F.. Form defects tolerancing by natural modes analysis. J. Comput. Inf. Sci. Eng. 2006;7(1):44-51.

[13] Taubin, G.. A signal processing approach to fair surface design. In: Proceedings of the 22Nd Annual Conference on Computer Graphics and Interactive Techniques. SIGGRAPH '95; ACM. 1995, p. 351-358.

[14] Vallet, B., Lévy, B.. Spectral geometry processing with manifold harmonics. Computer Graphics Forum 2008;27(2):251-260.

[15] Franciosa, P., Gerbino, S., Patalano, S.. Simulation of variational compliant assemblies with shape errors based on morphing mesh approach. Int. J. Adv. Manuf. Technol. 2011;53(1-4):47-61.

[16] Liu, S.C., Hu, S.J.. Variation simulation for deformable sheet metal assemblies using finite element methods. J. Manuf. Sci. Eng. 1997;119(3):368-374.

[17] Ceglarek, D., Shi, J.. Tolerance analysis for sheet metal assembly using a beam-based model. In: ASME, , editor. ASME Design Engineering Division Publication (1997 ASME International Mechanical Engineering Congress and Exposition); vol. 94. 1997, p. 153-159.

[18] Colosimo, B.M., Mammarella, F., Petrò, S.. Quality control of manufactured surfaces. In: Lenz, H.J., Wilrich, P.T., Schmid, W., editors. Frontiers in Statistical Quality Control 9. Physica-Verlag. 2010, p. 55-70.

[19] Hu, S.J., Wu, S.M.. Identifying sources of variation in automobile body assembly using principal component analysis. Transactions of NAMRI/SME 1992;20:311-316.

[20] Colosimo, B.M., Pacella, M.. On the use of principal component analysis to identify systematic patterns in roundness profiles. Qual. Reliab. Eng. Int. 2007;23(6):707-725.

[21] Camelio, J.A., Hu, S.J., Marin, S.P.. Compliant assembly variation analysis using component geometric covariance. J. Manuf. Sci. Eng. 2004;126(2):355-360.

[22] Lindau, B., Lindkvist, L., Andersson, A., Söderberg, R.. Statistical shape modeling in virtual assembly using pca-technique. J. Manuf. Syst. 2013;32(3):456 - 463. Assembly Technologies and Systems.

[23] Matuszyk, T.I., Cardew-Hall, M.J., Rolfe, B.F.. The kernel density estimate/point distribution model (kde-pdm) for statistical shape modeling of automotive stampings and assemblies. Rob. Comput. Integr. Manuf. 2010;26(4):370 - 380.

[24] del Castillo, E.. Statistical shape analysis of manufacturing data. In: Colosimo, B.M., Senin, N., editors. Geometric Tolerances. Springer London. 2011, p. 215-234.

[25] Schleich, B., Anwer, N., Mathieu, L., Wartzack, S.. Skin model shapes: A new paradigm shift for geometric variations modelling in mechanical engineering. Comput.-Aided Des. 2014;50:1 - 15.

[26] Anwer, N., Schleich, B., Mathieu, L., Wartzack, S.. From solid modelling to skin model shapes: Shifting paradigms in computer-aided tolerancing. CIRP Ann. 2014;63(1):137 - 140.

[27] Anwer, N., Ballu, A., Mathieu, L.. The skin model, a comprehensive geometric model for engineering design. CIRP Ann. 2013;62(1):143 - 146.

[28] Ballu, A., Mathieu, L.. Analysis of dimensional and geometrical specifications: standards and models. In: 3rd CIRP Seminar on Computer-Aided Tolerancing, Cachan, France. 1993, p. 157-170.

[29] Söderberg, R., Lindkvist, L., Carlson, J.S.. Managing physical dependencies through location system design. J. Eng. Des. 2006;17(4):325-346.

[30] Schleich, B., Anwer, N., Mathieu, L., Wartzack, S.. Contact and mobility simulation for mechanical assemblies based on skin model shapes. J. Comput. Inf. Sci. Eng. 2015;15(2):021009-021009.

[31] Henke, R., Summerhays, K., Baldwin, J., Cassou, R., Brown, C.. Methods for evaluation of systematic geometric deviations in machined parts and their relationships to process variables. Precis. Eng. 1999;23(4):273 - 292.

[32] Schleich, B., Wartzack, S.. A discrete geometry approach for tolerance analysis of mechanism. Mech. Mach. Theory 2014;77:148 - 163.

[33] Schleich, B., Wartzack, S.. Evaluation of geometric tolerances and generation of variational part representatives for tolerance analysis. Int. J. Adv. Manuf. Technol. 2015;79(5-8):959-983.

[34] Srinivasan, V.. Computational metrology for the design and manufacture of product geometry: A classification and synthesis. J. Comput. Inf. Sci. Eng. 2006;7(1):3-9.

[35] Zhang, X., Jiang, X., Forbes, A.B., Minh, H.D., Scott, P.J.. Evaluating the form errors of spheres, cylinders and cones using the primal–dual interior point method. Proc. Inst. Mech. Eng., B J. Eng. Manuf. 2013;227(5):720-725.

[36] Ballu, A., Bourdet, P., Mathieu, L.. The processing of measured points in coordinates metrology in agreement with the definition of standardized specifications. CIRP Ann. 1991;40(1):491 - 494.

[37] Schleich, B., Wartzack, S.. Approaches for the assembly simulation of skin model shapes. Comput.-Aided Des. 2015;65:18 - 33.

[38] Schleich, B., Wartzack, S.. Tolerance analysis of rotating mechanism based on skin model shapes in discrete geometry. Procedia CIRP – 13th CIRP Conference on Computer-Aided Tolerancing 2015;27:10 - 15.

[39] Borgonovo, E.. A new uncertainty importance measure. Reliab. Eng. Syst. Saf. 2007;92(6):771 - 784.

[40] Ameta, G., Lipman, R., Moylan, S., Witherell, P.. Investigating the role of geometric dimensioning and tolerancing in additive manufacturing. J. Mech. Des. 2015;137(11):111401-1-111401-10.