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Editorial:

Key research on computer aided tolerancing*

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Computer aided tolerancing (CAT) covers a wide range of subjects including specification and standardization, tolerancing in design/manufacturing process/product life management, verification and metrology, and functional tolerancing.

Dimensioning and tolerancing standards originated about 77 years ago in the form of various national and company standards that governed engineering drafting and documentation practices. These standards have evolved and their rapid development has brought about many significant changes to tolerancing in design and manufacturing. The release of ISO 14405-1:2010 (ISO, 2010) has introduced a rich new set of size specification modifiers, which includes two-point and spherical local sizes least squares, maximum inscribed and minimum circumscribed associations, and calculated diameters. Morse *et al.* (2012) present "size" as a fundamental engineering notion from several viewpoints, trace its evolution in engineering drawings, and discuss the implications of the use of size modifiers.

Many researchers have devoted their efforts to tolerancing modeling. Davidson *et al.* (2002) develop a tolerance maps (T-Maps) (Patent No. 6963824) model that is a hypothetical Euclidean volume of points, the shape, size, and internal subsets of which represent all possible variations in size, position, form, and orientation of a target feature. Jiang *et al.* (2014) describe the use of T-Maps and manufacturing maps (M-maps) to establish analytical relationships among all relevant design and machining tolerances for the transfer of cylindrical data. Clément *et al.* (1991) introduce a small displacement torsor (SDT) model using six small displacements to represent the position and orientation of an ideal surface in relation to another ideal surface in a kinematic way. Giordano *et al.* (2007) apply deviation domains to axi-symmetric cases and thus reduce the space to three dimensions at the maximum instead of six in the general case. Desrochers *et al.* (2003) put forward a unified Jacobian–Torsor model which combines the advantages of the torsor model and the Jacobian matrix. Ghie *et al.* (2010) describe how the same set of interval-based deterministic equations can be used in a statistical context. Anwer *et al.* (2013) investigate the fundamentals of the skin model at a conceptual, geometric, and computational level and present representation and simulation issues for product design. In another paper (Anwer *et al.*, 2014), they investigate the concept of skin model shapes that has been developed to address digital representation of "non-ideal" parts and extended to mechanical assemblies. This concept is an interesting solution for tolerance analysis in the same way of finite element analysis, inspection analysis, and other analysis in mechanical engineering based on discrete geometry.

Tolerance analysis, as an essential element in industry, carries considerable weight in concurrent engineering, and represents the best way to solve

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problems in order to ensure higher quality and lower costs. Dantan *et al.* (2013) deal with tolerance analysis formulation, more particularly, with the uncertainty that must be taken into account in the foundation of this formulation. Walter *et al.* (2013) consider an extension of the existing "integrated tolerance analysis of systems in motion" approach. Mansuy *et al.* (2011) present an original method that enables us to develop specifications based on standards and calculate tolerances for the case of serial assembly (stacking) without clearances. This method is based on the use of influence coefficients to obtain the relationship between the functional tolerance and tolerances associated with the geometry of the mechanism's interface surfaces. Qureshi *et al.* (2012) propose a statistical tolerance analysis approach for an over-constrained mechanism based on optimization and Monte Carlo simulation. Bruyère *et al.* (2007) propose an approach for analyzing tolerances that includes a vectorial dimensioning and tolerancing model. This allows gear conventional tolerancing practice and geometric tolerancing practice, a digital simulation based on tooth contact analysis and Monte Carlo simulation. Gao *et al.* (1998) introduce a direct linearization method (DLM) based on the first order Taylor series expansion of vector-loop-based assembly models which use vectors to represent either component or assembly dimensions. Worst-case tolerance analysis gives results that are overly pessimistic, resulting in the increasing cost of products. Statistical tolerance analysis takes the statistical behavior of manufacturing variations into consideration. Statistical tolerancing is a more practical and economical way of looking at tolerances and works on setting the tolerances so as to ensure a desired yield. By permitting a small fraction of assemblies to not assemble or function as required, an increase in tolerance for individual dimension may be obtained, and in turn manufacturing costs may be reduced significantly (Nigam and Turner, 1995). Statistical tolerancing methods or approaches include the root-sum-squares (RSS) method (Bender, 1968), system moments (Evans, 1975a; 1975b), quadrature (Evans, 1971; 1972), the reliability index (Parkinson, 1982; Lee and Woo, 1990), the Taguchi method (Taguchi, 1978; D'Errico and Zaino, 1988), and Monte Carlo simulations (Bruyère *et al.*, 2007; Dantan and Qureshi, 2009; Wu *et al.*, 2009; Qureshi *et al.*, 2012).

Quality control, verification, and metrology have been the focus of manufacturing enterprises. In the scope of quality control, accurate evaluation of measurement uncertainties is a real challenge in improving the use of coordinate measuring machines (CMM). Ballu and Mathieu (1996) propose a univocal expression of functional and geometrical tolerances for design, manufacturing, and inspection. This language has been retained by ISO for the future geometrical product specification (GPS) standards ISO 17450-1:2005 (ISO, 2005). Sprauel *et al.* (2003) describe a new method, based on a statistical approach to the problem, to deduce instantaneous measurement uncertainties directly from the set of acquired coordinates. Krämer and Weckenmann (2010) describe the fusion of multi-energy stacks to measure objects of high aspect ratios and parts consisting of different absorbing materials. Savio *et al.* (2002) compare two different experimental methods for establishing the traceability of freeform measurements on coordinate measuring machines: (i) uncertainty assessment using nodular freeform gauges, and (ii) uncertainty assessment using uncalibrated objects. They demonstrate the feasibility of the two approaches for freeform geometries through the calibration of a turbine blade. Moroni and Petrò (2014) propose a model for evaluation of the overall inspection cost based on uncertainty evaluation, and propose two methodologies for evaluating the uncertainty.

Functional tolerancing has now been well accepted by industry and become a major field of interest for academia. Mcadams (2003) develops tolerance design principles through a careful study of the literature, observation of commonly recurring tolerance solutions, and design strategies implied by the existing tolerance design literature. These principles provide a focus for developing new methodologies that will have high impact on engineering practice. Islam (2004) describes the development of a prototype software package for solving functional dimensioning and tolerancing (FD&T) problems in a concurrent engineering environment. Hunter *et al.* (2008) use a functional tolerance model providing a complete framework to define the geometric dimensioning and tolerancing and its relationship with the part geometry and the inspection process in order to establish a connection between a computer aided design and computer aided inspection system. Yang *et al.* (2013) make a brief comparison of existing 3D functional tolerance analysis models, and propose a statistical tolerancing approach based on variation of point-set. Cao *et al.* (2013) propose a scheme for functional specification in accordance with the new generation of geometrical product specifications. To study the functional tolerance specification methods consistent with the new generation of GPS, Yang *et al.* (2010) study the class of positioning joints of part assembling and the principle of determining its priority on the basis of definition of invariance class of GPS. In this paper, a new functional tolerancing method from geometrical functional requirement to geometrical specification is presented. Etienne *et al.* (2008) propose an approach in order to allocate the functional tolerances that provide the best ratio between functional performances and manufacturing cost.

The CIRP (International Academy for Production Engineering) Conference on Computer Aided Tolerancing (CAT) is initiated and supported scientifically every two years by two CIRP Scientific Technical Committees (STCs): Design (STC Dn) and Precision Metrology (STC P) to address the emerging problems of CAT, which has a prominent role at the interface between product design and manufacturing. The 13th CIRP CAT Conference held at Zhejiang University, Hangzhou, China during May 11–14, 2014 was the successor to the twelve earlier conferences held in Israel (1989), the USA (1991; 2003; 2005), France (1993; 2001; 2009), Japan (1995), Canada (1997), the Netherlands (1999), Germany (2007), and the UK (2012).

Note that the evolution of CAT involves far more than the results or research mentioned above and benefits from the efforts of people from many different cultures and backgrounds. We are pleased to publish in this special part issue a selection of six papers that were presented at the conference in Hangzhou. These papers cover a wide spectrum of current international research in CAT.

For purposes of automating the assignment of tolerances during design, a math model, called the T-Map, has been produced for most of the tolerance classes that are used by designers. Like deviation domains, T-Map is a hypothetical Euclidean volume which represents all possible deviations in size, orientation and position of a feature. The paper titled "Tolerance-Maps for line-profiles constructed from Boolean intersection of T-Map primitives for arc-segments" proposes a method to produce a T-Map for the complete line profile of any shape. The method firstly decomposes a profile into segments, then creates a solid-model T-Map primitive for each, and finally combines these by Boolean intersection to generate a T-Map of the profile.

Tolerance analysis is attracting increasing attention from different disciplines. In the paper titled "An iterative statistical tolerance analysis procedure to deal with linearized behavior models" analyzes the impact of a linearization strategy on the probability of failure estimation, and proposes an iterative procedure for the assembly requirement in order to provide accurate results without driving the entire Monte Carlo simulation. In the paper titled "A statistical method to identify main contributing tolerances in assemblability studies based on convex hull techniques" the authors propose a method to adopt a global sensitivity analysis based on deviation domains to obtain recommendations for optimizing tolerance values and apply the method to assemblability studies.

Tolerances influence the quality of manufacturing surfaces. The paper titled "Effects of geometric and spindle errors on the quality of end turning surface" develops an integrated volumetric error model applied to a lathe by the method of rigid body dynamics and homogeneous coordinate transformation. After the simulated surface is generated by a linear mapping of the volumetric errors on the ideal turning surface, the effect of volumetric errors on the precision and quality of the turning surface is analyzed. Since such errors affect quality, in the paper titled "An adaptive design method for understanding tolerance in the precision stamping process", the authors propose an adaptable control method for tolerance. Fluctuations of tolerance are analyzed which are caused by precision stamping elements in the manufacturing process firstly. Then, the condition-driven adaptive control system is constructed based on the monitoring system and hydraulic control system. Thirdly, executive parameters (such as velocity, pressure, gaps, etc.) are calculated in the control module. Then stamping tolerances of precision parts are ensured accuracy in precision stamping process.

Linear convolution and morphological (nonlinear) operations are two kinds of operations that have wide applications in the field of surface measurement. The paper titled "A theoretical insight into morphological operations in surface measurement by introducing the slope transform" introduces a counterpart transform, called the slope transform, which provides the analytical ability for morphological operations and offers a deeper understanding of morphological operations in surface measurement. By investigating the slope and curvature change, the slope transform can offer a deeper understanding of morphological operations in surface measurement.

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中文概要

题　目： 计算机辅助公差设计中的关键问题研究

概　要： 作为机械产品设计和制造过程中的一项重要内容，计算机辅助公差设计（CAT）是 CAD/CAPP/CAM 集成的关键技术，是国内外先进制造技术发展中亟需解决的问题。计算机辅助公差设计覆盖面非常广泛，涵盖公差规范和标准化、设计/制造工艺/产品生命周期管理中的公差设计、检测与测量以及功能公差设计。本文首先简要分析这些热点问题的研究进展情况，其次介绍本专辑收集的第 13 届国际生产工程科学院计算机辅助公差设计会议中的最新研究成果，分析该领域的最新研究进展，希望能帮助读者了解相关研究工作并促进研究人员开展讨论，进一步实现计算机辅助公差设计中的关键技术的突破，促进 CAD/CAPP/CAM 的集成。

关键词： 计算机辅助公差设计；公差规范与标准；公差设计；检测与测量；功能公差设计

Introducing Guest Editors-in-Chief:

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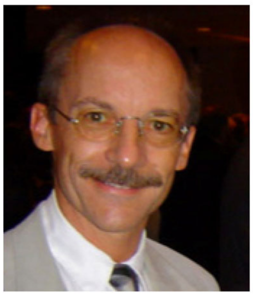
Dr. Yan-long CAO received his PhD degree in Mechanical Engineering in 2003 from Zhejiang University, China. Dr. CAO was a postdoctoral fellow from 2003 to 2005 at Zhejiang University, and a visiting scholar (2007–2009) at the University of Huddersfield, UK. In 2005, he joined Zhejiang University, where he is an active faculty member in teaching and research and was promoted to associate professor and full professor in 2005 and 2012, respectively. Dr. CAO currently is a professor of mechanical engineering at the School of Mechanical Engineering, Zhejiang University, leading his Tolerancing and Measurement Group with research interest in computer aided tolerancing and precision measurement. His research was supported by more than ten research grants, including the National Natural Science Foundation of China (NSFC). As an author and co-author, he has published more than 60 peer-reviewed journal papers and 10 conference papers, and has had about twenty patents in China approved.

Currently, Dr. CAO serves as the member of National Gear Standardization Technical Committees of China (TC52) and Member of National GPS Standardization Technical Committees of China (SAC/TC240).



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