Geometric Variations Management: New Challenges and Opportunities

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• Introduction
The Ubiquity of Geometric Variations

SPECIFICATION

Geometrical requirements

Functional requirements

Manufacturing and Assembly

Deviations

Variability

Design

Inspection and Testing

Real part

Uncertainty

Assembly process

Inspection Process Planning

Process Planning

Manufacturing requirements

Manufacturing specifications

VerIFICATION
Geometric Variations Management

- Parts/Assemblies are specified with geometrical deviations, variability and uncertainties
  - Functional Requirements are mapped to admissible geometrical and dimensional deviations
  - Part-to-part variability (Manufacturing Imprecision Axiom)
  - Deviations/Variability assessment (Measurement Uncertainty Axiom)

- There is an urgent need of
  - Model that covers all the Product Lifecycle
  - Representation and Computational Theories
  - Integration with actual CAX tools
  - Standardization

- Benefits
  - Improve product quality,
  - Decrease the manufacturing cost,
  - Reduce scrap in production (eco-aware), and product recalls (Toyota).
Geometrical Product Specification and Verification (GPS)

- "Chain of standards" in the field of macro and micro geometry specifications covering dimensional and geometrical tolerancing, surface properties and the related verification principles, measuring equipment and calibration requirements.

- Extended Uncertainty to describe the ambiguity (description of the Function, Specification) and Measurement Uncertainty.

- Cover the basic layout and explanation of drawing indications (GD&T).

- Features and Operations.

- Harmonize specification with verification of product tolerances.
• Research on Tolerancing
Research on Tolerancing

- Tolerance analysis has been the most popular research topics in recent decades
- Geometric variations interaction and accumulation
  - Mathematical representation of deviations and interfaces
  - Spatial tolerance propagation

Keyword analysis of CIRP CAT proceedings (1989-2012)*

* O. Rique Garaizar, N. Anwer, L. Mathieu, L. Qiao
Exploring the proceedings of CAT CIRP Seminars and Conferences: A scientometric analysis (Keynote paper)
13th CIRP Conference on Computer Aided Tolerancing (CAT 2014), Hangzhou, China, May 11-14, 2014
Evolution of Research

Many methods and mathematical models
- Vectorial/Matrix models
- Substituted surfaces Models (no form errors)
- TTRS, SDT, Polytopes, Domains and Tolerance maps
- Shapes and their Statistics

Few holistic approaches
- Vectorial Tolerancing
- TTRS/SDT
- Tolerance Maps
- Skin Model Shapes

Various Research Efforts in Tolerance Analysis
- Conformance (ISO, ASME)
- Dimensionality (1D, 2D, 3D)
- Method (Worst case, Statistical)
- Kinematics/DOF (iso-constrained, over-constrained)
- Accumulation/Propagation (deviations, tolerances)
- Scale (Micro, Macro)
- Solution(Mathematical model, Computer Simulation)
Existing CAT Systems

- Integration with CAD (PMI/MBD/STEP)
- Semantic Tolerancing Advisor
- Visualization capabilities
- Retrofitted for CAD/Solid Modelling
- Rely on established tolerancing methods (90s)

- Conformance to ISO/ASME standards
- Consideration of form tolerances, datum precedence, ...
- No benchmark set for the evaluation/comparison of CAT systems
- Poor Tolerance Specification and Synthesis capabilities
- Proprietary systems
Tolerancing and the CIRP

- A permanent and important research issue in the long history of CIRP
- Interest to undertake cooperative projects on:
  - Tolerancing for function
  - Tolerancing for production
  - Tolerance technologies for CAD/CAM
  - Assessment of form deviations
- In 1989, Prof. Weill organized the first seminar on CAT
  - Since then, every two years, the CIRP CAT held 14 times
  - > 600 papers* / > 700 authors*
  - Important research achievements

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An overview of Tolerancing in France (GRT*)

> 2001

26 seminars
› 2 days
› 2 times a year

2 European seminars
E-GRT (FAU Erlangen Nuremberg, Chalmers Univ., Poli Milano)

› 10 French laboratories
› About 50 researchers

GRT: Groupe de Recherche en Tolérancement
Important contribution

• “Torsors” as a model for small displacements of the associate surfaces of real parts
• 3D Simulation of an assembled product considering surfaces and links deviations

Hypothesis
– The displacements of a rigid body or a surface, except for the degrees of freedom, are **supposed small**
– The rotations are **small enough** that can be linearized

\[
T_{\text{plane}} = \begin{bmatrix}
rx & U \\
ry & U \\
U & tz
\end{bmatrix}
\]

\[
T_{c1,c5} = -T_{1,c1} - T_{R,1} + T_{R,5} + T_{5,c5}
\]

Gap requirement
Important contribution

- 3D Simulation of the feasibility and quality of an assembly using variations domains.

- Deviation Domain \([D]\)
  - The Deviation Domain represents the limits of a Deviation Torsor

- Joint Domain \([J]\)
  - The Joint Domain represents the limits of a Link Torsor

Domains and Polytopes
(Giordano, Duret, Teissandier)
PolitoCAT/Politopix (GNU LGPL license)
Important Contribution

General theory of dimensioning (TTRS)
(Clément)
ISO GPS, CATIA

Nominal model

Dimensional parameters
Important Contribution

\[ \text{d} = \text{AM} \cdot n \quad \forall \ M \in (S1) \]

\[ \text{Max}(d) \leq t \]

**GEOSPELLING**
(Ballu, Mathieu)
ISO GPS, CATIA
Important Contribution

- New computational framework for tolerancing
  - Ground on shape discretization and digital/computational geometry researches
  - Holistic approach for integrating design, engineering, manufacturing and inspection from geometric variations and tolerancing perspective
  - Coherent and complete tolerancing process based on GPS
Our contribution

Skin Model Representation (1993)

Skin Model Shapes (SMS) (2014)

SMS for AM (2016)

SMS for DT (2017)

Operationalization

Concepts

Physical Modeling

Assembly

Industrie 4.0

AM: Additive Manufacturing

DT: Digital Twin

\[ \Delta r(\theta) = a_0 + \sum_{k=1}^{M} [a_k \cos(k\theta) + b_k \sin(k\theta)] - r_0(\theta) + \varepsilon_\theta \]
• Research on Tolerancing: Challenges and Opportunities
From Functional Requirements to ISO Specifications

1 - Set-Up
2 - Chain/Loop
3 - Tolerance Synthesis (automatic)
4 - Tolerance values

CAD
Assembly
Manufacturing

Consideration of other Geometric and non-geometric Functional Requirements
Complex Geometries

Specification, Simulation and Verification of complex shapes
Conceptual Design

**Conceptual Design**

- Requirement
- Function
- Behavior
- Form / Structure

**Tolerancing process**

- Decomposed Function
- Geometrical requirement
- Functional tolerance

**Detailed Design**

- Geometry
- Tolerance
  - ...

**Kinematics**

Geometric Variations Management Early in the Design Process
Manufacturing considerations

Phase 11: Casting
Phase 12: Milling
Phase 21: Casting
Phase 22: Milling
Phase 30: Braze welding
Phase 40: Milling

Specification/tolerance Transfer
Product Manufacturing Information (PMI) & Model Based Definition (MBD)

Presentation

- From 2D Drawings to 3D Models
- Exchange of Product data with guarantee of syntax and semantics based on relevant standards (ISO GPS, ASME Y14.5), STEP related (AP 242)
- Integration/Interoperability with CAX tools
Lifecycle issues

- How to identify the different key characteristics?
- How to build consistent 3D models for conceptual design, detailed design, manufacturing, assembly and inspection?
- How to integrate the 3D stochastic behavior of production (3D statistical tolerancing vs 3D worst case tolerancing)?
- How to extract the knowledge and reuse it for similar products (machine learning, transfer learning)
Form errors considerations

Generation & Assessment

Nominal Model → Skin Model Shape Generation → Skin Model Shapes → Skin Model Shape Preparation

Assembly Modelling

Assembly Process Definition → Assembly Simulation Model → Relative Positioning → Assembly Position

SMS Preparation

Partition of SMS using GeoSpelling operations

Skin Model Shape Preparation

Constrained registration approaches for the relative positioning of Skin Model Shapes

Relative Positioning

Result Visualization

Contact Quality & KC Evaluation

Evaluation
Geometric Variations and Industrie 4.0

- **Digital Twins**: computerized companions of physical assets
- **Cyber-Physical Systems**: mechanism controlled or monitored by computer-based algorithms, tightly integrated with the internet and its users

Ref.: Wartzack et al 2017
Digital Twin

- The **Digital Twin** refers to an entangled relation between a physical artefact and the set of its virtual models.

- Its **Reference Model** is based on the scientific fundamentals of GPS standards through a set of **Properties and Operations**

- **First** theoretical and conceptual framework.

- **Twinning**

![Diagram showing physical twin and digital twin with operations like conversion, composition, decomposition, and evaluation.

Design > Manufacturing > Assembly > Inspection

Operations:
- Functional Characteristics and Tolerance Specifications
- Generation of Skin Model Shapes
- Assembly Simulation for Skin Model Shapes
- Measurement of Skin Model Shapes

Partition Filtration Extraction > Association > Collection Construction > Evaluation

Decomposition > Conversion > Composition > Evaluation

Observation: Physical Twin
- Physical Operations: Conversion, Composition, Decomposition, Evaluation

Prediction: Digital Twin
- Operations: Conversion, Composition, Decomposition, Evaluation
Additive Manufacturing

- Accommodating geometry with material and manufacturing processes
- Complexity not for free
  - Complex Freeform Shapes with varying thickness and tolerances
  - Topology-Optimized Shapes/Features
  - Internal Features
- Process-driven Specification
  - Build direction and location
  - Layer thickness
  - Support structure
  - Scan direction and Strategy
- Functionnaly Graded Materials
Some recent efforts in Tolerancing for AM

- **Voxel-based Tolerancing**
  - Voxel based volumetric representation
  - Tolerance representation and verification
  - To specify a “tolerance” of the acceptable variation of the “Solid” of an additive manufactured component

- **Multi-Physical Tolerancing**
  - From Geometric to Physical Tolerancing considering Simulation and Measurement data
  - Variability Modeling

- **PMI/MBD**
  - ASME Y14.46 (Product Definition for Additive Manufacturing)
  - Extension of AMF to support features and tolerances
Education/Training

- Geometrical Product Specification and Verification as toolbox to meet up-to-date technical requirements
  - EU funded project (Erasmus+ 2015-1-PL01-KA202-016875), 2015-2018
  - Partners: University of Bielsko-Biala (Poland), Warsaw University of Technology (Poland), Friedrich-Alexander-Universitat Erlangen Nurnberg (Germany), Universita Degli Studi di Padova (Italy), Universitatea Tehnica Cluj-Napoca (Romania), University of Huddersfield (UK), Interstaatliche Hochschule fur Technik Buchs NTB (Switzerland), Volkswagen AG (Germany)
  - Topics: Geometrical Product Specification and Verification, e-learning, web-based access, vocational training and lifelong learning of mechanical engineers.
Conclusions

- Ubiquity of Geometric variations in Product Development.
- Geometric Tolerancing is evolving and consider more simulation and measurement during the whole Product lifecycle.
- Lack of digital tools to support tolerance specification, simulation, verification and education.
- Digital Thread, Industrie 4.0, data Analytics and Additive Manufacturing are developing as new applications

Questions:

- What are the most important applications of tolerances in your domain and business?
- What new requirements or processes are challenging the ability of traditional approaches to adequately ensure product quality?
Thank you
Questions?
Comments?

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