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Model-Based Definition for Non-Rigid Variation Simulation I: Automating Tolerance Analysis with the Quality Information Framework (QIF)

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Abstract

The Quality Information Framework (QIF) standard aims to cover the whole product quality ecosystem using a Model-Based Definition approach. Compared to the STEP AP242 and JT standard, QIF concentrates on semantically intertwining information from product design and inspection within one information carrier. Due to its strong focus on geometrical product quality, QIF is predestined to be used as the basis for activities that aim to assure product quality in the presence of geometrical variations. Still, its potential for variation simulation, virtually predicting the effects of geometrical part and assembly variations on the final product quality, remains largely unexploited. Methods for bringing information from QIF to variation simulation and translating it into deviations are currently lacking. This article presents a novel QIF-based method that fosters the automation of deviation modeling in non-rigid variation simulation of sheet metal assemblies. Building upon an inverse mapping method for registering QIF features within shell meshes leads to a hybrid model that combines the strengths of a parametric and discrete geometry representation. By exploiting this duality, size, location, orientation, and form tolerances are translated into mesh deviations using a joint Small Displacement Torsor and Skin Model Shapes approach. An exemplary application of the proposed method to a spot-welded sheet metal assembly illustrates QIF's potential for bridging feature-based GD&T specification and mesh-based variation simulation.

Keywords: Model-Based Definition; Quality Information Framework (QIF); Variation Simulation; Tolerance Analysis; Skin Model Shapes; Form Deviation

1. Motivation

Model-Based Definition (MBD) is a well-established paradigm in engineering practice. Software vendors for Computer-Aided Design (CAD) introduced their first modules to semantically annotate 3D models with Product and Manufacturing Information (PMI) already in the early 2000s [1]. Standards on practices for digital product definition, such as the ASME Y14.41 and ISO 16792:2006, followed soon [2] and were instrumentalized through standardized file formats, such as STEP AP242 and JT, to set up system-neutral authority models [3]. Tolerancing adopted MBD early on to exchange Geometric Dimensioning and Tolerancing (GD&T) information between the various variation management activities. A key advantage of MBD is the ability to automate variation simulation [4]. Using a discrete geometry representation, such as meshes, to model deviations, however, introduces structural inconsistencies with the original CAD geometry representation and requires mapping algorithms [4, 5]. Methods for mapping GD&T information, specified in Boundary Representation (BREP) geometry in CAD, onto mid-surface meshes and exploiting the resulting link for deviation modeling within non-rigid variation simulation are missing.

Building on established methods for non-rigid variation simulation and related works on the Quality Information Framework (QIF) standard, this paper presents a new MBD-based method for automated tolerance analysis of sheet metal assemblies. The article is organized as follows. First, Section 2 discusses the current state of the art to identify the research gap. After highlighting the challenges of mid-surface meshes used for variation simulation at the beginning of Section 3, Section 3.1 explains how to map information from QIF to mid-surface shell meshes. Section 3.2 introduces a joint Small-Displacement Torsor (SDT) and Skin Model Shapes (SMS) approach, using the mapped tolerance information to generate deviated meshes. The method is applied to simulate a spot-welded sheet metal assembly in Section 4, initiating a concluding reflection. Finally, Section 5 concludes the article with a summary and an outlook. The contributions of this work lie in establishing a semantic link between the QIF and discrete geometry representations, integrating inverse surface mapping in SDT- and

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SMS-based tolerance modeling frameworks, and extending the approach to non-rigid sheet metal parts.

2. State of the art

The "ability to simulate and foresee geometry problems early" [6] makes variation simulation an essential tool for variation management [6, 7]. By virtually assembling deviated parts, it simulates how unavoidable manufacturing and assembly deviations propagate and affect critical characteristics of the final product [8]. Nominal geometry and imperfections are often modeled through variational geometry approaches [8]. The parts' shapes are described by substitutes [9], where parameters are used to generate deviations from the theoretical geometry [8], for instance, expressed through a SDT [9]. These substitutes are named features [9] and simplify deviations to rotational and translational imperfections and neglect form deviations [10]. Meshes, in contrast, describe geometry as discrete shapes through a set of connected nodes [11]. Thus, they can model size, location, orientation, and form deviations and realistically represent parts with characteristic manufacturing signatures [10, 11]. Over the last few years, meshes have gained increased attention as an operationalization of SMS concept [9, 11] and for variation simulation based on Finite Element Analysis (FEA) [8].

The first models are typically created in the product design phase and used for tolerance analysis [5]. In this stage, statistical tolerance analysis is used to verify if the GD&Ts specified at the part level can, in sum, fulfill the quality-related product requirements [8]. The GD&Ts are translated into variations, a set of deviations resulting when manufacturing the parts multiple times with the same process [12]. The deviations are generated based on estimations or historical data [7] and serve as the input to variation simulation to study the probabilistic response of the assembly to the GD&Ts [8].

Ideally, the same model can be used throughout the entire development process and the lifetime of a product [11], and is continuously informed by data and information defined and acquired across different product life-cycle phases [11]. The idea of the Digital Thread, "linking all systems, processes, and virtual and physical data" [13] aims to pull all strings of relevant information together and intertwine them into one mutual thread [13]. MBD takes over a key role to set up the Digital Thread for variation management as it aims to unify all relevant information to describe the "as-planned" and "as-fabricated" status within a common 3D product model serving as the single source of truth [5, 14]. To overcome system interoperability issues, three neutral MBD standards, STEP AP242, JT, and QIF, have been developed so far [15]. QIF, the most recent standard [16], is designed to support the design and realization phases, enabling both the automation of deviation modeling for statistical tolerance analysis and the augmentation of the models with inspection data [4, 5]. Fig. 1 highlights the idea of a QIF-centered variation simulation workflow as proposed in [5]. QIF unifies all geometry, tolerance, and deviation information – obtained through real inspection or numerical process simulations – within one authority model [5]. Interfaces and mapping algorithms ensure an automated information translation into geometrical models [4, 5] (see Fig. 1).

Automating feature-based variation simulation is conceptually straightforward. The geometrical substitutes used in simulation and in QIF (as well as in JT and STEP AP242) are similar to those where GD&T information was semantically annotated in CAD [5]. Drawing on meshes to consider local shape deviations [11] and part compliance [17] makes mapping more difficult [5]. Information needs to be transferred from QIF to the respective mesh portions [4]. For volume and surface meshes, robust mapping and deviation modeling methods for size, location, and orientation deviations were proposed in the literature [5, 18]. Thin sheet metal parts are, however, often represented through mid-surface shell meshes [17]. Contact modeling avoids parts penetrating each other after joining while realistically considering the actual form of the mating geometrical surfaces [17]. Mapping GD&T from QIF onto mid-surface meshes and exploiting the created semantic link to model form deviations have not been studied so far. For this reason, the applicability of QIF for automating tolerance analysis of compliant sheet metal assemblies is currently limited.

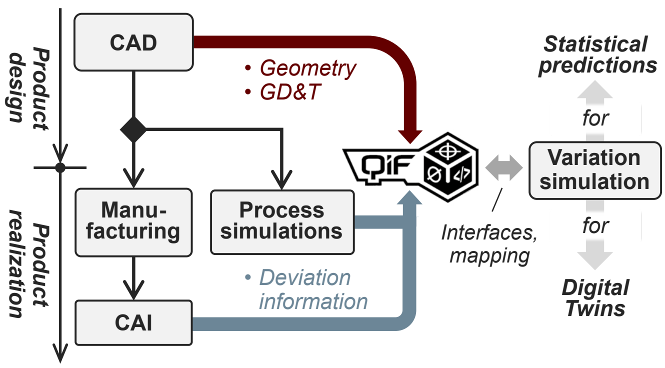

Fig. 1. Shaping the GD&T and deviation information flow to variation simulation for statistical tolerance analysis or Digital Twin optimizations via QIF.

3. QIF-based automation of non-rigid variation simulation for statistical tolerance analysis

Assemblies are typically categorized into two main types [19]. In Type-I assemblies, parts are assembled through part-to-part mating surfaces [19]. Type-II assemblies rely on external fixtures to position parts without any part-to-part constraints prior to joining [19]. Welded sheet metal assemblies are Type-II assemblies [19] and require a realistic modeling of all assembly steps, including part positioning, clamping, joining, and releasing from the fixture [17]. Using FEA enables mapping the non-rigid part behavior and manufacturing-induced deformations on the assembly response [8], which is additionally influenced by variations in both the part geometry and the fixtures [19]. It is common to linearize the parts' stiffness behavior based on the Method of Influence Coefficients (MIC) [20]. MIC substitutes computationally expensive physics-based mechanical simulations for stress or strain prediction by capturing only the main compliance effects relevant to variation simulation. The local stiffness matrices are calculated once for the nominal status [20]. Instead, locators' deviations and nodes within contact regions must be considered for each sample, as they define the part positioning and interaction [17].

Since sheet metal parts are thin relative to the other dimensions, using mid-surface shell meshes is applicable to keep FEA's computational effort low. However, the computational dimensionality reduction from 3D to 2D leads to several challenges in representing geometrical deviations (see Fig. 2):

1. Mid-surface extraction leads to topological reductions, since multiple opposing features $\mathbf{S}_j, \mathbf{S}_k$ collapse into one representative $\bar{\mathbf{S}}_m$.
2. Depending on the feature's orientation relative to the mid-surface, feature dimensionality reduction occurs when a lower-dimensional entity represents its geometry.
3. Feature locations shift from the parts' skins to the geometrical representative inside the material.
4. Depending on type and orientation, feature shapes change.

Automating tolerance analysis using mid-surface meshes requires handling these challenges properly, in particular, when bringing the GD&T information from CAD to variation simulation via QIF and mapping it to the Finite Element (FE) meshes (see Section 3.1), before using the augmented mesh to model the geometrical part deviations (see Section 3.2).

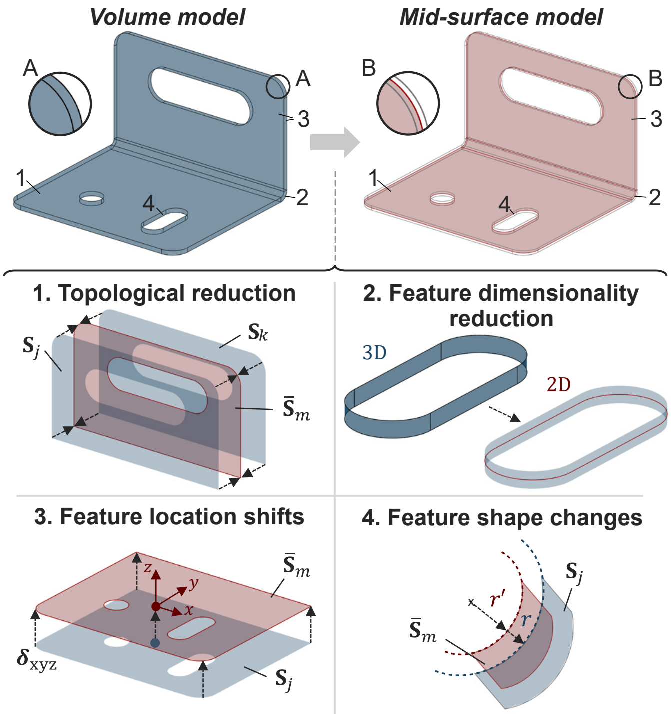

Fig. 2. Mid-surface mesh challenges in deviation modeling.

3.1. Mapping QIF information to mid-surface shell meshes

Meshing a solid CAD model converts the original geometry and topology into a discrete representation of the part as a whole. Individual surface information and PMI association are lost during meshing, so segmenting the mesh and remapping the GD&T information to the corresponding mesh nodes is necessary [5]. To solve this issue, an inverse mapping algorithm for QIF and FE volume meshes was proposed in [5] and is adapted for mid-surface meshes and their challenges in the following.

QIF uses a decoupled normalized relationship model, in which unique identifiers (id) link all objects to one another [16]. Following this logic, GD&T information, expressed through characteristic, feature, and datum reference system objects, is semantically coupled to the corresponding BREP geometry objects [16]. A surface profile tolerance, for example, refers to a characteristic, a control placed on a planar feature and linked to a parametric planar geometrical face (see Fig. 3). For an explanation of why characteristics do not directly point to geometry objects and details on how QIF is structured, the reader is referred to [5, 16, 18]. The semantic link to the geometrical faces can be exploited to segment the mesh into portions representing QIF surface elements and link them to the associated characteristics.

In QIF, geometry is described by parametric functions that map a point from a 1D or 2D parameter space to the 3D Euclidean space [16]. Inverting this relation, points with x, y, z-coordinates can be mapped back to the 2D parameter space of geometrical faces using their inverse surface function $\mathbf{S}_j^{-1}$:[1]

$$(u, v) = \mathbf{S}_j^{-1}(\mathbf{q}), \quad \mathbf{q} = (x, y, z). \tag{1}$$

To check which node $\mathbf{q}$ of a mesh $\mathcal{T}$ belongs to a geometrical QIF face $\mathbf{S}_j$, all nodes $\mathcal{N}_\mathcal{T}$ are first mapped into the corresponding 2D parameter space using Eq. (1) (see Fig. 3, STEP 1).

Though all points can be represented in the 2D space of $\mathbf{S}_j$, it does not mean they belong to it. The orthogonal distance $d(\mathbf{q})$ of a point $\mathbf{q}^*$ along the surface normal $\mathbf{n}(u, v)$ to S_j can be used as a filter condition with ε as numerical tolerance [18] (see Fig. 3, STEP 2):

$$d(\mathbf{q}^*) = |(\mathbf{q}^* - \mathbf{S}(u^*, v^*)) \cdot \mathbf{n}(u^*, v^*)| < \varepsilon. \tag{2}$$

However, offsets relative to the original surfaces must be considered, as these differ across features. While some lie directly on the mid-surface, others are shifted by about half the part thickness (see Fig. 2).

Geometrical faces have at least one outer boundary Γ_0 and optional inner boundaries Γ_i, trimming the original domain Ω_0 to its final domain Ω_j [18]. A mesh node $(u^*, v^*) \in \Omega_j^0$ only belongs to the face j if it is within the trimmed domain Ω_j [18] (see Fig. 3, STEP 3):

$$(u^*, v^*) \in \Omega_j = \text{region}(\Gamma_0) \setminus \bigcup_{i=1}^{n} \text{region}(\Gamma_i). \tag{3}$$

Eq. (3) can be treated and solved as a point-in-polygon problem [18]. As a consequence of topological reduction, points can be mapped to multiple faces and thus features and characteristics (see Fig. 2). In case of reduced feature dimensionality, an element K and its face $\mathcal{F}_K$ may also only be partially mapped to a $\mathbf{S}_j$.

[1] $\mathbf{S}_j^{-1}$ is mathematically defined for all regular geometries and given in [5].

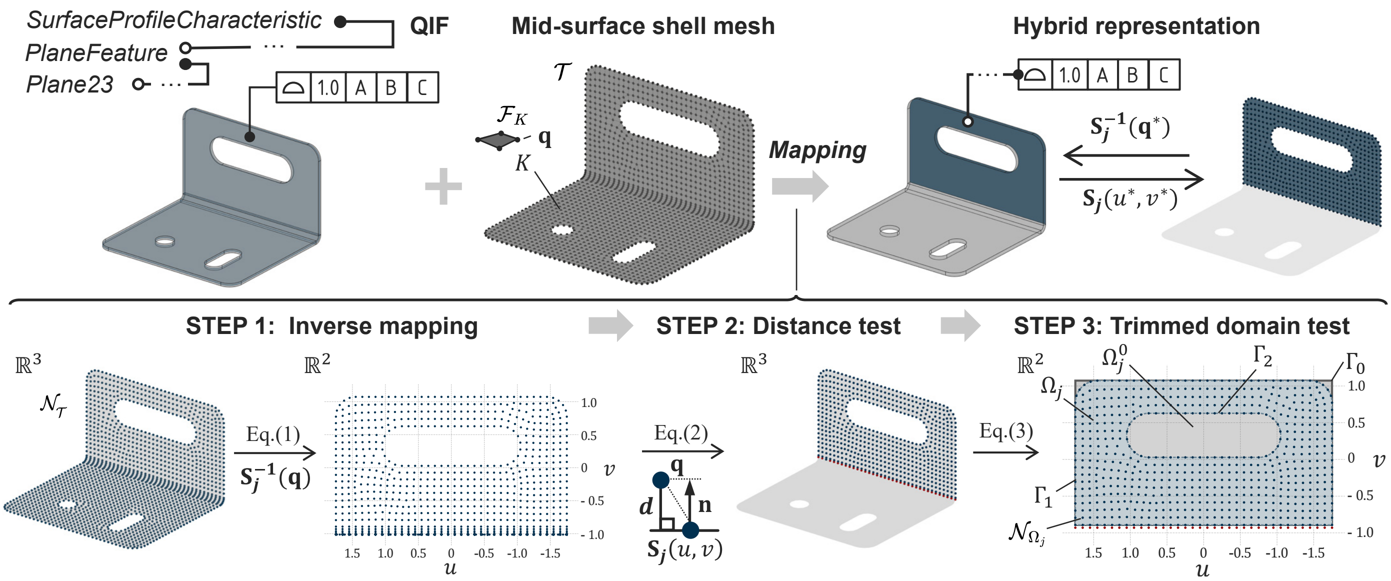

Fig. 3. Transfer of GD&T information from QIF to mid-surface shell meshes through inverse mapping, illustrated for a planar face of a bracket.

Repeating these three steps for all faces connected to characteristics or datums, the individual nodes are linked to the GD&T information carried in QIF.

3.2. Translating GD&T information from QIF into discrete shape deviations

After mapping the GD&T information, it needs to be translated into individual nodal displacements, which, in sum, represent the feature deviations. Using mesh-based deviation modeling methods developed for SMS seems reasonable. The inverse mapping method, however, further links the mesh nodes to parametric surfaces. This link can be exploited by combining the SMS and the SDT concept, an idea proposed in [21]. In this article, 3D deviations are intrinsically modeled using the 2D parameters (u, v) of the mapped nodes. A surface profile tolerance applied to the planar surface of the bracket from Fig. 3 serves as an example in the following (see Fig. 4).

A mesh surface $\mathbf{S}_j$, with $\mathbf{Q}_j \in \mathbb{R}^{N\times3}$ collecting all $i = 1, \dots N$ linked nodes $\mathbf{q}_i$, can be deviated by superpositioning several fields for location, orientation, and systematic and/or random form deviations added to the corresponding mid-surface mesh nodes to derive their new positions $\mathbf{Q}'$ (see Fig. 4 a)):

$$\mathbf{Q}'_j = \mathbf{Q} + \overbrace{\mathbf{S}'_j(u,v) - \mathbf{S}_j(u,v)}^{\delta_j^{\mathrm{l,o}}} + \overbrace{\overline{F}_j(u,v)\cdot\mathbf{n}'}^{\delta_j^{\bar{\mathrm{f}}}} + \overbrace{\underline{F}_j(u,v)\cdot\mathbf{n}'}^{\delta_j^{\underline{\mathrm{f}}}}. \quad (4)$$

Modeling the location and orientation deviation field $\delta_j^{\mathrm{l,o}}$ is straightforward with feature logic. The SDT concept, combined with a set of geometrical constraints, helps to describe the tolerance zone for a given feature type [21]. The planar surface, for instance, is allowed to be rotated around the x- and z-axis, and translated in surface nominal direction along the y-axis, but staying within the tolerance zone. Sampled translational and rotational SDT entries are used to modify the characteristics of the linked QIF surface $\mathbf{S}_j$, i.e., axis location and direction, leading to a modified surface description $\mathbf{S}'_j$. Feeding $\mathbf{S}'_j$ with the u, v-parameters of all N nodes leads to the deviation field for the entire mesh segment (see Eq. (4), Fig. 4 b)) [18].

Further, it is possible to model systematic deviations directly in the 2D parameter space through $\overline{F}_j(u, v)$ if the deviation field to represent is continuous and single-valued. The normal vector $\mathbf{n}'$ of the deviated feature $\mathbf{S}'_j$ projects them in the surface's normal direction of the feature and creates an orthogonal deviation field $\delta_j^{\bar{\mathrm{f}}}$ (see Eq. (4)). Figure 4 c) exemplifies a systemic deviation generated using a low-order Discrete Cosine Transformation (orders 1 and 2) [21], one possible modeling approach to replicate process-specific manufacturing signatures.

Gaussian fields are a common way to create a correlated random form deviation field for the mapped 2D parameter mesh node grid $\underline{F}_j(u, v)$ (see Fig. 4 d)). The spatial correlations between the points are covered by a covariance function [11], ensuring a smooth but continuous deviation sampling directly in the 2D space of the surface. Again, taking $\mathbf{n}'$ into account leads to $\delta_j^{\underline{\mathrm{f}}}$ (see Eq. (4)).

When generating deviation fields, the final shape must conform to GD&T tolerance zones [21] while considering correlations between the features, such as shared tolerance zones or reference datums [18]. The method has limitations when GD&T features are subjected to dimensionality reduction, particularly for holes and slots perpendicular to the mid-surface planes. These features are not recommended for contact modeling, and applying form deviations is thus of limited value. Part positioning within fixtures is simulated by defining a locating scheme with multiple points that lock at least the six Degrees of Freedom (DOF) of a part. Holes and slots only lock in-plane translational and rotational DOF. For this reason, midpoints derived from and coupled with the nodes describing the hole's or slot's curves are typically used as locators. Position tolerance effects can be simulated as location deviations by moving the corresponding mid-shell nodes within the plane.

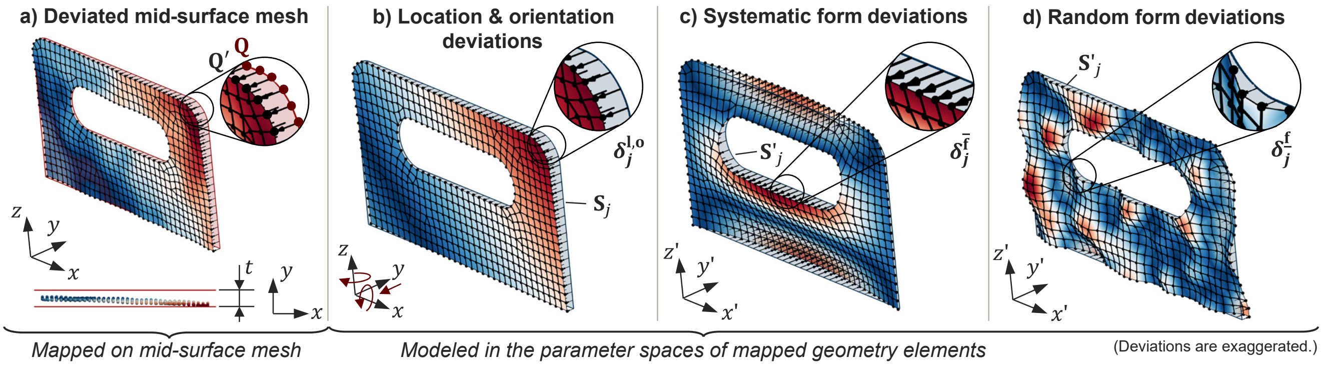

Fig. 4. Discrete deviation modeling in the 3D Euclidean space using the mesh nodes representation in the 2D parameter space of the respective QIF surface element.

4. Application

The subsequent example aims to illustrate the proposed method and initiate a concluding discussion. Fig. 5 shows the case study, a spot-welded sheet metal assembly, which is freely adopted from [22]. The 0.8 mm-thick steel parts, with a stiffness of 210 GPa, are positioned in their fixtures using a 4-2-1 locating scheme, then welded together, the joined assembly released from the fixtures, and inspected (see Fig. 5 (mid)). The software RD&T is used for non-rigid variation simulation [24], where the user needs to set up the nominal assembly model, with semi-automatic functions assisting, e.g., in contact modeling. The hitherto manual steps for translating GD&Ts into node tolerances and deviations are now automated. Fig. 5 (top) shows the parts with their GD&T annotations in Autodesk® Inventor® Professional 2026, which are exported as QIF-files. Relevant information is extracted using open-source code [23], mapped to the mid-surface shell meshes (see Sec. 3.1), before the meshes are deviated, taking all QIF features and characteristics into account (see Sec. 3.2). All nodes were correctly linked with the QIF faces and features, demonstrating robust and reliable mapping performance, in line with the findings made using inverse surface mapping for volume meshes in [18].

Monte Carlo Simulation using MIC with n = 10 000 samples was performed, randomly joining the deviated meshes and virtually measuring the absolute deviation of the location of the center point of the cut-out (see Fig. 5 (mid)). Size tolerances and material-condition modifiers effects are considered in deviation modeling on part level, but clearances in the locators are neglected in assembly simulation in this study. A mean of 0.133 mm and a standard deviation of 0.078 mm were obtained. Fig. 5 (bottom) shows one instance of the two parts with deviations, released from the fixture after their joining. The time required (for the lower & upper part) for one-time QIF parsing (1.1 s & 3.2 s), mapping (1.4 s & 1.8 s), and deviation modeling (on average 0.15 s & 0.24 s per sample) on an average workstation indicates that it is low in comparison to the time needed for non-rigid assembly simulation (on average 13.8 s per sample).

Aside from setting up and verifying the simulation framework, the example given demonstrates that QIF can bridge the gap between CAD and non-rigid variation simulation. Though the hybrid geometry representation generated by the inverse mapping of BREP and mesh geometry offers benefits for deviation modeling, process-specific knowledge of the shapes is needed to make realistic predictions. This is especially crucial for the shape of features in contact. Lack of information forces the simulation engineer to make many assumptions about the actual shapes (as in this study) or to simplify them, which remains a major bottleneck for variation simulation in general and for automation in particular. The integration of ISO 14235 is thus essential for addressing all occurring uncertainties and making reliable conformity decisions.

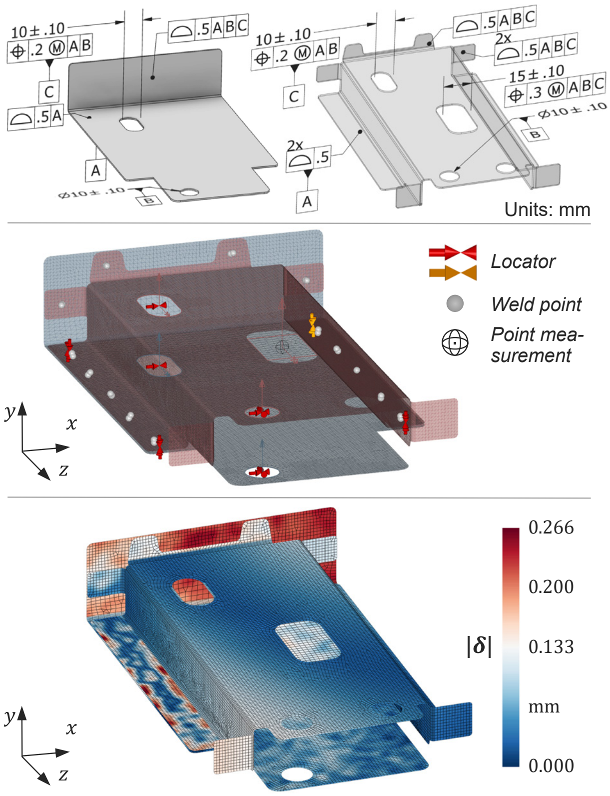

Fig. 5. Case study: Parts with tolerance specification (top). RD&T model with part shell meshes, locators, weld points, and virtual measure; contact points between the parts are suppressed for better visibility (mid). One instance of a virtual spot-welded assembly, composed of two deviated meshes (bottom).

This article aimed to introduce a new method and illustrate its potential for automation through a simple case study. Future research must study its applicability to more complex problems, including further tolerance specifications and feature types. Though the deviation modeling of free-form surfaces in the 2D planar parameter spaces is straightforward, shape changes when projected to mid-surfaces need to be handled properly. Detailed studies on shell meshes for deviation modeling are required to investigate the consequences of the challenges highlighted in Fig. 2 and quantify their limitations. A comprehensive verification of QIF's tolerance analysis automation potential requires further in-depth usability studies with different users, case studies, and alternative workarounds for benchmark.

5. Summary and outlook

Deviation modeling based on mid-surface meshes is a major challenge for automating tolerance analysis of sheet metal assemblies. A novel inverse mapping algorithm was introduced in this paper that semantically links nodes of mid-surface meshes with QIF features and GD&T annotations. The linked GD&T information is translated into deviated meshes using a joint SDT and SMS approach, exploiting a hybrid representation of nodes in the 2D parameter space and the 3D Euclidean space. The example shows that QIF enables the automatic translation of GD&Ts from CAD into discrete shapes with geometrical deviations for non-rigid variation simulation, but also emphasizes the importance of data availability to reduce the influence of assumptions on distributions and actual shapes. Future research is needed to reduce the remaining manual pre-processing steps, such as defining fixtures, weld points, and measurements. In-depth studies are required to extend the proposed method and to identify and quantify the limitations and limits of using shell meshes for variation simulation.

Acknowledgements

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