

VISUAL ANALYSIS METHODS FOR NON-IDEAL ASSEMBLIES

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1. Introduction

Tolerances define the allowed deviation of manufactured parts from the ideal geometry, which is given by the product developer in a CAD system. Tolerances limit the allowed errors of dimension, shape and position of real parts and have critical impact on a designed product. The proper definition of tolerance values influences aesthetic requirements as well as product function. Coarse tolerances often allow cheaper production, fine tolerances ensure high product quality (functional compliance, consumption, abrasion, noise emission, etc.) but lead to expensive manufacturing and inspection methods.

It is an important and as well difficult task of the product developer to find a trade-off between quality and costs by choosing suitable tolerance values and tolerance types. There exist several commercial support tools for tolerance analysis which aim to find these optimal values. These tools are used by tolerancing experts with specific knowledge, experience and education. As a result of statistical analysis (i.e. Monte-Carlo simulation), the experts are able to acquire important statistical data about the studied assembly and its defined tolerance values, e.g. which percentage of the assembled non-ideal parts will not fulfil all functional requirements. The tolerance analysis tools typically show a distribution curve and statistical properties of the defined measurements. These values are therefore meaningful for the tolerancing experts, but difficult to interpret for product developers.

Another drawback of these statistical results is the missing connection between numeric values and analysed geometry. The tools show that certain tolerances lead to critical values, but give no geometrical explanation.

We follow the “generate and test” approach to analyse tolerance specifications: Based on toleranced CAD data, *non-ideal parts* are generated, which are defined as parts that deviate from the nominal shape but stay within tolerance boundaries. For these non-ideal parts we propose several visualization methods to reveal the geometric consequences of the defined tolerances on the resulting product. One set of methods is used to reveal the geometric properties of individual assemblies, like surface quality and progress of gaps. The other set is intended for visualizing the spatial relations between multiple assemblies, like collision probabilities, based on a statistical analysis of these assemblies. The intention of these methods is to provide an intuitive view of the complex relations between tolerances and resulting geometry.

2. Related work

Typical tools for tolerance analysis (i.e. VisVSA, emTolMate, CETOL) have the following workflow: CAD geometry and tolerances are defined by a product developer. The data is imported and prepared in a tolerance analysis program by a tolerancing expert. Assemble operations and mating conditions as

well as studied variable parameters (i.e. length of a part, angles, distances...) are chosen. To generate non-ideal parts, the tolerance program generates assemblies with either extreme (High-Low-Median simulation) or random (Monte-Carlo simulation) parameter values. To gain statistically relevant data, between 10.000 and 30.000 variants have to be generated in Monte-Carlo simulations. The results of measurements defined by the tolerancing expert (i.e. distance between two parts) are presented as distribution curves and statistical properties like mean value, standard deviation or Cp and Cpk values (see Figure). See [Siemens 2008] for further information on VisVSA and emTolMate.

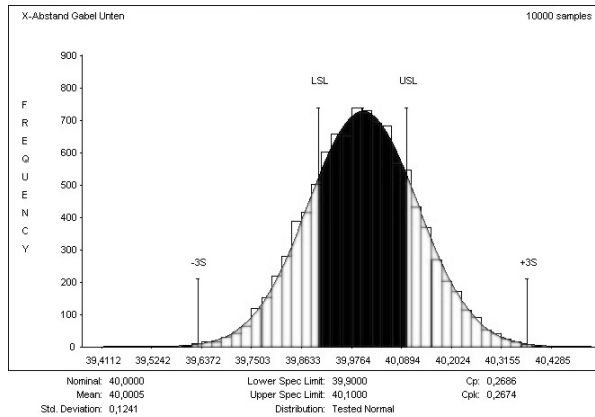


Figure 1. Typical result representation of statistical tolerance analysis tools (here: VisVSA[®])

In [Söderberg 2006], an overview of current commercial computer aided tolerancing software and research projects is given, structured into concept phase (definition and simulation of tolerances, robustness analysis), verification and pre-production phase (inspection preparation, virtual trimming) and production phase (Root Cause Analysis, Six Sigma Method).

The papers [Maxfield 2002] and [Koch 2005] demonstrate methods for the visualization of non-ideal parts resulting from defined tolerances. They are limited to a single combination of non-ideal parts per scene. In [Maxfield 2002], the use of free form deformation and force density method for the generation of non-ideal parts is described. The commercial software Aesthetica[™] is based on Maxfield's research project VITAL (Visualizing the impact of tolerances) at the University of Leeds It focuses on the realistic rendering of automobile assemblies to reveal aesthetic problems

In [Koch 2005] different visualization methods for non-ideal parts are presented, structured in geometric representation methods and color coding of deviations. Non-ideal surfaces are visualized as point or sphere clouds and scaled indexed face sets. Color gradients in different color spaces are applied on the geometric representation to make small deviations recognizable; textures are used to add contour lines and to mark regions above and below the nominal surface.

When analyzing shape- and position-tolerances, there exists no definite "worst case" of deviations for a complete assembly (one extreme value), but numerous critical combinations. Consequently, it is useful to show combinations of non-ideal parts to interpret impacts of the used tolerances. In [Löf 2006] a method to calculate a modified convex hull of geometry is presented, which preserves geometric details like holes. For each triangle of the used non-ideal geometry mesh, the vertices are varied in the allowed range to generate a tolerance hull by combining the results.

For the analysis of non-ideal components, all deviated parts have to be repositioned to avoid collisions and floating of the parts. In [Stoll 2007], this problem is solved by heuristic optimization.

In this paper, we present several developed, implemented and tested visualization methods and explain their benefit for tolerance analysis in product development. The methods address visualization of single non-ideal assemblies as well as statistic analysis of several possible variations in a single scene. The presented work was part of a collaborative research centre of the German research foundation (DFG) and has been supported by industry partners.

3. Visualization of individual assemblies

In this section, methods to visualize individual non-ideal assemblies are presented. This is useful for the detailed study of extreme non-ideal variants. The main problem addressed by the visualization is the fact that deviations in the (sub-)millimeter range are hard to detect and judge in virtual environments, especially for rather large assemblies. So the purpose of the visualization is to expose these small deviations as well as their impact on product aesthetics and resulting functional problems. The visualization of deviations of individual assemblies is helpful to highlight critical regions. We present two different methods for visualizing non-ideal assemblies: First, a method to visualize the smoothness of assemblies is described, which is useful for aesthetic studies. Thereupon, a way to visualize gaps between adjacent parts is introduced, which can be used for aesthetic as well as functional examinations. As pointed out in [Wickmann 2007], the properties surface smoothness, gap and flush between parts have great impact on the *visual quality appearance* of products, especially in the automotive industry.

3.1 Considered input data

For the digital representation of non-ideal assemblies, triangle meshes have been used because of their universal applicability. The meshes can be obtained either from surface measurements or with the help of statistical tolerance simulations. Deformation methods like freeform deformation (FFD) and FFD extended with force density method are used to transform an ideal surface mesh into surface descriptions of non-ideal parts, while preserving defined tolerances, see [Maxfield 2002] and [Stoll 2006]. In contrast to [Koch 2005], the developed visualization techniques are not based on a comparison with the ideal counterpart. Instead, they make use of derived properties of the non-ideal geometry.

3.2 Visualization of surface smoothness

The smoothness of an assembly's surface can be derived from its gradients or the normals of the corresponding triangle mesh. To analyze an assembly, the user defines one surface normal vector as a reference value. Afterwards, a visual comparison between this reference and all other normals of the surface is provided. The main intention of this method is the use as an interactive tool where the user selects a normal of a region to analyze part continuity and continuity of adjacent components. After selecting a normal vector, the vertex normals of the examined triangle meshes are compared to this reference normal by applying the dot product and calculating the angle between these vectors. The resulting angles represent the deviation from the reference normal. This deviation value is mapped to a color value to visualize it on the assembly's triangle mesh.

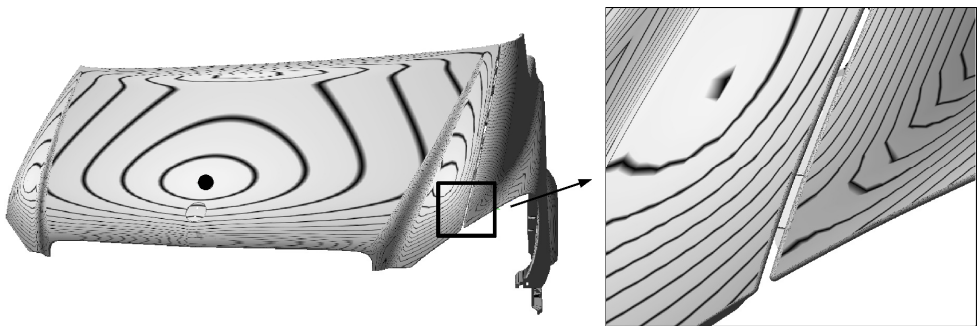


Figure 2. Smoothness visualization of an engine hood and a mudguard

Figure (left) shows this smoothness visualization approach applied to the engine hood and mudguard of an automobile. The reference normal was chosen on the center of the engine hood (marked by a filled circle). The color mapping for the deviation from the reference normal was chosen such that the greater the deviation is, the darker the color gets. Furthermore, isolines have been used for better

estimation of the deviation. It can be seen that the engine hood has been constructed symmetric to the middle axis and that it bends more to the front than to the sides. Furthermore, the breaks in the surface at the top and near the sides are well visible, visualizing the sudden increase in curvature at these points. Figure (right) provides a scaled view of the area marked by the rectangle in Figure (left): Here, it is visible that the transition between engine hood and mudguard is not as smooth as supposed but there is a small gap in deviation of the normals, which leads to the visible offsets in isoline visualization.

3.3 Gap visualization

The second method provides a visualization of the gap between a chosen part and the surrounding assembly. The main purpose is to get an impression of the distance distribution between these parts along the gap and the progress of the gap.

3.3.1 Gap detection

For accurate analysis of the progress of a gap, many sample points that follow the gap on the surface of the assembly have to be selected. Since the progress often may be of high geometric complexity, e.g. for curved gaps, this can be a challenging task.

Therefore, a semi-automatic approach is adopted for gap detection: First, the user has to select the parts to be examined as well as a starting point which lies on or very near to the gap border. With this initial information, the detection algorithm tries to find more points placed on the gap border. To accomplish this, all vertices that are directly connected to the user-selected vertex by a triangle edge are taken into consideration. For each of these vertices, the corresponding normal is compared to the user-selected vertex normal by computing the dot product between these normals. If the product is above a specified threshold (i.e. the angle is small enough), the corresponding vertex is stored in a queue to be processed. Each of these queued vertices will then be used as “user-selected” vertices in the next iteration step, until the queue is empty. The output of the algorithm is a list of all vertices that lie on the gap border. For every detected point on the gap border, the nearest point on the surrounding parts is calculated. The resulting pairs of points are used for gap visualization.

3.3.2 Visualization of gaps

Between each pair of points a colored line is drawn. The color of the line depends on its length, which is the distance of the corresponding parts or the size of the gap. In Figure (left), large distances are mapped to dark colors while short distances are mapped to bright ones. In the case depicted here, the visualization shows that the gap between engine hood and the left mudguard widens at the car front.

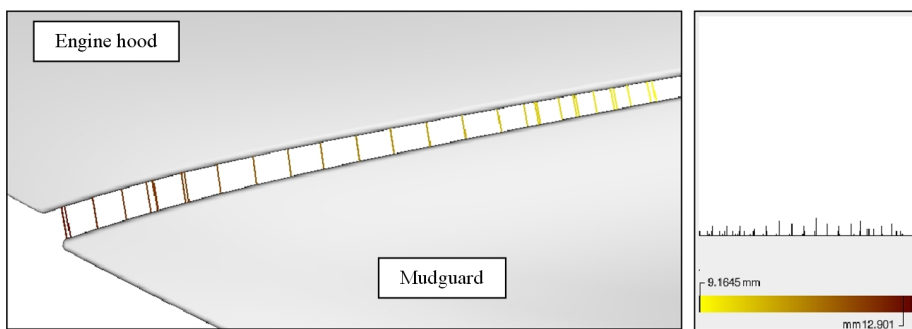


Figure 3. Gap visualization with color-coded lines and distance histogram

Additionally to the color-mapping of distance lines, histograms can be used to analyze statistical gap information. This way, it is possible to get information about the smoothness and distance distribution of the gap. The user may also select certain distance ranges in the histogram in order to restrict the gap

visualization to those ranges. Figure (right) shows the corresponding histogram as well as the color-mapping used for the examined gap between engine hood and mudguard.

4. Statistical analysis of multiple non-ideal assemblies

For the meaningful analysis of tolerance effects on a mass product, a high number of virtual combinations of non-ideal parts has to be examined. A functional failure of the “worst case assembly” is often acceptable if the probability of this combination of parts is very low. By allowing an unlikely failure, cheaper manufacturing methods can be chosen for the assembly components. Usual tolerance analysis tools only present statistical results for the studied assembly, or allow the visualization of a single variant. The geometrical study of 10.000 (a common minimum value for statistical tolerance analysis) virtual assemblies is not feasible this way.

4.1 Volume visualization and analysis

In this section, we present a method for the geometrical analysis of multiple datasets in a single visualization scene. To transform all non-ideal variants into one statistic volume visualization, the following steps are performed (for details, see [Wittmann 2007]): The user selects an area of the examined assembly. This space is subdivided into small boxes of the same size, so called “voxels”, with typical edge length below 0.1 mm (symbolically shown in 2D in Figure a-c). Successively, simulated non-ideal parts are loaded into the volume. For every voxel which is intersected by a non-ideal part, a hit-counter is increased by one (Figure a). This is done for all available simulated variants of the part (Figure b). The resulting 3D scalar dataset can be visualized by assigning colors to hit values, e.g. a bright color for low hit values and dark one for high values (Figure c) and adding adequate transparency values.

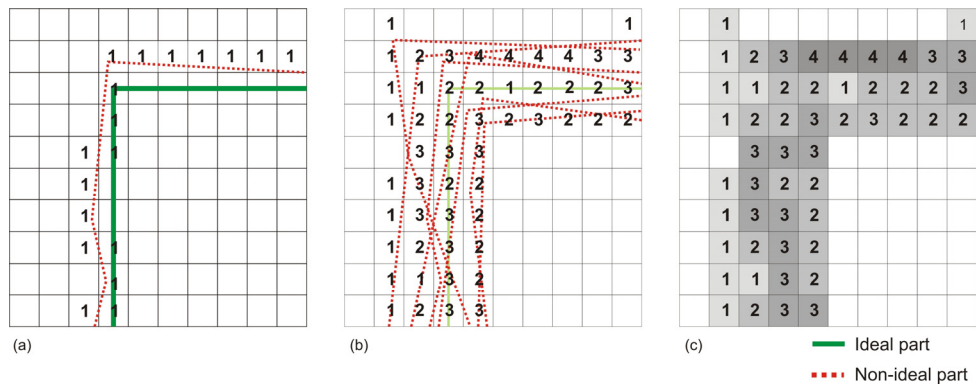


Figure 4. Generation of a volume dataset for non-ideal parts (shown in 2D)

After this “voxelization” process was repeated for every non-ideal part of the input dataset, the value of each voxel in the generated volume dataset represents the probability that this discretized space is intersected. Hence the resulting volume dataset stores the probability distribution of the surface position in space. In contrast to point measurements, the volume visualization method allows the product developer to analyze selected *areas* within a large group of similar non-ideal assemblies. Additionally, the 3D volume visualization still represents the geometry of the analyzed assembly. Generated volumes can also be displayed combined with the ideal assembly. Furthermore, the visualization gives an overview of the analyzed assembly group and helps to find critical regions that may require more attention. These characteristics make the results easier to comprehend for people that are not familiar with tolerance analysis. Even for experts, the visualization reveals more information than the common result representation.

The previously described approach has been recently applied on a dataset provided by an industry partner. It represents real proportions, tolerance types and values of a manufactured product. The

dataset consists of 10.000 cylinders, which were created in the tolerance analysis software eM-TolMate by a Monte Carlo simulation run. The cylinders have variable axis endpoints and diameters. The resulting volume visualization (Figure , left) shows regions with high hit probabilities (dark color) and regions with low probabilities (bright colors). The original geometrical aspects of a cylinder are still visible, additionally the statistical deviations are visualized on the cylinder geometry. Figure shows that the non-ideal cylinder mainly vary along the y-axis, they have a preferred direction. This can also be seen in a 2D slice image through the volume (Figure , right). The slice view shows a broader footprint in y-direction.

A typical two point measurement wouldn't have revealed this spatial behavior. Dependent on the chosen position of measurement points, high or low deviation values would have been presented.

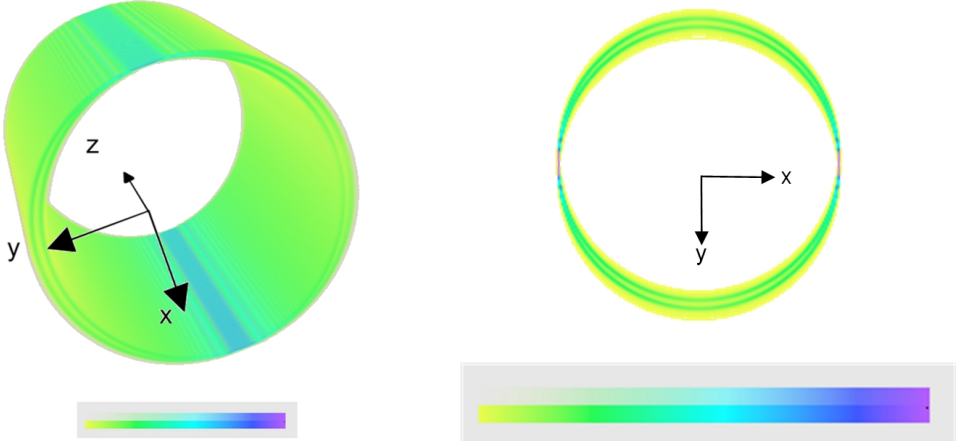


Figure 5. Volume visualization of 10.000 non-ideal cylinders (left) and slice view through the volume (right)

4.2 Statistical collision analysis

An important issue in tolerance analysis is the joining of non-ideal parts. To calculate the probability of collisions between parts, an extension of the previously described volume method has been developed. The method is now explained for the assembly of non-ideal cylinders and bore holes (Figure , left). At first, independent volume datasets of the examined region have to be generated for all non-ideal variants of both joined components of the assembly (cylinders and bore holes). In contrast to section 4.1, the volumes have to be generated for solid objects, not only for the object hulls. Figure (middle) symbolically shows a detail of the volumes with hit counters for all cylinders(top) and bore holes (bottom). The calculated volumes are combined by multiplying the normalized voxel values (which represent spatial probabilities) of volume *a* and volume *b*. Equation 1 calculates the collision probability v_{ab} of the joined parts for every voxel. Figure (right) shows the probabilities in percent. The collision probabilities can also be visualized by color-coding.

$$v_{ab} = \frac{v_a}{n_a} * \frac{v_b}{n_b} \tag{1}$$

v_a, v_b : voxel hit values; n_a, n_b : number of voxelized non-ideal variants

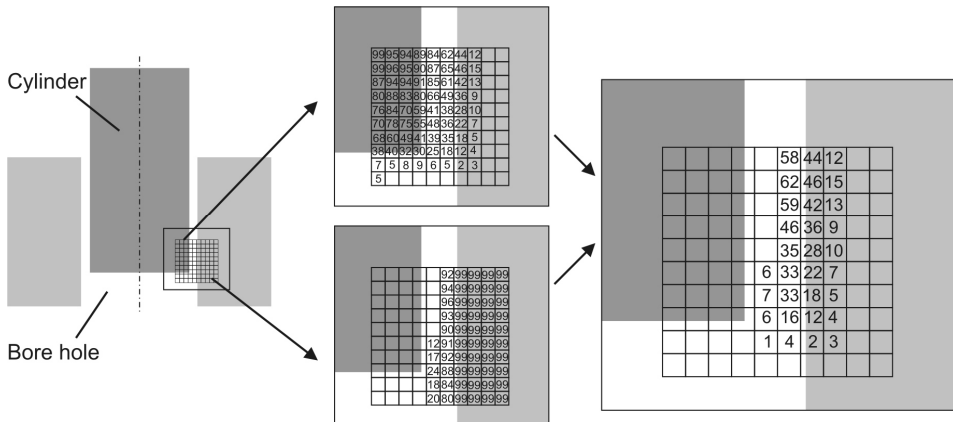


Figure 6. Intersection calculation of volumes (shown in 2D for $n_a=n_b=99$ cylinder and bore hole variants): generation of volumes for cylinders and bore holes, combination of both

The usage of probability volumes has the advantage that all possible collisions can be calculated in a single step. If the calculation would be performed on triangle meshes, the enormous number of $n_a * n_b$ intersection calculations would be necessary.

In Figure , the 10.000 non-ideal cylinders described in section 4.1 have been intersected with 10.000 bore holes. The cylinder positions are independent of the bore holes. The figure shows the cylinder volume (left), the bore hole volume (middle) and the intersection of both (right).



Figure 7. Combination of cylinder (left) and borehole (middle) variant volumes to generate a statistical collision region (right)

As can be seen on the intersection, the cylinders do not collide uniformly at all sides of the bore hole, but only at two areas. This corresponds to previous results (Figure), which revealed that the inner cylinder mostly varies in y-direction. For functional reasons, the parts of the studied assembly should not touch. The visualization revealed that this is not the case for the simulation results.

5. Conclusion

In this paper, we presented several developed visualization methods for the analysis of non-ideal parts. Objective of these methods is the support of product developer by giving a geometric interpretation of tolerance impacts. For each presented visualization method, the underlying concept is explained and a

suitable visualization example is given. We suggest the usage of different methods for the analysis of individual non-ideal parts and assemblies and for statistical analysis of multiple variants in a single scene.

For the analysis of surface data, surface smoothness can be examined by comparing surface normals. In contrast to pure distance measurements, this method reveals discontinuity of parts. It is especially useful to find dents on large sheet metal parts and unsteadiness of adjacent parts. Gaps between parts can be examined by a high number of distance measurements. Therefore a tool for semi-automatic gap detection has been implemented. The resulting point-to-point measurements can be displayed color-coded with an additional histogram of value distribution.

A method for the geometric analysis of huge numbers of non-ideal parts has been presented. In contrast to the numeric output of common tolerance analysis tools, the volume visualization method preserves part geometry as well as statistic information. Probabilities are mapped to color and transparency values in a three-dimensional scalar dataset. Due to the advance of modern graphics hardware, these datasets can be rendered in real-time on standard PCs. The volume visualization of deviations has been extended by statistical analysis of collision probability for independent parts. The resulting visualization shows where parts can collide due to their allowed deviations of the ideal shape and how probable these collisions will occur. Advantage of the volume visualization is, that results of statistical simulations can be analyzed in a comprehensible way. Aim of the developed visualization is not the replacement of established statistic methods, but their enhancement. It can be used to support both tolerance analysis experts and product developers. For analysis experts, it offers the opportunity to study a whole region of a product instead of a single measurement value and therefore contains more information. For product developers, it offers better insight and understanding of tolerance effects because of a geometric representation. This way, it also improves communication between tolerance analysis experts and product developers.

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