VOLUME VISUALIZATION OF GEOMETRIC DEVIATIONS

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ABSTRACT

Manufactured parts always have deviations from their nominal geometry designed in the CAD-system. These deviations are restricted in range by the tolerances the product designer has defined. The synthesis of appropriate tolerances is typically supported by tolerance simulations which return statistic results like distribution curves at defined measurement points, but the related geometry cannot be visualized within the tolerance simulation. Preparation and statistic analysis of toleranced CAD geometry is currently done by experts, not by the product designer himself.

We present an approach that allows geometric interpretation of tolerances and their interactions. The method is divided into three steps: Multiple non-ideal parts are generated by a simulation. Afterwards they are combined into a single dataset by finding an appropriate transformation which is collision-free with respect to the surrounding assembly and does not violate the defined position tolerances. The resulting volume dataset that represents all non-ideal parts can finally be visualized using techniques known from medical data analysis. The proposed method assists the product developer in tolerance synthesis by providing three-dimensional views of the impact of the defined tolerances, instead of presenting the output of statistic analysis. These views help to define meaningful, coordinated tolerances for new design solutions or to reconsider existing tolerance concepts. Another application of our method is the analysis of huge amounts of measured surface data in quality assurance.

Keywords: Tolerance Analysis, Visualization, Relative Positioning

1   INTRODUCTION

Real parts always have deviations of their ideal geometry, which is fixed in the modelled CAD-geometry. The origins of these deviations are faults and inaccuracies in manufacturing process, which accumulate in the assembling process. The result of deviations in dimension, shape and position can be that the parts do not fulfil the aesthetic design requirements or even functional requirements. The engineers are responsible for this task by allocating tolerances to limit permissible deviations. Tolerances therefore represent geometric boundary conditions. Their placing is an important instrument to protect the product quality. With the placing of tolerances the designer also considerably influences the product costs. High demands on tolerances of parts (close tolerances) lead to special accurate manufacturing and inspection methods and thereby cause a more expensive product in the end. The designer has therefore a high responsibility when defining tolerances, with regard to both costs and product quality.

For function compliance of a product usually several types of tolerances have to be taken into consideration. Every single one of the identified dimension, shape or position tolerances is described by complex definitions. Additionally several types of tolerances influence themselves mutually. These aspects lead in the end to the fact that the tolerance allocation becomes very hard to understand. Unfavourable combinations of tolerances and resultant failures in the product functionality can not be predicted by the product designer when only CAD-data is available. Often resulting failures will be recognized in manufacturing or assembly processes.
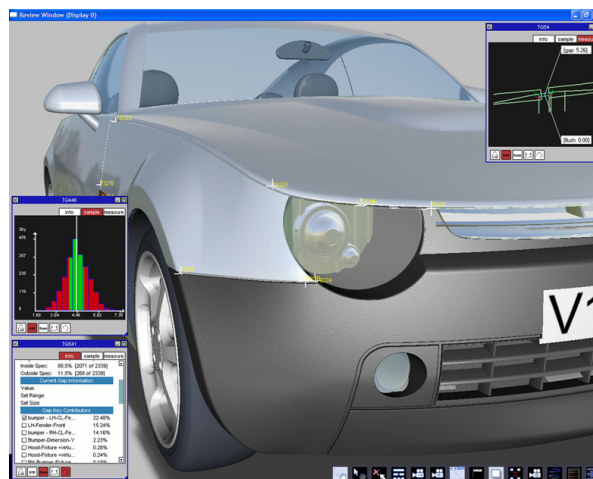
To support the designer in his responsible work, commercial analysis-tools for tolerance simulation are available. With the assistance of such tools optimal default values for tolerances should be determined. In the result the engineer acquires statistical data for varied deviations and curves of distribution for the area of critical dimensions. The main problem of using such analysis-tools is the

appropriate interpretation of the simulation results. Therefore, tolerancing specialists with specific knowledge and education are necessary. On the one hand this leads to the fact that the development process is extended by additional process steps to carry out the tolerance analysis. Besides, it requires special competences in the enterprise to interpret the results. Iterations in the development process can not be avoided to carry out corrections in the design of the product as a result of the investigations. On the other hand the resulting statistical data is not offhand interpretable for the product designer. The consequences of the tolerance definition are often not clearly enough perceived or not interpreted as critical because the simulation results are detached from the geometrical objects. For a better understanding, it is obvious to combine the CAD-data with the data from tolerance simulation and to visualize the results in a suitable way. Our goal is to provide the product designer a tool to show him the geometric consequences of the defined tolerances and existing connections between the tolerances. This would give him greater insight and understanding than the correction of tolerance values by analysis experts.

2   RELATED WORK

This chapter will give a short overview on related research in computer aided tolerancing, ranging from works on assistant systems to specialized deviation visualization techniques.

A system to derive tolerances from a description of form elements and their functional criteria is presented in [1]. The resulting tolerance zones are analyzed concerning manufacturing, using modelled stochastical simulations of machine precision for different processes (turning, grinding, milling etc.). Furthermore, inspection criteria are checked with a database of measurement uncertainty for stored measuring instruments. Söderberg et al. [13] give an overview of current commercial computer aided tolerancing software and research projects. They structure the process of geometry assurance 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). For each phase, examples of software tools are mentioned, especially new developed tools for visual tolerance data analysis. The commercial software Aesthetica™ (see [14]) is based on the research project VITAL (Visualizing the impact of tolerances) at the University of Leeds. Maxfield et al. [5] describe the use of free form deformation and force density method to generate non-ideal parts. Their software focuses on the realistic rendering of certain areas to find aesthetic problems.

Figure 1: Visualisation of geometric variations in Aesthetica™ [14]

Koch and Meerkamm [8] present different visualization methods for non-ideal parts, structured in geometric representation methods and color coding of deviations. Surfaces within the tolerance 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.

The papers [5] and [8] mentioned above demonstrate methods to visualize non-ideal parts resulting from defined tolerances. They are limited to a single combination of non-ideal parts per scene. As Wichman et al. [10] point out that there is no such thing as "the worst case" of deviations for a

complete assembly. Consequently, it is useful to show combinations of non-ideal parts to interpret impacts of the used tolerances. Lööf et al. present a method to calculate the convex hull of geometry variations from computer aided tolerancing software [4]. For each triangle of the used mesh, they vary the vertices in the allowed range and generate a tolerance hull by combining the results. An advanced version of the software is used in [16] to show the tolerance hull of measured motor movement.

In this paper we describe the visualization of several possible variations of parts in a single dataset and the representation of the probability of appearance in the visualization. Intermediary results of the volume visualization concept can be read in [9].

3   VOLUME VISUALIZATION OF DEVIATING GEOMETRY

The following subchapters describe the proposed process of generating and visualizing a volume dataset representing the impact of defined tolerances on the geometric results. They are structured in generation of deviating parts, joining of these parts, transformation in a discrete representation and analyzing with different methods.

3.1   Simulation of non-ideal parts

The geometry used for the proposed method is a triangle mesh of high quality converted from CAD-data. The maximum edge length and tessellation error of the mesh is set according to the used measures and has to be much smaller than the defined tolerances.

The proposed method is situated early in the design process. Manufacturing methods or even assembly machines are not known in this stage, so we do not try to simulate a manufacturing or assembly process with Finite Element Analysis like [11]. Instead, we generate possible geometry variations within the defined tolerance zones.

Our method works with the triangulated mesh of the ideal geometry which consists of vertices connected by edges. To generate non-ideal parts, the vertices of the mesh are displaced within the tolerance zone. For certain methods (e.g. random change of each vertex) it is necessary that every vertex of the ideal mesh has unique coordinates. We implemented different methods which can change the height, width or depth of a part, and methods which apply sinus curves to the ideal part.

It is necessary that the deviating parts cover the whole tolerance zone; otherwise the resulting volume visualization will not provide accurate results. Therefore our implemented method is able to generate different variations of one part equally distributed around the tolerance zone. Details on the used methods to create non-ideal variants out of triangulated ideal parts can be read in [3].

3.2   Relative positioning / Registration

The non-ideal geometry produced by the geometry simulation has to be rotated and translated in space in order to replace the ideal parts of the assembly with the simulated parts. For this purpose, an optimal positioning has to be calculated where the deviating part does not collide with its environment and it does not float, see Figure 2.
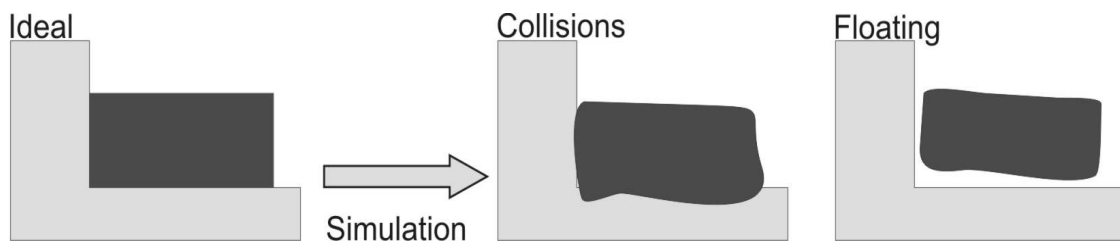

Figure 2: Positioning problems of the non-ideal geometry (exaggerated)

Furthermore, defined position tolerances have to be taken into account. To solve this so called relative positioning problem, an optimization framework has been implemented [15].

Criteria describing the boundary conditions were formulated as objective functions which are summed up. For example, if collisions of the positioned non-ideal part with its environment are detected, a high constant value is added. To achieve a position close to the nominal geometry, a distance function between ideal and simulated part is calculated. Goal of the optimization process is to minimize the

sum of objective values, in this example to find a position close to the ideal part, but without collisions with the surrounding assembly. Other currently implemented functions are: Hausdorff distance, contact points and position tolerances. Further objective functions can be integrated as new boundary conditions, which gives this method a high flexibility to solve arbitrary positioning problems. Result of the positioning process is a transformation and rotation value for each part. The calculation time of this process depends on the complexity of the used geometry and on the objective functions. Example: The positioning of a part with 1223 triangles in an assembly of 3592 triangles, optimizing summed squared distance, parallelism, collisions and contact points took about one minute on a Pentium 4 3.2Ghz with 2GB RAM. More experimental results and details of the optimization framework can be found in [15].

3.3   Voxelization

When the position of each part is known, the parts can be combined in a single volume dataset. At first a rectangular box with axis-aligned edges has to be chosen as region of interest. The box is divided into very small areas, so called "voxels" (volume elements), which means voxels are the smallest discrete unit in three dimensions (analog to the term "pixel" in two dimensions). Figure 3 shows an example of 64 voxels.
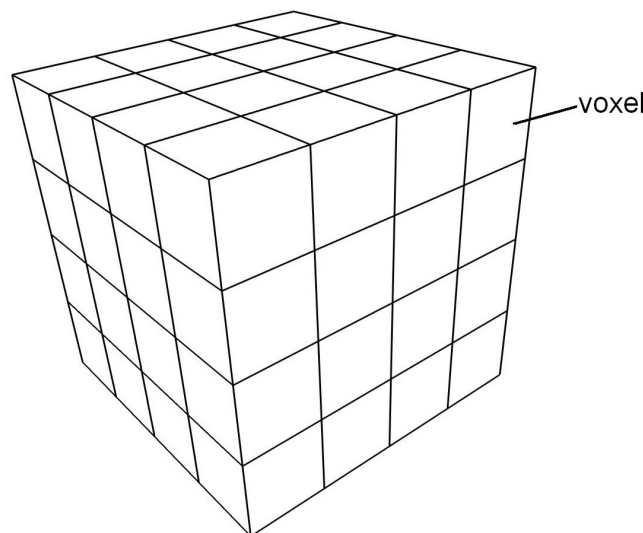

Figure 3: Volume data

Each voxel can store a numerical value. The chosen voxel size depends on the size of the considered part and the used tolerances. To be visualized interactively, the volume data has to fit in the texture memory of the graphic card; 256 Megabyte RAM is common in modern graphic cards. We use an unsigned short value (2 bytes) per voxel, so it is necessary to use less than 512^3 voxels. The algorithm which is used to create the volume dataset is shown in Listing 1. This algorithm is called for every generated non-ideal part.

```
For each triangle t inside area of interest
        Calculate bounding box b of t
        For each voxel v in b
            If v.hits not increased yet
                If t intersects v
                    Increase value of v.hits
```

Listing 1: Algorithm to create the volume dataset

After this process every voxel contains the achieved number of hits. In Figure 4, our approach is illustrated in two dimensions. By normalizing the number of hits, we obtain the approximate probability that the surface of the toleranced part will intersect this voxel.
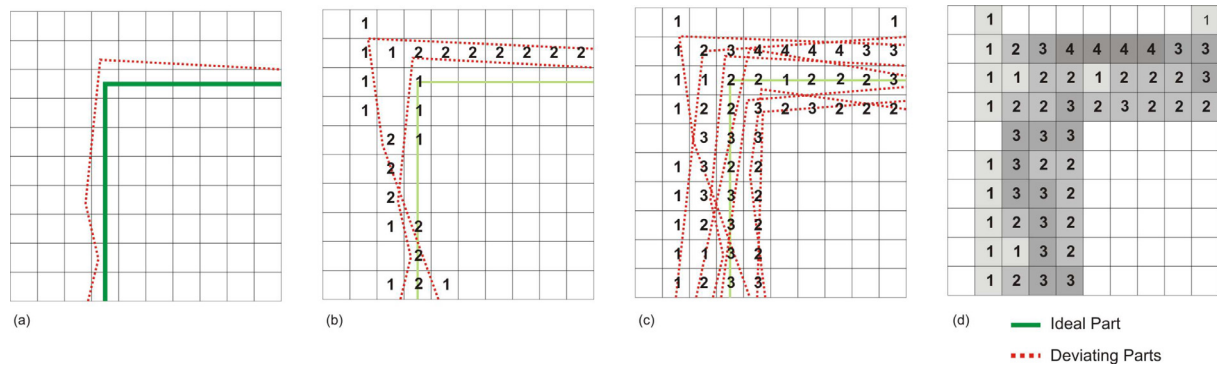

Figure 4: Successive generation of the volume dataset (source: [9])

3.4   Visualization

The previously generated volume dataset can be compared to data from three-dimensional medical data acquisition. There exist several visualization techniques developed for this type of data, ranging from slice images to real-time volume rendering on modern graphic hardware.

Data Preparation

Each voxel stores a density value between zero and one. To create a visualization, it is necessary to map every scalar value to a graphical interpretation, for example a color and a transparency. This is done by so called transfer functions or lookup tables. In Figure 5, high values (which mean high probability of intersecting geometry in our case) are completely opaque, lower values are semi-transparent or invisible. Figure 4(d) shows an example of color assignment dependent on hit numbers.
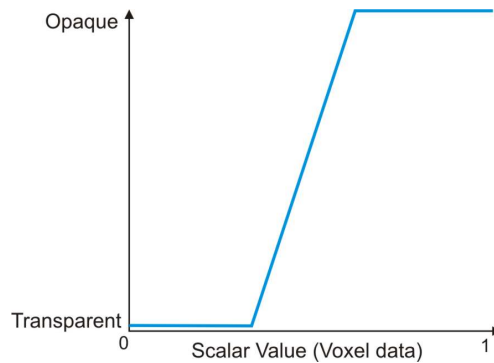

Figure 5: Mapping of scalar voxel data to transparency values

For the color mapping of red, green and blue, additional transfer functions have to be defined. The transfer functions can be used to classify the data and to mask certain voxel values, for example voxels with very low hit probability and empty voxels.

Slice Images

A possibility to obtain conventional 2D images from the three-dimensional data is to intersect the volume cube with a cutting plane. This method allows the analysis of very large datasets because the visualization can be preprocessed. The cutting plane can be moved through the volume by the user, either axis-aligned or in arbitrary direction. Result of the visualization is an image comparable with X-ray images. The slices do not show the integral of rays through the volume but the intensity values (in our case from the voxel hit values).

Iso Surfaces
The volume can also be transferred into triangle meshes. This can be done by the selection of a threshold value. Algorithms like Marching Cubes [7] extract surfaces with the same threshold from the volume, these are called Isosurfaces.

Direct Volume Rendering
The whole volume dataset can also be rendered as a volume object on the graphic hardware. With current graphic cards, it is possible to load up to 256 Megabyte data in the texture memory. A 2D-texture can be used to implement the transfer function, the final color- and transparency-value is a combination of both textures. By showing a high number of slices through the volume cube, the data can be viewed with interactive framerates. This method is limited by the high memory consumption of volume data.

4   EXAMPLE

To demonstrate this concept, an assembly of a carrier and a guiding has been modeled and toleranced in Pro/Engineer. The carrier consists of a countertop and two rails, the guiding is made up of a pillar and two hollow sections, as illustrated in Figure 6.

Critical in this assembly is the mating of the rails with the guiding: If the allowed shape deviation of the rails is too high or the rails are not approximately parallel, they won't fit in the hollow sections. Consequently, the focus of visualization is the zone between rails and hollow sections. In the nominal design, there is a seam of 1mm between rails and hollow sections at each side.
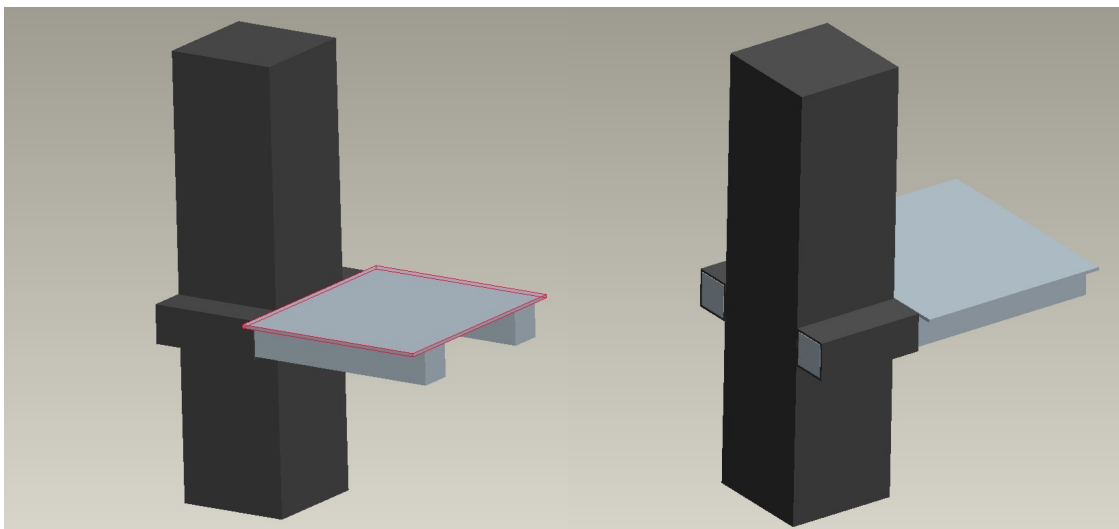

Figure 6: The modeled carrier (grey) and guiding (black)

In this example, we assigned profile tolerances for the countertop and the two rails. The tolerance of the countertop has been set to a very high value, so if the deviations are close to the maximum value, the countertop cannot be placed inside the hollow sections anymore.

The carrier was modeled with 14325 triangles (7183 triangles countertop, 3571 triangles for each rail), the nominal guiding has 99 triangles. The low number of triangle for the guiding produces no tessellation error because its surfaces are completely flat.

To provide meaningful results, a high number of simulated non-ideal carriers is needed. The generation of the carrier is realized by the combination of different non-ideal countertops and rails. For the countertop, different degrees of variation between maximum and zero deflection in variable directions were created within the tolerance zone. A similar algorithm was applied to the rails. This way, parts with different deviations that cover the whole tolerance range are created and assures that the non-ideal geometry covers the complete tolerance zone. All variations of the countertop were then combined with all variations of the rails by applying the relative positioning algorithm described in [15]. Used objective functions were "Summed Squared Distance" and "Collisions".

After this step, there exised 121 different variations of the carrier assembly. Finally, the carriers were assembled in the nominal guiding, using the same objective functions as above for positioning. The simulation only needed a few seconds to generate all parts, but the relative positioning of one assembly needed about 7 minutes, therefore we limited the generation to 121 different assemblies. As an intermediate result, the carriers which could not be assembled without collisions were detected; they can be filtered out if wanted. The non-ideal carriers in assembly space were successively inserted into a volume dataset of 400x400x400 voxels (128 Megabytes) with a voxel edge-length of 0.1 mm. The volume dataset contains all variants of the end section of one rail, assembled in the hollow section. Figure 7 shows the selected discretization area as a red box.
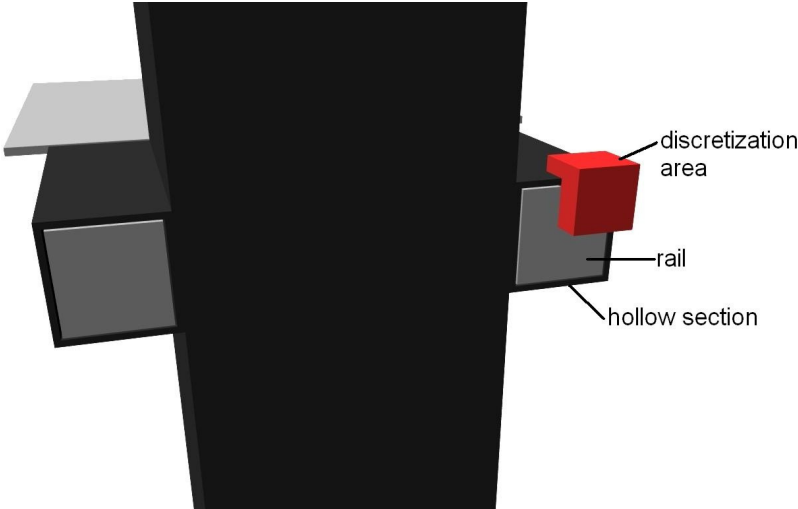

Figure 7: Selection of the discretization area

As a visualization tool for the volume, the commercially available software Amira® was used. The transfer functions of Figure 8 and Figure 9 were defined by the authors. The corresponding colormap is rendered in the lower left corner of the visualization, defined for voxel hit values between 0 and 80. The visualization in Figure 8 shows the discretization area viewed from inside the hollow section, looking into the reader's direction. It reveals that all variants of the vertical right rail edge lie in an area of small geometric range with high probability, represented by voxels with high hit values (yellow and green). Just a few variants show greater deviations of the nominal position; these are rendered as a red cloud with high transparency. All variants of the vertical rail edge (visualized red-yellow-red) fit in the hollow section and preserve a seam, which means there are no assembly problems at this area.

Note: Because of the color coding, Figure 8 and 9 can not be interpreted when printed black/white.
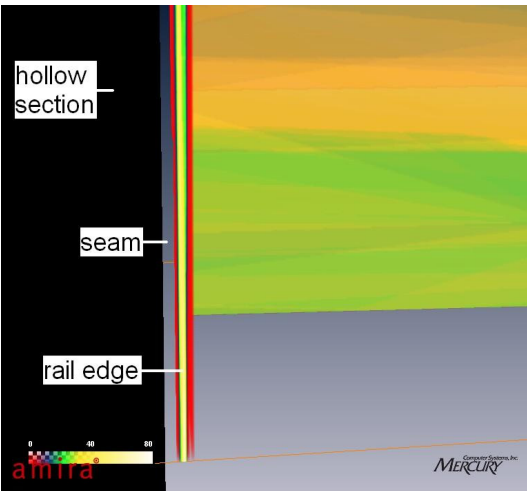

Figure 8: Direct volume visualization of the rail edges

The second visualization scene (Figure 9a) shows in contrast the horizontal rail surface at the upper side, which bears high geometric variance. The surface has an area of increased hit values (blue voxels) in the middle, but the hit values are way below the maximum possible hit values. Most of the positioned variants of this surface appear less than 5 times per voxel, resulting in a blurred red area around the ideal position. There are many variants close to surface of the hollow section, leaving a very small seam, which indicates a mating problem. The front of the rail which points out of the hollow section is rendered yellow and green with a thin red coating, which means this surface barely varies.
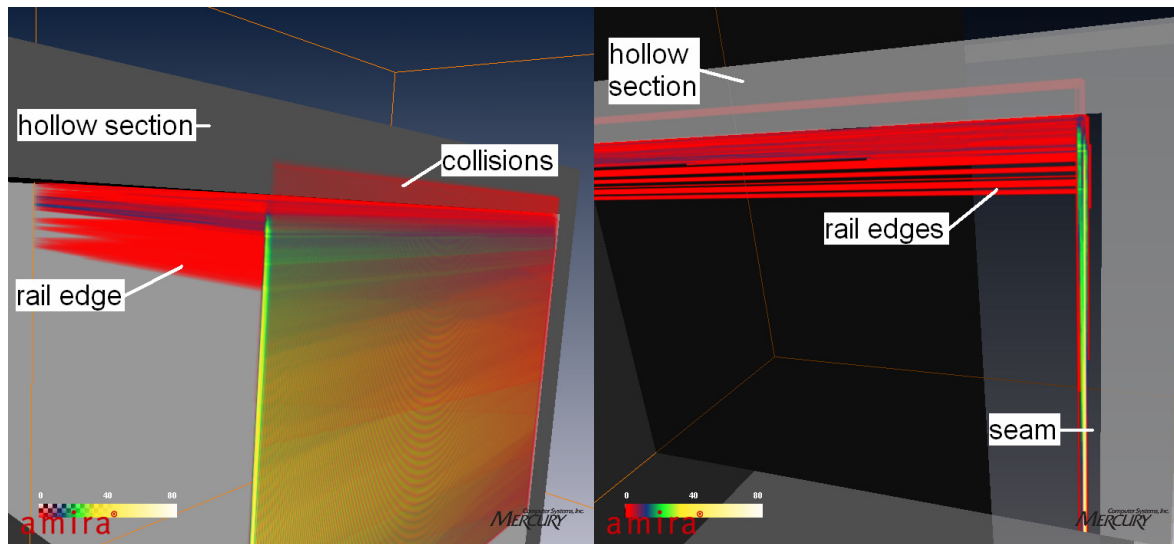

Figure 9(a,b): Volume and slice image visualization of high geometric variance

Figure 9b shows a single slice image through the generated volume dataset. The red voxels within the hollow section reveal that some variants of the geometry could not be positioned without collisions of the rail with the hollow section and lie above the other variants.

5   CONCLUSION AND FUTURE WORK

In this paper, we present a visualization method for large quantities of non-ideal parts. Purpose of this method is the support of the product designer in tolerance definition, to give him better understanding of the impacts of tolerance definition. The three-dimensional display of simulation results improves the interpretation of tolerance effects and is intuitively understandable for the product developer, in contrast to the statistical results of commercial computer aided tolerancing software. A mapping of statistic values to a graphical representation (i.e. transparency) establishes the direct connection between abstract simulation results and part geometry. By the integration of an arbitrary number of simulation results in a single volume dataset, it is possible to visually process and interpret great amounts of data. The visualization in a scene is an advance compared to the ordinary way of analyzing distribution curves for chosen measurement points. It is no longer necessary to choose measurement points for the analysis, instead, a whole area of interest can be analyzed.

For fast and efficient use of the proposed method, the deviating geometry has to be generated automatically by a Monte Carlo simulation that preserves the defined tolerances. Also, the positioning of non-ideal geometry, which is currently the bottleneck of our method, has to be accelerated to allow faster analysis. This can be done by parallelizing the needed calculations. The combined visualization of volume dataset and nominal mesh of the examined geometry is not yet solved satisfying. It has been tried to render the nominal mesh as a semi-transparent face, but this interfered with the visualization of the volume. In the current implementation, a surface can either intersect a voxel and increase the counter by one, or not. The hit value is increased by one even if the intersection area is very small, for example through a voxel corner. A better quality of the visualization could be reached by raising the voxel value dependent on the size of the intersection surface, comparable to anti-aliasing.

Another possible analysis method that will be tested is the calculation of differences between two calculated volume datasets. This would enable the visualization of the geometric position and degree of variations when changing the tolerance definition.

The volume visualization could also be applied on real measured surface data. Results of thousands of measurements can be combined in a single image for easier interpretation. The volume datasets of surface measurements and simulations can be compared to check if tolerance simulations produce realistic output.

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