TOLVIS – VISUALIZATION OF POSSIBLE SHAPE VARIATIONS RESULTING FROM SHAPE AND POSITION TOLERANCES

Alexander Koch, Harald Meerkamm

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Abstract

To receive a technology leadership in global markets an explicit competitive advantage is the optimized tolerating of components regarding high-quality products and economical production. The correct tolerance specification within the design process is already very complex and requires a fundamental knowledge about the problem as well as a large experience in tolerating. The effects of complex shape and position tolerances in interaction with lightweight sheet parts are very extensive and difficult in their interpretation. A detailed computer support, that already is state of the art in many fields of the product development today, is not satisfying in fields of interpretation of tolerance analyses, because their results can still be evaluated only by specialists. The results preparation and representation of tolerance-afflicted components and assemblies by common understandable possibilities of visualization can facilitate their interpretation substantially and thus results can be interpreted also by developers and designers themselves. This paper describes a project with the objective of visualizing shape variations resulting from shape and position tolerances. These shape variations are the starting point for the simulation of position variations of parts inside assemblies. If those variations can be visualized the interpretation of tolerance analysis results is much more comprehensible and cost extensive tolerancing decisions can be made more safe and funded.

1   Introduction

Virtual Reality (VR) is a very effective and useful tool for visualizing geometry in all stages of product creation. Particularly in the product design stage there are many possibilities for an extensive usage of immersive stereo projection units. Starting from design reviews via assembly inspections concerning e. g. accessibility of tools or disassembly up to ergonomic simulation VR can be used in nearly every partial stage of the product design process (cp. Figure 1). Especially design reviews are widely-used in different branches and company sizes.

Figure 1. Examples for the use of virtual reality in different stages of the product design process

Normally no additional information besides geometry is displayed, which means only the geometry of a part or an assembly is displayed and no information is included about e. g. material, stiffness or something like that. Also information about manufacturing and the herefrom resulting surface quality is usually not included in VR-scenes. Another point is the use of colors in VR-scenes. Usually colors represent only different parts in assemblies which means every part has an explicit assigned color respectively diverse parts with the same color are combined to groups e. g. with the same functional context. Additional information is neither attached to the geometrical presentation nor to the color presentation like known from FEM analyses, where colors represent for example different stresses, temperatures or displacements of the nominal shape.

The conclusion of these facts is the visualization of solely nominal shape of parts and assemblies in VR. State of the art engineering workbenches offers the possibility to enlarge nominal shape of design objects with additional information about different categories. Usually not only materials and surface qualities can be assigned to parts and assemblies. Manufacturing methods and their appropriate specifications, join technologies or even functional details of parts or subassemblies can be set. Some of this information could be used to extend conventional VR-scenes and to open up a new era of immersive visualization – but they aren't. All this additional specification can contribute to a more realistic and more detailed visualization of single parts, components and assemblies or the whole product.

Shape and position tolerances contain a combination of functional and viewing aspects of a product. They sustainable affect the functions of a product. If tolerances are chosen to generous the production costs are low but the number of subsequent machining increases. Are they chosen to tight the functionality can be guaranteed but the costs for their achievement will grow dramatically. Further the variation of shape resulting from the shape and position tolerances causes – added up in assemblies – variations of the position. That means for example a cars door fits into the side panel but the gap is unbalanced which causes a reduced sense of quality. If it is possible to visualize not only the nominal shape of parts and their nominal position within the assembly but also show possible shape variations and herefrom resulting position variations design reviews could be get much more realistic. Decisions about tolerances often are costly and therefore they mostly are made by managers and chiefs which usually not are experts in tolerancing. Visualizing the impact of tolerances on the product functionality and behavior can help to make these decisions faster and safer to reach.

This paper describes a project with the objective to show a new way of visualizing parts from CAD in VR and their possible shape variations resulting from the shape and position tolerances given within the design process. First it will be explained how the CAD system and its data model have to be enhanced for storing and providing tolerance information to other software tools. In a second step the simulation of shape variations is shown. The third part of this paper will explain new possibilities of displaying geometry in VR, how colors and textures can be used and a completely new way of representing surfaces is introduced.

2 Common interpretation of tolerance analysis results and potential for optimization

Common tolerance simulation applications are very powerful and extensive tools for experts. Most different kinds of tolerances, mounting situations and geometrical conditions can be simulated. In the meantime it is possible not only to simulate inelastic parts. The integration of elasticity in conventional tolerance simulation software is the subject of current research projects (cp. [1]). All of those software tools provide distribution curves, process capability

indices and tabular contributor reports as the simulations results – exemplarily mentioned can be VisVSA® (cp. [2]). These results are very significant but not easy to interpret and understand. Experts are needed not only for the simulations preparation but also for the interpretation of the results. An example of a common procedure in tolerance synthesis, simulation and analysis is given in Figure 2. Usually geometrical and tolerance information are exported separately from CAD system to the tolerance simulation application which means that in most cases the tolerance information must be redefined. After the simulation process different reports and graphs are generated for the following analysis. In case of needed corrections of the designed tolerances all steps must be done again which means in most cases there is no direct way back from analysis to the tolerance design stage.
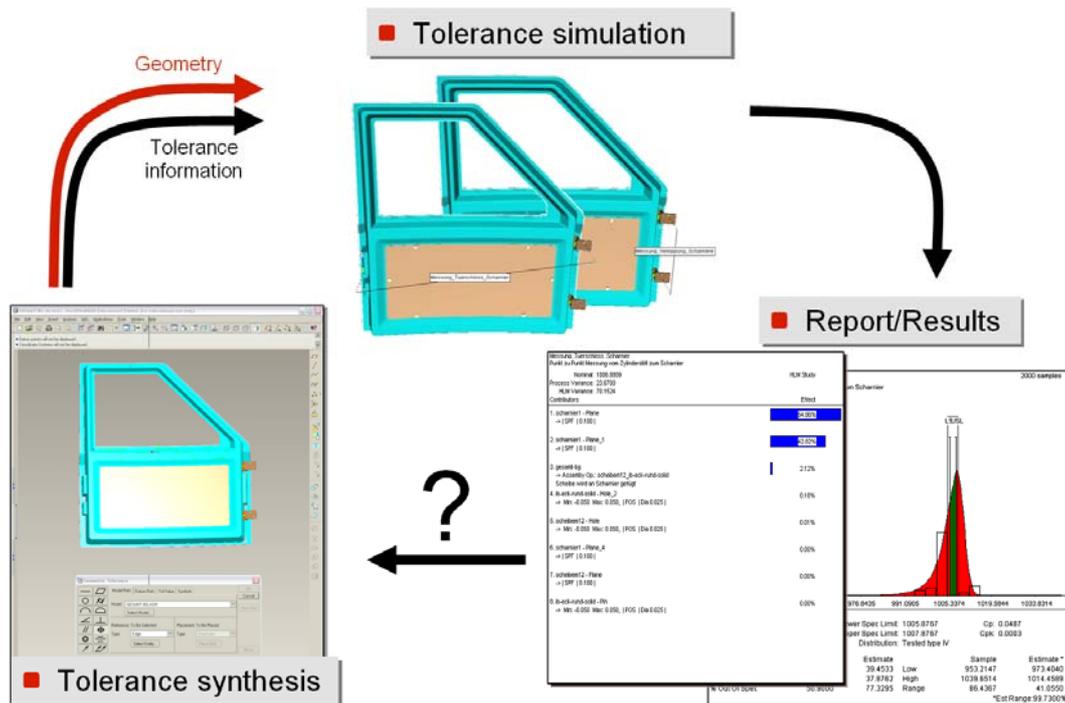

Figure 2. Process of a common tolerance simulation and analysis procedure

As noted above the interpretation of analysis results is laborious, extensive and can only be made by experts. Therefore this papers objective is to introduce a new possibility of results preparation for the presentation in VR to make them more comprehensible for non-experts and easier to evaluate for the designers. A first concept of the visualization of shape variations is given in [3] and [4], intermediary results and their integration into the product creation process can be read in [5]. All results introduced here in this paper as well as the whole engineering workbench and all modules are descended from the project A1 "Optimization of the process chain by choosing the most suitable topology and design for manufacturing aspects of products" of the Collaborative Research Centre CRC 396 "Robust, shortened process sequences for lightweight sheet parts", funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG).

3   CAD model preparation for the visualization of shape variations

Common CAD systems provide the possibility to apply tolerance information to geometrical elements of the design object. In case of position tolerances additional information concerning reference systems can be defined. But the problem is the nonexistent possibility to export this information together with the geometry to an application independent data set for further

processing. As an example for this possibility the CAD system Pro/ENGINEER© and the tolerance analysis application VisVSA® can be named. Some solutions with large scale integration are available so that the whole model preparation (which means the definition of geometry and tolerances) takes place in the CAD system and the complete information is transferred to the tolerance analysis software. But the data format is encapsulated so that other applications later in the product creation process are not able to use this tolerance information for example in manufacturing or quality assurance. An example for such an integrated but enclosed solution is CATIA V5® and 3DCS©.

At the Institute for Engineering Design at the Friedrich-Alexander-University of Erlangen-Nuremberg an engineering workbench was developed and implemented for the holistic assistant of the designer accomplishing the design tasks. A detailed description of this engineering workbench and all provided functionalities is specified in [6]. Also described is the product data model laying behind the engineering workbench. This data model is a hybrid data model for storing all product attributes concerning geometry and semantic information and is introduced in the following subchapter.

3.1 Hybrid data model for storing and providing both geometry and semantic product information

Basis of all applications and functionalities provided by the engineering workbench is the hybrid data model (cp. Figure 3). This model is explained in detail in [6] and thus it is only superficially specified in this paper.
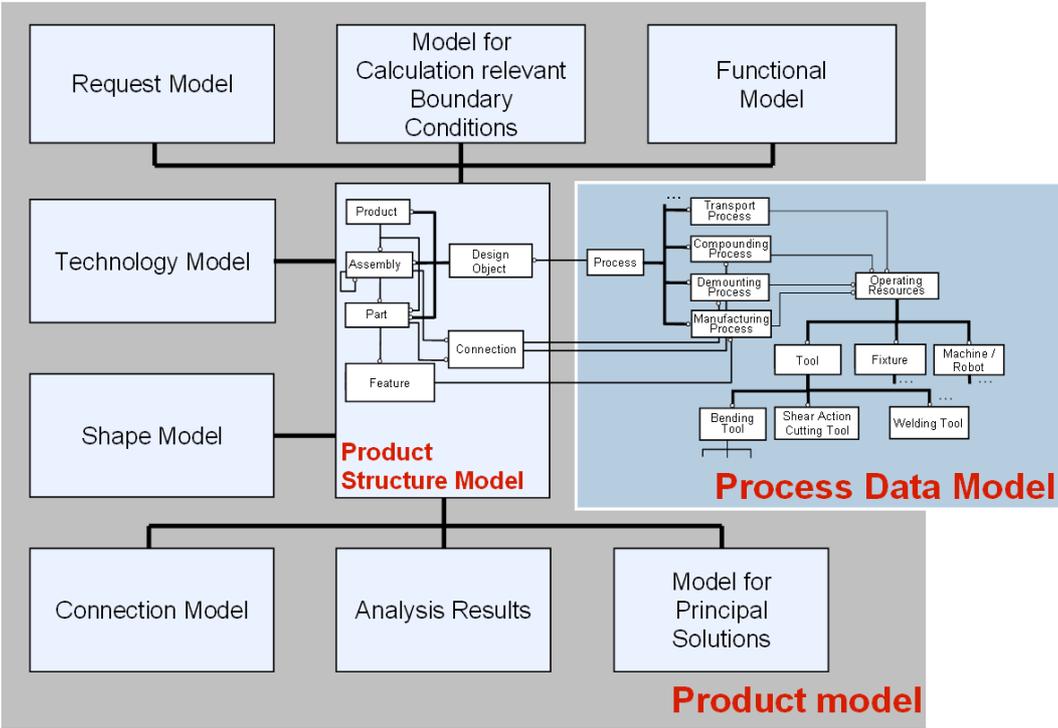

Figure 3. Structure of the hybrid data model of the engineering workbench

The product structure model has to be seen as the structural kernel of the model and holds all information about geometrical correlations like the hierarchy of a product and so on. To each element of this model a process like manufacturing or compounding processes can be assigned that are situated in the process data model. Connected to the product structure model are different partial models like a request model – holding specifications of the design task, a

functional model – holding information about the functionality of the product and e. g. the technology model for storing and providing all kind of semantic information concerning the technologies to be used. In this partial model technology all additional information about tolerances (cp. [7]) can be stored, too. With the realization of this partial model technology the starting point for the visualization of shape variation resulting from shape and position tolerances is set and the tolerance information is not only provided to specialized software.

3.2 Tolerance definition and model preparation

In this paper a continuous example is used for presenting the functionality and benefits of the tolerance visualization module. This example contains a section of a cars door bodyshell inside the side panel and the resulting cars door gap. In a conventional tolerance analysis of this example the main influencing factors for the position of the door were detected. One of these elements is the door locks mounting plain like shown in Figure 4 and their flatness. All results presented in this paper refer to this example. It is abstracted to a flat cuboid and one tolerated, simulated and visualized surface.
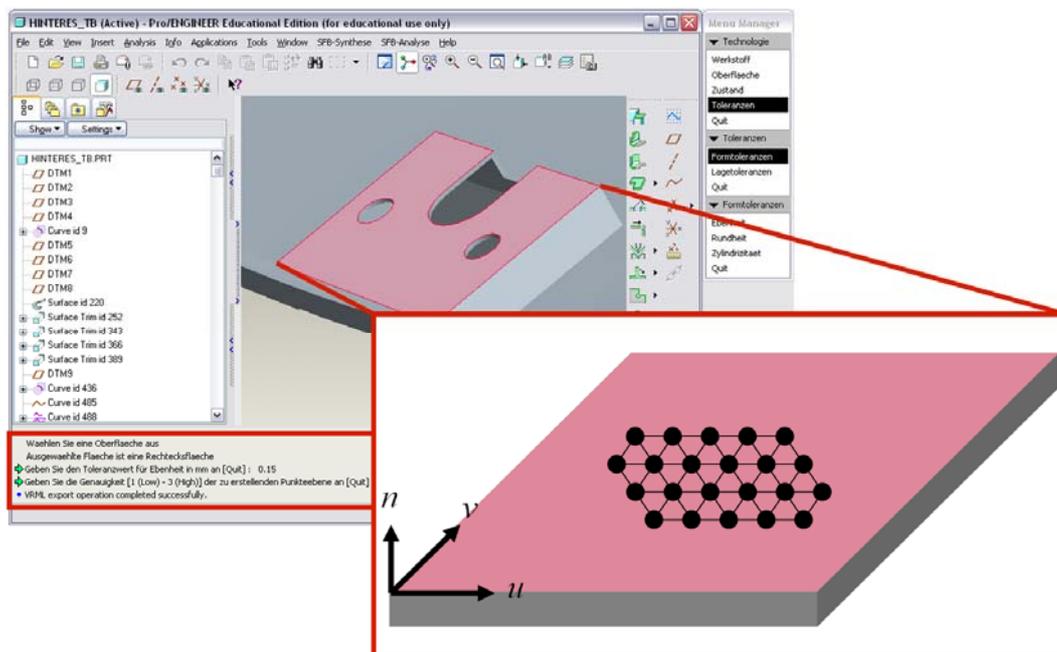

Figure 4. Tolerance definition and model preparation inside the CAD system

Because of the integration in the existing engineering workbench the tolerance design module is structured like all other existing modules. Starting at the synthesis menu with the selection "technology" first the tolerance to be given has to be set. All tolerances handled in this tolerance module refer to geometrical elements like surfaces or axes – the tolerancing of points or edges is not yet implemented. The next step is the selection of a geometrical element to be tolerated – in this example a plain using the flatness tolerance. Subsequent the tolerance range must be specified by entering a numerical value in millimeters. In the third step of the toleration and model preparation a factor for the density of the following meshing process of the surface must be given – this value can be "1" for the lowest density up to "3" for highest density of surface meshing. Finishing user operation of model preparation is the confirmation of all selections – with this confirmation a meshing process is initialized that meshes the whole surface to triangles. This triangular meshwork is not only used for the surface simulation explained in the following subchapter but also for further processing in the visualization process. The notation of the meshwork is an *IndexedFaceSet* – known from the VRML specifica-

tion. This is because the finally generated visualization scene is in VRML 2.0 format for being independent of operating systems, hardware platforms and projection units.

As the result of the tolerance arrangement and the model preparation three elements are exported out of the CAD system. First of all the whole geometrical model in VRML 2.0 format for the visualization of the topological context around the tolerated and simulated geometrical element; secondly the meshwork as an *IndexedFaceSet* as the starting point of the simulation and thirdly the tolerated surface as the *IndexedFaceSet* again but not to be simulated. This surface can be used inside the final visualization scene for comparing the original CAD surface and the simulated surface, which is explained in chapter 5.

4   Simulation of possible shape variations

Tolerances define a range in which the entire real occurrence of the tolerated element has to be located (corresponding to [8]). That means inside the tolerance range every technically realizable variation is allowed. But otherwise it means that a variation is not allowed if only a small area is located outside the tolerance range. An example of a cuboid with its upper surface tolerated with the flatness tolerance, the resulting tolerance range and two possible shape variations of the plain are shown in Figure 5.
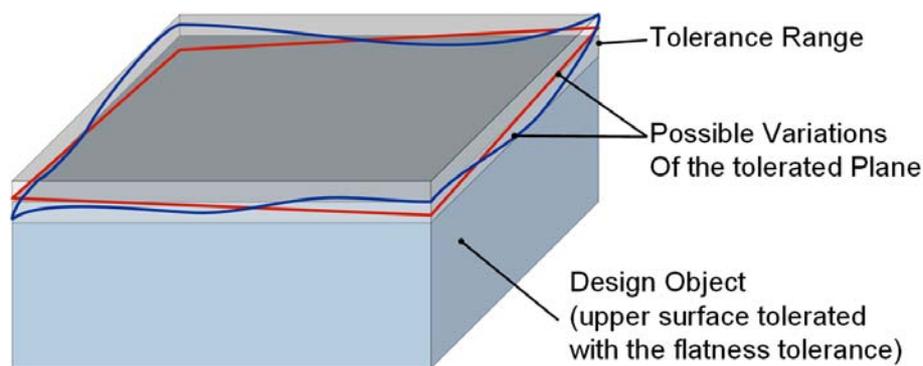

Figure 5. Tolerated cuboid and possible shape variations of the tolerated plain

Doing conventional tolerance analyses with specialized commercial software tools all possible shape variations are included. Their allocation is usually not dependent to different manufacturing and production processes like casting, milling or forging. Only a segmentation by Gauss or similar is included. The conceptual formulation for the simulation module consequently is to enable the possibility to simulate possible and allowed shape variations of the tolerated element according to the chosen and stored manufacturing process.

4.1 Simulation of a random shape variation

Initial Point of the simulation is the *IndexedFaceSet* described in chapter 3.2. That means the tolerated surface in this example is described not by mathematical equations but by points and connecting edges represented in a connectivity table. Additional the normal vector for each point of the point set is available too. These vectors are very important for the simulation of non planar surfaces which is described below in this chapter. Output of the simulation should be a deformed surface inside the tolerance range. Because of the further processing of all geometrical data in VRML scenes the output also should be approximately in VRML format. Therefore the *IndexedFaceSet* is predestinated to be directly manipulated by the simulation. Inside the *IndexedFaceSet* the order of all triangles is predefined and therefore the order of the points too. Starting at point number one the simulation manipulates the position of each point

inside the point set the same way. In Figure 6 a cut view through the point set is shown. The procedure of the point's manipulation is described in the following paragraph.
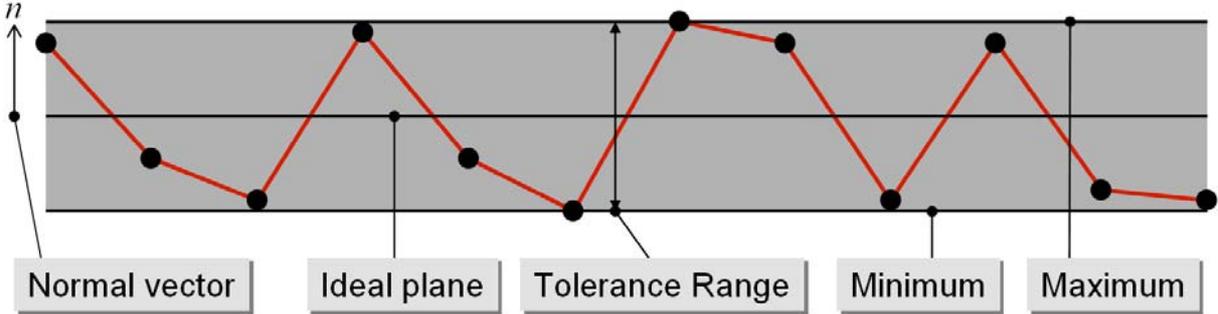

Figure 6. Side view of a random simulated shape variation of the tolerated plain

First of all a random number is generated and normalized to 1. This normalized number is assigned to the first point and describes his location inside the tolerance range. The value 0 causes a variation to the minimum – the point is located at the tolerance ranges minimum. The other way round the value 1 causes a variation to the maximum and the point is located at the tolerance ranges maximum. Thus a point stays at the original position if the random value is 0,5. The direction of the point's variation is according to the direction of its normal vector. That means each point is moved along the direction of its normal vector to its simulated position inside the tolerance range. This approach enables the possibility to simulate not only plains but all kinds of surfaces that can be tolerated according to [7] like a cylinders shell etc.

This procedure is executed for each point inside the meshwork. Finishing with the last point of the point set the simulation of a random shape variation of the tolerated surface is finished. The result of the simulation is a manipulated meshwork with an assured random position inside the tolerance range. Certainly this result is valid because of the definition of the simulation algorithm. But it is not close to reality because there is no control of neighboring points in this simulation method. So each neighboring points can vary from minimum to maximum. Therefore it is necessary to introduce a method to control each point's neighborhood for getting a shape variation close to reality like described in the following subchapter.

4.2 Consideration of a correction factor for the simulation

Like shown in chapter 4.1 it is possible to generate valid shape variations resulting from the tolerances given within the design process. But the variations are not stringently close to reality because of the random dispersal of the points inside the tolerance range. In most simulated cases the surface structure is very rough and looks like typical surfaces with processing scars. But firstly a shape variation close to reality should be simulated. For this it is necessary to manipulate the first result to get a variation less swaying like shown in Figure 7.
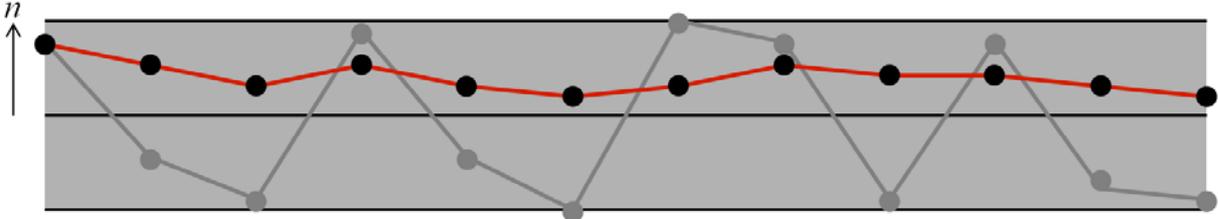

Figure 7. Simulated shape variation with consideration of the correction factor

This result can be reached by introducing a correction factor for neighboring points. That means each points neighbors may not differ more than the factor allows to. With every simu-

lation step the random number generated by the simulation algorithm is compared to each result for all neighboring points and – if necessary – corrected not to differ more than the factor allows. For example if the factor is set to 10% each neighboring point is corrected not to differ more than 10% in its normal vectors direction. With this adjustment it is possible to get a smooth swaying variation of the tolerated plain close to reality and certainly allowed according to the tolerance definition. The definition 10% of the correction factor is arbitrary and can be modified to any other value needed for a realistic simulation. But this factor opens up another possibility of variation manipulation which is explained in the following subchapter.

4.3 Introduction of manufacturing processes to the simulation

The simulation algorithm originally does not include any possibilities to create attributes according to manufacturing or producing processes. But with the correction factor described above it is possible to include rules for different process types. If a part is designed to be milled, processing scars according to the feed motion can be included for each simulated point. This corresponds to a manipulation in micro scale and does probably not affect a position variation of flanking parts but changes the friction behavior in assembly simulations.

The other possibility is to arrange the correction factor to an algorithm that manipulates the simulated surface in macro scale. Not only neighboring points have to be adjusted. A global rework for all points has to be applied to the simulation result for getting typical shape characteristics according to different manufacturing processes. This possibility is not yet implemented but planned. The impact of the simulation results and the subsequent effect for the visualization will be reported in future publications.

5 Possibilities of a manipulated shape visualization in VR

Like described in chapter 1 many possibilities for the use of VR within the product design process are known. Data from very different application can be visualized and the visualization can also be realized in many different ways. In this project a one-wall VR solution is used with typical attributes for immersive stereo projection like eye-tracking and so on. This VR unit provides the possibility to visualize VRML 2.0 data. So the CAD geometry data and the simulation results need not to be translated for the use with this VR unit. Another big advantage of this fact is the ability to use VRML scenes also in non immersive systems like browser plug-ins. So the simulation results can be visualized platform and operating system independent in the designers computing environment or in immersive VR units. Many other options of visualizing geometry are known (cp. [9], [10]). The decision on polygon nets in VRML format was made because of the hard- and software situation explained above.

Starting from this decision different visualization strategies were developed and implemented in a single application called TolVis for generating VRML scenes out of the shape simulation. TolVis provides the possibility to select different geometrical, coloring and texturing options for the entire visualization scene. All VRML constructs used in TolVis are only mentioned here in this paper – a complete description can be read in [11]. These strategies are exemplary and in constant advancement. In the following subchapters the geometrical representation, the color coding and the use of transparency is described.

5.1 Geometrical representation of simulated shape variations

In the stage of model preparation the tolerated element is attached with equidistant points all over the whole surface. In the next step these points are moved inside the tolerance range to a new position. The consequently easiest way of displaying the tolerated element is to visualize

the point set in VR. VRML offers the construct *PointSet*. Using this construct every point is represented in the VRML scene by a small square dot on the screen and to each point a color is assigned. The point cloud is not illuminated as well as no collision detection is available. An example for the visualization of a simulated surface by point clouds is given in Figure 8.
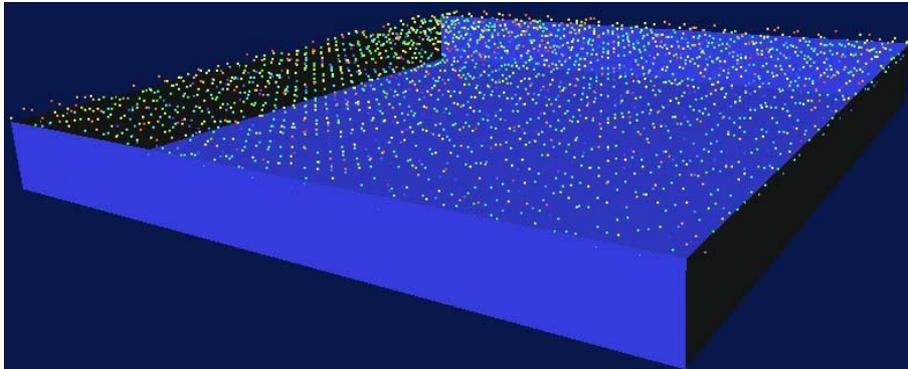
Figure 8. Surface representation by a point cloud

Further development of the point cloud is a sphere cloud. For this purpose the VRML construct *Sphere* is used. Instead of a point at each position a sphere is displayed. An Example for a sphere cloud is shown in Figure 9. The density of the meshwork is much lower than in case of the point cloud. The diameter of the spheres can be varied so that the impression of a closed surface can be given. This causes a much more spatial impression. But the impression of the surface is displaced because not the surface of each sphere but the center point is located on the simulated shape variation. The lower the density of the meshwork and the smaller the diameter of the spheres are selected the closer to reality is the visual impression of the simulation result.
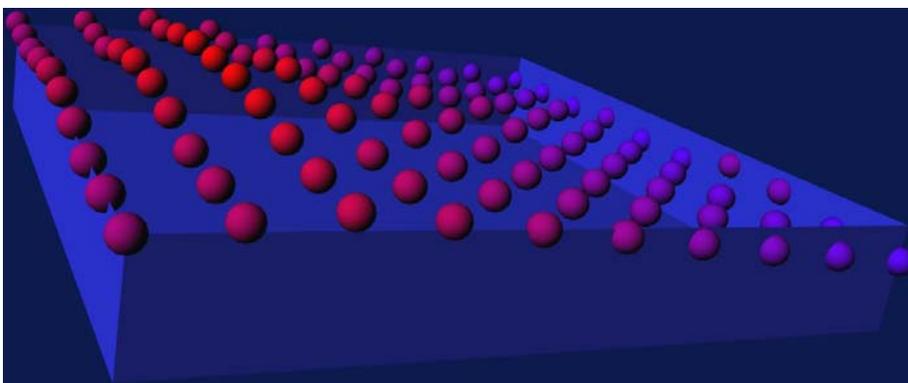
Figure 9. Surface representation by a sphere cloud

A third method of surface representation is implemented in TolVis – the visualization of a triangular meshwork. This is the most comprehensible and recognizable mode of representing the tolerated surface in VR. Therefore the VRML construct *IndexedFaceSet* is used. On the one hand side this construct imparts the impression of a consistent and holistic visualization scene. On the other hand side optimal further possibilities of color coding, texturing and the use of transparency are given. These options are explained in the following subchapters. In case of using a part with a simulated surface the meshwork offers the best possibility for collision detection and so the visualization of position deviations resulting from the shape variations is enabled. An example of a simulated surface visualized as an IndexedFaceSet is shown in Figure 10.
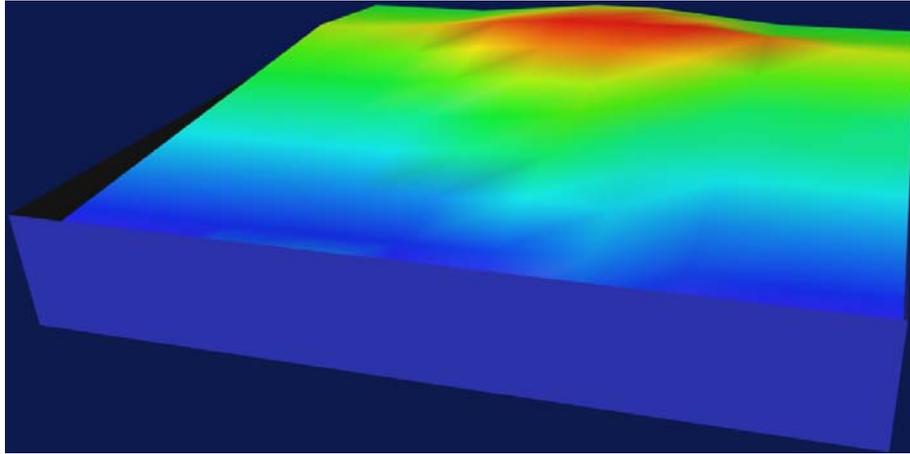
Figure 10. Visualization of the simulated surface as an IndexedFaceSet

5.2 Color coding and texturing of simulated surfaces

Typically geometry is displayed in VR only in single color mode. That means every single part or functional connected assemblies have a unique color. But the use of different colors for one object respectively one surface of the object offers much more potential. Well known from FE applications or something else a color gradient can be used for the different location of the surface inside the tolerance range. In Figure 10 a color gradient in the HSV (Hue, Saturation, Value) color space is applied to the simulation result starting at blue for positions near the minimum following clockwise through the HSV color space and ending at red for positions near the maximum. The variation shown in Figure 10 is displayed inflated to get a better spatial impression, but in case of non inflated representation the position of each piece of the surface can be associated with a definite variation because of the color coding.

Instead of color spaces it is possible to apply specific texture files to the simulated surface. If the interest focuses to a special region the texture can be adjusted to point out these regions and take others back. For a better understanding of the simulated surface the textures can generate contour lines as known from tourist maps. In Figure 11 two examples of textured surfaces are shown.
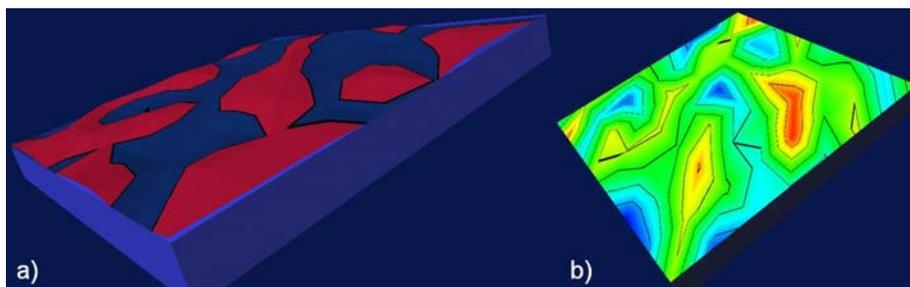

Figure 11. Example of textured surfaces

In Figure 11 a) all areas above the ideal plain are colored in red and all areas below the ideal are colored in blue which enables a spontaneous recognition of the two areas and their allocation. In Figure 11 b) a color gradient and contour lines are combined in one texture for a better and clearer understanding of the arrangement. Example b) is none inflated but anyway the exact position in space can be immediately recognized because of the color coding and the resulting contour lines.

5.3 Transparency assignment to different elements of the visualization scene

Additionally the color coding or texturing can be combined with the use of transparency for different parts of the scene. In some cases it might be useful to hide single elements of the scene to get a better view of the interesting area. This is a common procedure in VR scenes. But a new approach is to use the transparency to fade out specified areas and focus to sectors of special interest of the simulation results. In Figure 12 an example is given for a scene with a simulated plain with contour lines and a semi transparent ideal plain. In this example it is recognizable immediately which regions of the simulation result is located above the ideal plain and which are located below. And because of the transparency of the ideal plain the exact characteristic of the whole simulation result is visible. Another possibility of a controlled focusing on special areas is the use of transparency in the texture files. Dividing the alpha-channel of the texture file in black and white areas this information can be used for fading out regions of lower interest and focus on critical spots.
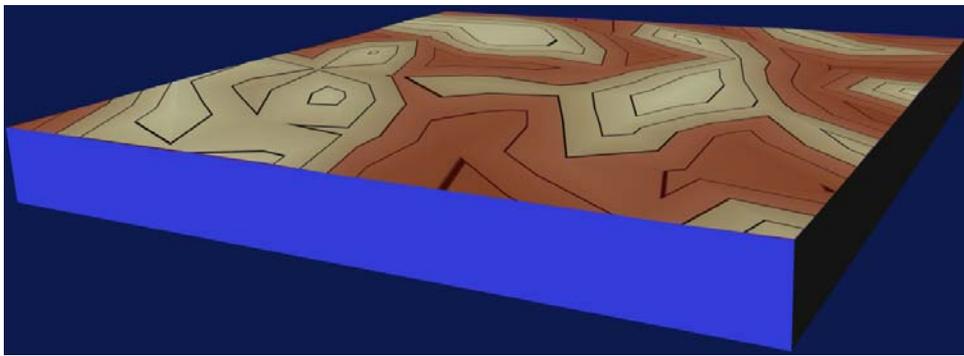

Figure 12. Texture with contour lines and a partial transparent ideal plain

All geometrical, color and texture options introduced in the subchapters above are implemented in TolVis. A more detailed explanation of TolVis is given in [5]. With the approach described in this paper it is possible to visualize shape variations resulting from shape and position tolerances, which are defined within the design process. The starting point for the visualization of position variations resulting from the simulated shape variations is also reached by this approach. So the designer gets the possibility to prepare and visualize tolerance analysis results for presentation much more understandable for non experts and decision makers. This step is very important to get fast and secure clearer and well-defined decisions.

6 Summary and conclusions

Virtual Reality is a powerful and extensive tool for presenting, reviewing and visualizing geometry in the product design process and many more possibilities are supposable. But in most cases only geometry originating from CAD systems is visualized which means all elements have an ideal shape. In reality all geometrical elements are non ideal and affected by manufacturing variations. Many of these variations are dependent to shape and position tolerances set in the product design process. So their visualization helps to get a better understanding of their impact on the products functionality and appearance.

This paper describes a new approach of visualizing parts that are affected by shape and position tolerances. Starting from a typical CAD data set it is shown how tolerance information can be used for the simulation of possible shape variations close to reality. Different ways for the visualization of simulated surfaces are introduced and examples are given how to enhance a VR scene with additional information like shape variation etc.

In this paper only shape variations are presented. The real benefit of visualizing tolerance affected surfaces comes up with the visualization of position variations resulting from the simulated surfaces. Therefore the next step in this project is to simulate not only surfaces but all other tolerable elements as a volume and then put them together in VR scenes to assemblies. Including a method for collision detection the parts can be re-arranged and their new position within the whole assembly can be visualized. The Results of these operating points are not yet achieved and will be presented in future articles.

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Dipl.-Ing. Alexander Koch
Institute of Engineering Design
Friedrich-Alexander-University of Erlangen-Nuremberg
Martensstrasse 9
D-91058 Erlangen, Germany
Tel: +49 (9131) 85 23218
Fax: +49 (9131) 85 27988
Email: koch@mfk.uni-erlangen.de
URL: http://www.mfk.uni-erlangen.de