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A SYSTEM FOR HAPTIC TOLERANCE ANALYSIS REGARDING NON-IDEAL GEOMETRY

S. Wittmann, A. Stockinger, T. Stoll and K. Paetzold

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1. Introduction

Within the product development process, tolerancing is "a critical task for the fulfilment of […] requirements" [Armillotta 2007]. Incomplete or inconsistent definition of tolerances can cause aesthetic and functional problems like varying gaps on car bodies or leaking seals for example. Performing tolerance analysis implies the handling of small deviations in a typical order of magnitude between 0,005 and 0,1 mm. In a virtual environment the visual representation is not precise enough to reveal such deviations. Therefore we propose the use of the human haptic sense for this task, which contains the sense of touch (tactile sensibility) as well as human joint conditions (kinaesthesia). Due to [Blaurock 2004] the human sense of touch is very precise and so its potential within the evaluation of product quality has to be employed efficiently. This paper therefore presents a suggestion for a haptic analysis platform focussing on the evaluation of deviated geometry. Starting from an overview of related work the different requirements of a VR-integrated haptic tolerance analysis platform are discussed, followed by the implementation of the system. Experimental results are presented in detail and the future work arising in this research topic is derived.

2. Related work

Haptic devices were first used in the nuclear and subsea industries [Stone 2000]. With decreasing costs they have been used in several other fields, like medicine, aerospace and defence. In the last years haptic feedback systems have been introduced to support engineers in the design phase. They are used to enhance the level of realism of 3D virtual environments (e.g. powerwalls or caves). The aim is to reduce the amount of physical prototypes, which leads to shorter and less expensive processes.

One of the most common applications of haptic devices in the design process is maintenance simulation. In [Drieux 2005] the platform "SAMIRA" is described, a system where a haptic device with six degrees of freedom (6 DOF) is used to simulate different maintenance tasks. To assure that engineers will use the provided system, three preconditions are outlined which have to be fulfilled to enable the integration of the simulation in the development process:

- data is taken from the product Digital Mock-Up (DMU)
- simulation results are available fast and easy
- the results have a known, high accuracy

If any of these preconditions is not fulfilled, the application will not be used by product developers, since the simulation results are not up to date or cannot be trusted.

Another work on haptic device integration for maintenance tasks is presented in [Lècuyer 2001]. The use of a 3 DOF haptic device to simulate mounting and unmounting operations is described. Since both translation and rotation forces are needed to perform the operations, a 6 DOF haptic would be needed to give the user force-feedback for both effects at the same time. To use 3 DOF haptic devices, two different modes are available to rotate and translate parts separately. The translation mode only allows the user to move the part, a rotation is not possible. The modes can be switched so that the part can be rotated too. This procedure is not as comfortable and intuitive as the use of a 6 DOF haptic device, but gives a user of a 3 DOF haptic the possibility to perform maintenance simulation.

[Wickman 2007] analyses the impact of different visual evaluation methods on the perception of gap and flush. Different non-nominal scenes are visualized in this work, and the effect of several visualization methods on the gap and flush recognition of the user is outlined. It is proposed that visualizations with stereographic view combined with texture significantly improve the perception of gaps.

Regarding the state of the art an enhancement of existing techniques, especially the integration of tolerance effects on assemblies is favourable. Therefore this work focuses on the combination of stereographic visualization techniques, haptic simulation and non-ideal geometry for tolerance analysis.

3. Requirements on a system for haptic tolerance analysis

The aim of a haptic system is to serve as an integrated analysis environment to support engineers in their activities and decisions. This will only be achieved if objective design criteria for virtual product evaluation can be produced. Furthermore a general aim is the shortening of the control loop built by the design steps of synthesis and analysis. The requirements can be divided into these main aspects: general analysis process requirements and system requirements, haptic analysis requirements and tolerance analysis requirements.

The first category addresses the process of analysis. Main requirements are the integration of the analysis tools in the preliminary stages of design. The aim is to benefit as soon as possible while developing products. In these stages especially a quicker and more systematic use of simulations must be accomplished [Direux 2005]. Furthermore the generation of appropriate 3D-Models is necessary because DMU is not appropriate for usage in Virtual Reality (VR). According to [Direux 2005] fast and robust preparation of data from DMU must be possible. In our application the virtual prototypes must be represented as a fine triangle mesh. This mesh is adapted to a subset of analysis requirements like precise gap and flush representation. These steps of data preparation should be automated in order to receive correct, healed tessellated geometry. To conclude, a general requirement is the setup of a process in order to achieve integration in the design process [Direux 2005]. Moreover adequate tools for documentation and communication of the analysis results must be provided to the engineer.

Besides these general requirements some haptic analysis requirements must be taken into account. The haptic system has to permit an easy evaluation of simulation results. Especially the physical behaviour of objects has to be simulated realistically. The detection of forces and torque by user interaction due to collisions or gravity must be assured [Direux 2005]. An adequate user interaction and synchronous visualization must be provided in order to get a 3D-haptic perception of the manipulated and analyzed objects in the scene. Furthermore the system accuracy of the haptic device must be at a level that allows the judgement of large and very small deviation as well. There are two types of haptic devices available: active devices and passive devices. Whereas passive devices are only able to retard movements, active devices are able to generate movements based on electric drives. For the haptic detection of deviations, particularly gap and flush, both types of devices can be employed. But active devices have multiple advantages and offer a broader range of application. There are multiple cases during analysis of gap and flush where forces have to be generated in order to detect for example the direction of the flush unambiguously. Furthermore the clearance of the haptic system has to be taken into account. It must be in a lower order of magnitude than the studied deviations. Otherwise the user will not be able to analyze the geometry employing haptics. Besides the mechanical requirements on the haptic device also the aspects of signal processing and numerical processing must be taken into consideration. The response time of the interfaces and the actors must be at an accurate level. Also the response time of the software for calculating the collision of objects is one element of the system chain. All the mentioned aspects have to be adjusted to another. In addition to the haptic feedback the user needs a visual representation of the scene in order to coordinate movements. An immersive display like a powerwall is advantageous to navigate to relevant sections for analyzing the area of interest. The three dimensional view is required in order to determinate the spatial position of the sensing device.

The most important aspects contributing to a reliable analysis result are the tolerance analysis requirements. They afford the consideration of many boundary conditions. In order to be able to detect the influence of tolerances, data of deviated geometry has to be generated and made available within the analysis platform. Furthermore the geometry has to be repositioned in order to get reliable and realistic analysis results [Stoll 2007]. It is not possible to use deviated geometry and their initial, CAD-based position in the scene, because deviations can cause unrealistic gaps between or collision of parts. The geometry must be tessellated in an adequate manner to be able to represent the small geometric deviations caused by manufacturing processes limited by tolerances. Therefore, high resolution meshing tools have to be used to ensure the possibility of representing any manufacturing deviation [Stoll 2006]. This is even more of relevance regarding the heterogeneity of the parts dimensions and the applied tolerances and resulting deviations.

The haptic system is a type of downstream application from DMU according to [Direux2005] and can be described by the following black box. This box represents the VR-integrated haptic system and has defined input and output parameters. The important ones for analyzing the impact of tolerances are the geometric data with physical model properties like e.g. friction and the tolerance information. Further data is as mentioned above the deviated geometry. The physical haptic system requires electric energy and gets kinetic energy caused by the users movement as input. The two main outputs of the platform are visualization and force feedback as the results of the computations in the virtual environment. It is imperative to mention and take into account the boundary conditions of the system and the environmental disturbances affecting the system behaviour and thus the analysis results. Therefore the disturbances are listed in Figure .

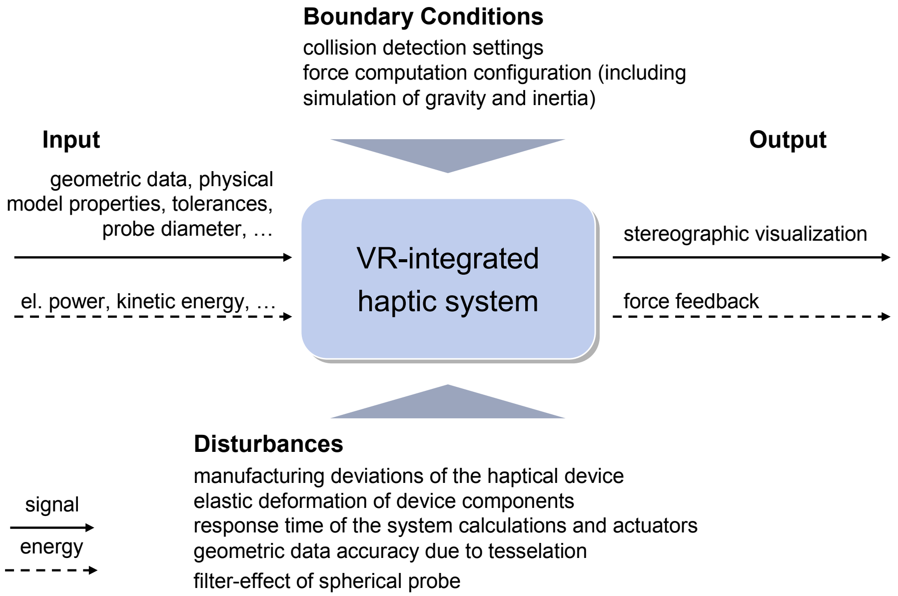

Figure 1. Black box model the VR-integrated haptic analysis platform

4. Implementation of a haptic analysis system

Based on these requirements a system has been set up and analyzed. The following hard- and software components were used for the implementation of a haptic analysis system: As a haptic device, "Haption Virtuose 3D-1525" produced by Haption, France (see Figure) has been utilized. It is an active force feedback device, which means it is capable of generating forces. The Virtuose unit has sensors for six degrees of freedom (hand movement in x, y and z-direction, hand rotation along the x, y and z-axis). Forces are generated by servo motors for the three translational degrees of freedom. Rotation forces cannot be generated. Hand rotation is detected by sensors, but can not be blocked.

The user grips the handle with his hand, changes of the hand position are detected by optical incremental encoders. Hand rotations are retrieved via potentiometers. Additionally, two push buttons exist on the handle. They are used for grasping and repositioning.

Figure shows the connection of the system components. A control unit computes the input signals for the motors and also reads the sensor data (translation and rotation) from the haptic device. It is connected with a PC by a network cable. The implemented simulation software runs on the PC, it consists of a visualization, a physics engine, a geometry loader and several analysis tools.

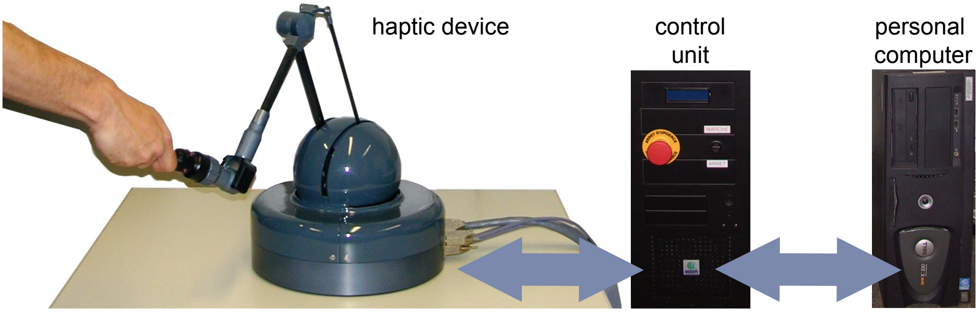

Figure 2. Connection of the system components

The free Open Dynamics Engine ODE [Smith 2007] was used to calculate rigid body dynamics. The ODE provides methods to create objects within the physics simulation, either primitives (sphere, cylinder, box etc.) or complex objects (triangle meshes). ODE performs collision detection and calculation of object movement. The target positions are sent to the control unit which calculates the necessary forces to move the handle from the current to a new position.

The visualization was set up using the OpenGL Utility Toolkit (GLUT) on a Quattro FX graphics card. To generate three-dimensional images, the screen is rendered twice with slightly different camera positions (one for each eye). The picture is displayed on two beamers with polarisation filters on a single screen. By wearing polarization filter glasses the user gets a 3D-impression of the scene, which simplifies the manipulation of objects in space and the estimation of distance between virtual objects, see [Wickman 2007].

To analyze non-ideal geometry, the following approach was chosen: The parts are modelled in a standard CAD-System. Tolerances for dimensions, shape and position are defined using the standard CAD-operations. A tolerance analysis in a statistical simulation is performed. Monte Carlo Simulation sets random values to vary parameters (i.e. length or angels of the examined parts) within their tolerance limits. This way, a high number of non-ideal parts (typically between 10.000 and 30.000) is generated. For the haptic analysis, extreme variants are chosen by the user, for example settings with maximum distance or angle between two parts. Tolerance analysis systems do not generate the whole geometry, so it is necessary to reconstruct the non-ideal parts with the given extreme values. To perform the generation of non-ideal geometry, at first the CAD-geometry is converted into a triangular mesh. Therefore a high resolution meshing tool has been used which allows the setting of the maximum error in normal and tangent direction. For our application the meshing error must be several magnitudes smaller than the least tolerance of the part. The vertices of the mesh are changed according to the results of the tolerance analysis. The surrounding geometry is also adjusted by interpolation.

The resulting triangle mesh has to be loaded into the haptic analysis application. In computer games, ODE is usually used to compute a fast but coarse approximation of the physical behaviour of objects.

For example, a moving car is represented by a box and four spheres for fast collision detection. To perform haptic tolerance analysis, small part deviations have to be detectable. For this purpose, the generated fine triangulation of the part was also used in the physics simulation. The ODE offers no tools to load triangle meshes, so a loader for the Virtual Reality Modelling Language format (vrml-files) has been implemented, a standard format available in all CAD systems. The resulting implemented mesh class consists of a geometry representation in the ODE format and rendering instructions to display the mesh.

5. Haptic tolerance analysis

The haptic analysis of tolerances is performed using a virtual probe to "touch" the studied geometry in the virtual environment. There have been two types of implemented and tested probes (see Figure).

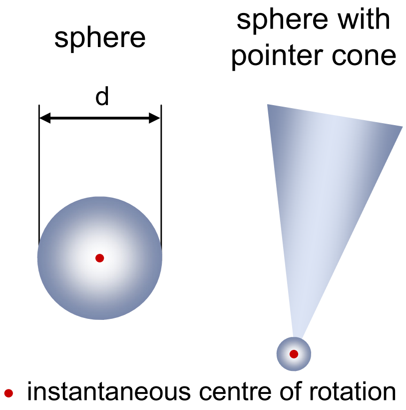

Figure 3. Types of probes

In order to be able to feel surface deviations or to test for gaps and flushes on the objects of interest, a spherical probe and a cone with a spherical tip have been implemented in the software. The instantaneous centre of rotation is located in a way that allows the user to position the probe normal to the surface to be analyzed. In many cases it is necessary to use very small probes in order to evaluate e.g. small deviations. Therefore the cone was introduced as marker to highlight the position of the sphere. The pointer cone has a visual representation only but is not included in collision detection. An advantage of the spherical pointer is the ability to resize it in the scene during runtime. The active diameter is displayed in millimetres when the probe is resized. Due to the fact that the used device with 3 DOF force feedback is not able to provide torque, only spherical probes were employed. Alternative solutions are addressed in [Lécuyeer 2001] where the replacement of a 6 DOF device by a 3 DOF device is discussed.

Based on the implementations made on the platform, the development of analysis techniques, namely analysis of gap and analysis of flush, was possible.

Analysis of gap

The haptic analysis of gaps is one of the major applications of the presented platform. Varying gaps along the joint of rigid and especially compliant parts have to be evaluated in many cases for aesthetic and functional reasons. Quantitative distance measurement values are not suitable for providing an objective impression of gaps. In order to be able to analyze the accuracy of the platform, scenarios built up of standard shapes like cubes or boxes have been set up. The analysis is performed using three configurations: ideal gap, enlarged gap and narrowed gap (see Figure). The diameter of the probe was left constant during this experiment.

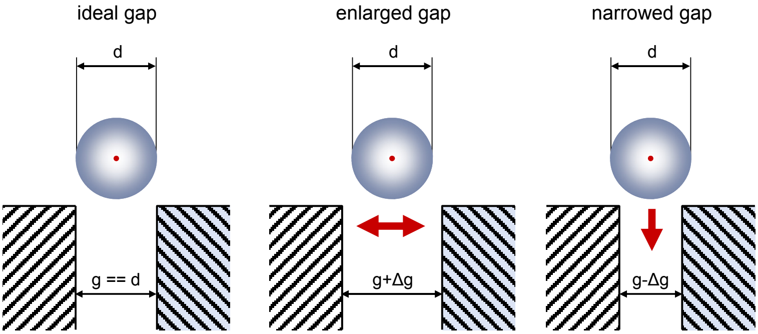

Figure 4. Analysis scenarios for gap evaluation

Analysis of flush

In parallel to the experimental design of gap analysis a scenario representing flush was implemented and evaluated. Propagation of manufacturing deviations in an assembly often result in assembly problems. This often leads – depending on the construction – to unconsidered constraints and thus to forces and torque that cause elastic deviations of compliant parts. An analysis of flush requires the distinction of three cases (see Figure). Regarding an ideal assembly the user is not able to identify a flush between the components when moving the probe on the surface. If there is a flush Δf originating from tolerances, the movement can be performed upwards or downwards the stair. In order to be able to detect the flush correctly, the spherical probe must have an appropriate size. The ratio of the probe diameter d and the flush Δf is a characteristic parameter of the simulation.

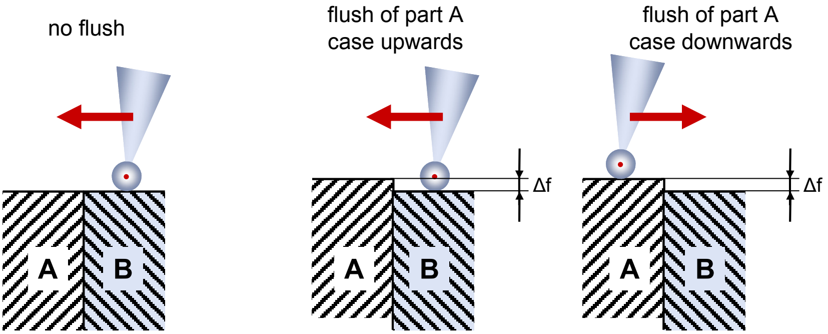

Figure 5. Analysis cases for gap evaluation

Analysis of gap and flush on an exemplary automotive assembly

The two methods of analysis presented above are based on examinations of primitives. The two effects have been analyzed separately. In automotive applications for example, the geometric deviations of gap and flush arise concurrently. So an exemplary, non ideal assembly of a mudguard and an engine hood was modelled and prepared for analysis. The mesh was generated with a known accuracy and imported into the scenario. It is discussed in the next section (see Figure).

6. Experimental Results

The experiments showed clearly that the user can detect deviations that are invisible using the haptic device. During the analysis of narrowed gaps with the probe the user perceives resistance force when entering the gap. If it is not possible to move the probe tip into the gap, a deviation from the ideal distance is obvious. Expanded gaps can be detected by moving the probe between the adjacent parts. The following results have been acquired by performing the tests shown in Figure :

Table 1. Gap analysis results

	Probe diameter *d* in mm (equals ideal gap size)	Smallest detectable deviation *s* in mm	Smallest detectable deviation compared to *d*
Narrowed gap	0,1	0,099964	0,036%
	0,05	0,049965	0,07%
	0,01	0,009976	0,24%
Expanded gap	0,1	0,1017	1,7%
	0,05	0,0520	4%
	0,01	0,0126	26%

One can conclude that the perception of narrowed gaps is more precise than the detection of expanded gaps. Because of the horizontal movement during analysis of expanded gaps, a distinction of the clearance resulting from extended non ideal gaps and the mechanical clearance of that device can hardly be made. Furthermore the results show that the behaviour of the system is nonlinear.
The analysis of the system behaviour regarding flushes shows different results depending on the probe movement direction (see Table).

Table 2. Flush analysis results

	Smallest detectable flush in mm	
Probe diameter *d* in mm	**Case downwards**	**Case upwards**
0,1	0,0002	0,00009
0,01	0,0002	0,00003
0,001	0,0003	0,000004

This result shows that the system is capable of analyzing flushes with a high accuracy. The detected deviations are of a magnitude below one pixel in the visualization.

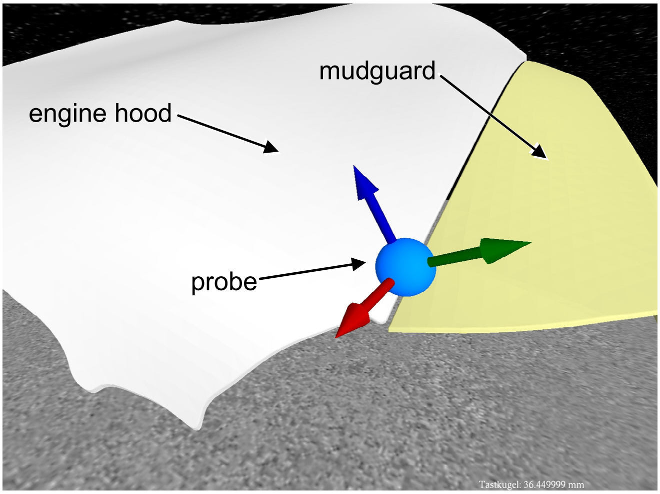

Figure 6. Analysis of engine hood and mudguard

Regarding the gap between the engine hood and the adjacent mudguard, no visible deviations can be perceived. Using the adjustable probe, deviations in different directions along the gap can be detected. By sliding along the gap, local elevations can be revealed when the probe leaves the trajectory of the gap. The chosen model representation (high resolution triangle meshes) proved to be appropriate for the study of tolerance effects.

7. Conclusion and Future Work

Based on a detailed view on the related work, a platform for haptic tolerance analysis was presented in this paper. An analysis of requirements on such a system from a general point of view was performed and outlined. The most important aspects are the precise representation of geometry, realistic simulation of physics and a stereographic visualization. A haptic platform was identified as an integrated analysis environment supporting engineers in their activities and decisions. Furthermore the platform components, the system itself, the simulation and visualization techniques as well as the data preparation process were presented. Basic experiments have been performed to acquire data about the system accuracy for gap and flush analysis. Finally, the system was used in a case study for the analysis of sheet metal parts of an automobile. The haptic system offers a high accuracy and extends the immersion in VR-environments by including the haptic sense. Therefore the presented platform resembles a suitable tool to support tolerance analysis of virtual prototypes.

Future work will include examination of assembly/disassembly processes for non-ideal parts. Problems to be solved are for example the integration and simulation of compliant components as well as a calculation of required joining forces during manual assembly processes. The integration of an alternative physics simulation library for comparison is also planned.

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Dipl.-Inf. Stefan Wittmann
University Erlangen-Nuremberg, Institute for Engineering Design
Martensstraße 9, D-91058 Erlangen, Germany
Tel.: +49-(0)9131-8523218
Fax.: +49-(0)9131-8523223
Email: wittmann@mfk.uni-erlangen.de
URL: http://www.mfk.uni-erlangen.de