Potentials of Full-Vehicle CT Scans within the Automotive Industry

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Abstract. The use of computed tomography (CT) for the investigation of oversized objects allows the non-destructive evaluation of complete vehicles. This is currently possible by using a system developed at the Fraunhofer Development Center for X-ray Technology (EZRT) in Fürth, which is able to scan oversized objects such as vehicles, with either geometry and/or material complexities. One of the main applications for this technology is to compare prototypes of new cars with design data, in order to increase the predictive power of the virtual design for the investigation of the structural integrity of entire cars. However, the processing of such a large amount of CT data is still a challenge. In order to convert CT data into geometry models several steps are needed. Among others, a mesh refinement is required to manually reduce the coarseness of it, which lessens the number of elements/memory usage according to the specifications. The main purpose of this work is therefore to offer a solution that enables the segmentation of these 3D datasets by using appropriate software solutions. The created models can then be exported in any format supported by all leading CAE packages for further investigations. Other applications for this technology are the defect analysis of different automotive components as well as quality and assembly checks of components and joining techniques (e.g. welded, adhesive bonded and sealed connections). A strategy for the integration of this new CT technique into the automotive industry along with the results of entire vehicle CT-scans will be presented.

KEYWORDS – Computed Tomography (CT), CAE and CT integration, 3D image processing, finite element modelling, structural integrity, image-based meshing

Introduction

The use of computed tomography (CT) as a non-destructive testing method for volumetric inspections within the automotive industry is gaining more and more importance. The increased capabilities of this technology have led to completely new applications, which were not possible before. Besides conventional X-ray industrial applications, a High-Energy X-ray Imaging system has been developed at the Fraunhofer Development Centre for X-ray Technology (Fürth, Germany), as the industry’s first CT system able to scan large-scale objects, with high-complexity multi-material distributions. The X-ray chamber with inner dimensions of about 20 x 20 x 16 mm along with walls up to 3m thick provides the ability for CT applications of complete vehicles.
A geometric resolution of approximately 0.4 millimetres for the scan of full vehicles is achievable, discerning even the tiniest detail with the resolution on objects that are several meters in size. [1] The generation and detection of photons occurs in the MeV range, by using a linear accelerator. It is well known, that the absorption of the X-ray radiation in penetrating a material will depend on different interaction factors, based on the x-ray energy range. With energies up to 10 MeV, the photo-effect interaction is nearly irrelevant. For low density as well as for high-density materials, the Compton scattering will be the most dominant absorption effect, which leads to a high linearity of signal and a low signal/noise ratio (SNR), regardless of the combination of materials. [1]

The output data provides a virtual decomposition into different materials and components (aluminium, CFRP, steel...), in areas which could not be inspected otherwise in a non-destructive manner. Based on three-dimensional data, some of the potential uses for this technology include the inspection of material failures, such as ruptures or fatigue issues on components, in their assembled state. The material behaviour of structural parts under impact loading along with their significant load path can also be inspected. In fact, information about the crashworthiness of new vehicles makes CT a very powerful method for the validation of numerical simulation impact models. According to the building block approach for Plastic and Composites Intensive Vehicle (PCIV) structural components, it is known that the amount of possible tests to be performed decreases from the element coupons level through the components and sub-assemblies up to the full-scale level, such as the crash tests of prototypes of new vehicles, while the complexity increases. [2]

For the case of crashworthiness assessment of vehicles, output data from crash tests are an important input for the assessment of a vehicle structure. Important knowledge is gained, which is needed for design and dimensioning of a vehicle structure as well as interior components and restraint systems. Finite Element simulations have been a key to reduce the required number of expensive crash tests to a minimum while increasing the variety of car models available for the customer. Highly detailed crash simulation models are substantial for this achievement. These models have to be validated repeatedly with data from physical crash test during the design phase. At the crash facility at BMW’s Forschungs-und Innovationszentrum (FIZ, Center for research and development) in Munich, more than ten crash tests are carried out every week. Besides the well-known crash dummies which measure the occupant loading, a variety of measurement devices is installed in the vehicle. Amongst others, those are high-speed cameras, accelerometers and pressure gauges. Measurement targets are applied to important areas of the vehicle structure to capture deformations. Those are especially vital for comparison of the deformation during crash test with the prediction provided by the finite element model. If those targets or regions of interest are hidden beneath interior components or other structural parts of the vehicle, lots of effort and time has to be spent on disassembling. In addition, some bits of valuable information might be destroyed by dismantling. By means of the information provided from a full-vehicle CT scan, it is possible to optimize this challenging process and to maximize the amount of information to be extracted from a crash test. Disassembling of a crashed vehicle will therefore not be necessary. Besides the significant amount of work necessary to perform the scanning, one of the most challenging tasks is the elaboration of the CT-data. Especially the segmentation of all these relevant structures has to be integrated into the BMW CAE-based design process. To date, there is no established process, which can convert CT scan data into the CAE-based design process. The main purpose of this work is therefore to develop a process to integrate CT volume data into CAD/CAE environment in an efficient way. For the three-dimensional visualisation, analysis and the further segmentation of voxel data, the commonly used high-end software VGStudio Max (version 2.2) with its unique functionalities was utilized. In the following, each step of these procedures will be thoroughly described.
1. Processing of large scale CT data

During a CT scan, independent from the scale, the test object is irradiated from one side with X-rays and the resulting radiation after interaction is registered on the opposite side by means of a detector system. The stack of projection images originates directly from the CT-scanner. Depending on the intensity of the incident radiation, different grey values are assigned to each voxel, based on the attenuation coefficient of different materials and their geometries. Several thousand two-dimensional X-ray images from different directions around the test object have to be acquired, from which a three-dimensional volume through a mathematical algorithm is reconstructed. Most likely, they have a data range of 16 bit. Those files must be logarithmized, and can optionally be normalized using one or more additional calibration images before the 3D rendering process.

The complexity of a CT-Scan of large-scale objects increases with the measured object’s size along with the size [GB] of the generated data. The line detector for the acquisition of the projections has a length of 4 meters and a pixel pitch of 400 µm. Therefore, every line projection consists of approximately 10000 pixels. By choosing a horizontal and vertical resolution of 0.8 mm and a measured height of circa 2 meters, a 12,5 Megapixel projection is generated. The resulting volumetric voxel dataset (*.rek format file) consists of over 60 gigabytes of image data, including thousands of parts composing the vehicle, made up of more than 10 different materials, such as aluminium, CFRP, plastics, glass, foam filler materials, etc… The minimum free main memory only for visualization should be at least 2 times the size of the data set to be imported. Assuming the size of a XXL-CT volume is about 60 GB, the recommended system should have at least 120 GB of free main memory for visualization. This is still much smaller compared to several hundreds of gigabytes a full resolution volume (horizontal and vertical resolution equal to 0,4mm) would generate. Obviously, additional memory is then required in order to perform any kind of analysis out of this data. [3]

Based on this consideration, it is noteworthy that a significant quantity of memory has to be used for rendering a full vehicle, which means the ability is limited by the hardware configuration, e.g., the available disk space. Even if the software uses all available GPUs for rendering the data set, in order to speed-up the elaboration processes of this data, the necessary capacity is still significantly far away from what can be handled today. Despite the excessive quantity of generated and stored data, this technique is still to be considered extremely capable in the field of inspection and quality assurance, even on a large scale. Picture 1 shows the 3D volume resulting from the rendering process of a BMW i3, which has been scanned on behalf of BMW AG at the Fraunhofer EZRT, after an ECE R94 frontal crash test. [4]

![Picture 1](image_url)

*Picture 1. 3D view of virtual data after crash test ECE R94 (left side) as well as the rendered voxel dataset (right side) of the BMW i3 [4]*

The 3D rendered volume can be broken down “virtually” into 3D sectional volumes and 2D cross sections.
As exemplified in the picture below, the virtual decomposition based on the grey value association enables the distinction of a part made either out of metal, foam or plastic material.

![Picture 2. 2D cross sections through the voxel dataset of the vehicle [4]](image)

Small material features as well as defective components can be displayed in a millimetre range. The accuracy of assembled components, welded or adhesive connections can also be inspected, even in areas that could not otherwise be examined in a contact-free manner.

On the other hand, voxel data can further be converted into surface data, to be used in reverse engineering applications. Therefore, the main intent of this work is to utilize computed tomography (CT) as an image-based approach to convert segmented voxel data of entire vehicles into individual volume meshes, suitable for export to FE packages. Typically, μ-CT data allows easy segmentation based on greyscale values only. However, XXL-CT data is usually more difficult to be segmented - mainly due to geometry complexities and material combinations. In this paper, a method for generating high-quality segmentation output results will be presented, which relates to the concept of the so-called “Region of Interest (ROI) from CAD/Polygon model”. A ROI may consist of one or several unconnected areas of a CT volume and allows analyses to be restricted to specific areas of a data set. ROIs can be further modified, by creating intersections or combinations of several ROIs. [3]

This method starts from image-based (CT) data and consists essentially of a series of steps directed to different output targets, the final of which implies the generation of tessellated models (.*STL output file format). Each of these steps could be either automated or require partial user interface. The more automated the workflow, the better the control over the whole process because of less manual intervention, thus ensuring high reproducibility and reliability of the results. Each step will be explained in subsequent detail.

The first step, which involves the determination of the surface, is used to define the material boundary of the subpart of the volume that has to be segmented. If the surface cannot be determined automatically, it is recommended that the iso grey-value for defining the boundary is manually specified. This helps to define the local thresholding more accurately in areas adjacent to the subpart of the component for which we are creating an ROI. Afterwards, the corresponding polygon/CAD model has to be imported into the CT workspace. The software supports the import of most common CAD/Polygon formats (STL, IGES, STEP, etc....).

However, it only makes sense to create a ROI from a polygon/CAD model that describes the subpart of the volume object almost perfectly, apart from tolerances.

Next, the CAD/Polygon model has to be registered against the CT data set. A couple of advanced options are available in order to adjust the registration results, based on the complexity of the part. It is also possible to specify arbitrary reference elements (such as...
points, planes, surfaces, etc.) against which the CAD model can be registered. Remember that before proceeding to the next step of this method, the two objects (CT volume subpart vs. Polygon/CAD model) should be superposed and share the same coordinate system. [4] After the correct registration, the next step relates to the extraction of the voxel-based subpart of the volume, within the CT workspace. Here, the surface determination again enters the picture: advanced options enable the imported CAD/Polygon model to be used as starting contour. Excess material or eventual artifacts around this object will not be taken into account and will not negatively affect the registration results.

Finally, tessellated models out of the segmented subparts can be extracted (.stl format file is generally used, other file formats for the extraction of the polygon model are also supported.). Here, the extracted surface is defined through a set of points (point cloud), which will then be connected to each other in order to form a triangle mesh. Several algorithms can be used to set out the coarseness of the mesh. The finer the level of detail, the more points will be generated, the bigger the output data set. [5] Moreover, additional pre and post-processing tools are used in order to enhance the usability of this data in correlation with the BMW CAD/CAE like model organization.

Without limiting the generality as reflected in picture below, the flow-chart diagram shows each step of the segmentation approach – as described above - considered for the segmentation of the deformed aluminium frontal bumper.

![Data processing workflow for export.*STL models](image)

A surface mesh based on the boundaries of the segmented region is generated. By means of high-end pre-processing tools (e.g. ANSA), standard meshing functionalities can then be applied in order to downsize the mesh. The best suitable file format can be generated according to the specifications (e.g. NASTRAN). Besides, it can happen that the extracted ROI might have a shape, which slightly differs from the polygon/CAD model. Especially for components that underwent deformations after crash tests (e.g. frontal bumper), this will result in higher user interactions to ensure consistency. Thanks to the output data after segmentation, a correlation between physical and virtual data can be performed. Whether performing crash simulations, structural analysis or any kind of virtual tests on vehicle data, this will provide insight and understanding hidden inside the data. Based on this information, optimizing designs and physical observations can be carried out, which helps to improve the predictability of the simulation results.

Making use of this approach, different parts from the subsystems of the BMW i3 have been segmented and then exported as polygon data, such as body components, chassis components, interior and exterior trim parts.

The hardware configuration of the machine used for the data elaboration is defined as follows: Win 7, 2x NVIDIA Quadro 6000, 2x Intel Xeon E5-2690 GPUs, 2,9 GHz, 128 GB Ram.
2. Discussion and conclusion

A method to segment three-dimensional voxel data of an entire vehicle for the generation of polygon models was developed and verified, using voxel data of an entire vehicle. Valuable information regarding the structural design of components, joining techniques as well as deformation states after crash tests are obtained and integrated into the correction process between virtual and physical data.

However, the presented approach still implies significant user interactions and often still involve some appreciable simplification of the model geometry.

The main reason for the lack of automation relates to the use of the CAD/Polygon model as reference geometry for the segmentation and extraction of interesting regions of the vehicle. Parts in the CT data with high deformation levels (e.g. frontal crash bumper) along with not easily accessible locations may result in an imprecise generation of polygon models, which in turn lead to a poor design basis.

The future goal is to optimize the described method so that it becomes part of the correlation process between physical and virtual design, throughout all stages of the CAE-based design process.

References


[4] Energy dissipation and structural integrity in frontal impact, Ferenczi, Izabella; Dr. Stefan Kerscher; Dr. Frank Möller, BMW Group, Munich, Germany