

# Optical Coordinate Measuring Techniques for the Determination and Visualization of 3D Displacements in Crash Investigations

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## ABSTRACT

The measurement of 3D coordinates using optical techniques is well known for more than 50 years. Today, modern photogrammetric systems are based on handheld digital cameras and are used to identify the location of any circular marker or feature on the object's surface. The ease of use and the accurate and automated derivation of 3D coordinates from 2D digital images helped to establish a powerful tool for position control, assembly checks and reverse engineering.

A new application is the analysis of real vehicle crashes. The location of hundreds of markers on the damaged vehicle can easily be determined in vehicle body position. These coordinates are being compared to the undeformed geometry and provide herby 3D information on any displacement. Using reverse engineering techniques, surfaces are created from the 3D points and thus a 3D model of the crashed vehicle is available for an easy visualization of the deformation.

## INTRODUCTION

Volkswagen pursues accident research. Numerous accident statistics and local accident surveys have been analyzed statistically to gain knowledge of the accident event. The goal is to improve vehicle safety.

The main target of the accident research is the determination of the deformation during the course of the accident. Comparison of passenger injuries and deformation during all phases of an accident allows to draw conclusions which could lead to an optimization of vehicle safety.



Figure 1: Accident research at Volkswagen AG

## FORMULATION OF THE PROBLEM

In order to determine the energy absorption of an accident vehicle, detailed information concerning the vehicle structure and the structural deformation during the course of the accident are required. For this reason, vehicles for crash tests are measured before and after the test at pre-defined distinct points. Typically, coordinate measuring machines are applied for this task. The relationship between the loading of the crash test dummies and their contacts with the vehicle interior during the single crash phases can then be estimated.

The energy absorption during the course of a crash can be estimated based upon the change of the points' position in conjunction with other measurements. Besides the energy, these measurements also provide information on intrusions into the passenger compartment and their risks of injuries for the occupants. The measurement expenditure grows with the increasing demand for the accuracy of the evaluation.

In standard crash tests, typically not more than 100 measuring points are measured. The entire measurement procedure is time consuming, since just the obligatory transport of a crashed vehicle to the evaluation center adds a lot of extra time.

For real accidents, the determination of the actual energy absorption by way of this method is not possible. The accident analyst lacks precise information about the situation before the accident. Usually the acquisition of the accident vehicle can not be realized because of the costs. Therefore the analyst has to use different methods to measure the deformation and thus the absorbed energy of real accident vehicles.

An important factor for the utilization of these methods is the exact measurement of the deformations. Examples of typically applied tools are shown in figure 2. It is obvious that the expected accuracy is fairly low. In addition, the actual way of determining the deformation energy does not help to improve the measurement results. Typically, this energy will be derived from a comparison of the damage based upon pictures. Often it is even necessary to compare different generations of the same model, to gather additional information.

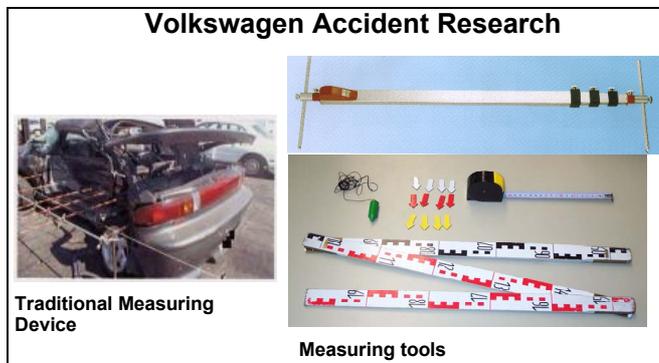


Figure 2: Traditional measuring tools for the measuring of accident vehicles

For the goals of accident research such a procedure is not sufficient. It is important that good information of the deformation energy can be determined and in addition, a detailed description and measurement of the deformations is required for the evaluation of the injury mechanisms.

Modern design procedures enable the manufacturer to refer to its CAD data sets as their 'prior' condition and to have them set in comparison to the 'post crash' situation.

## REQUIREMENTS FOR THE MEASURING SYSTEM

The acceptance of accident vehicle analysis always depends on the quality and the accuracy of the derived measurements.

The traditional crash analysis takes place in a laboratory environment. Tactile coordinate measuring machines are used to determine the deformed contour of a crashed vehicle. This work typically delivers results with a sufficient accuracy but is time consuming and hardware intensive.

For the analysis of accident vehicles outside a laboratory environment, a measurement system is needed which

can substitute the in-house metrology equipment. Thus the requirements for such a system are as follows:

- Portability,
- Flexibility,
- Easy to use,
- High number of measure points.

## OPTICAL COORDINATE MEASURING SYSTEM "TRITOP"

The photogrammetric measuring device TRITOP is based upon the principle of triangulation.

Multiple images are taken from the desired object using a handheld camera. Knowing the projection equations of the used optical elements, 3D coordinates can be calculated from as many object points as needed.

### PHOTOGRAMMETRIC DETERMINATION OF 3D COORDINATES

#### Basics of photogrammetry

Using photogrammetry, the position of a point in 3D space can be determined by triangulating multiple bundles of observation rays. If the spatial orientation of each bundle is known in the object coordinate system, the intersection of the rays delivers the desired 3D object coordinate, as shown in figure 3.

#### Camera model

The camera model is used to describe the projection of an object onto the image plane of a camera. This model is based upon a pinhole perspective device with the camera lens as the pinhole.

In the following, light waves are described as straight lines – as typical for the incoherent metrology.

An object point  $P(X_p, Y_p, Z_p)$  and its observation  $p(x_p, y_p)$  in the image plane  $B$  as well as the projection center  $O(X_o, Y_o, Z_o)$  are on one projection line, see figure 4 with the image plane being mirrored for better illustration.

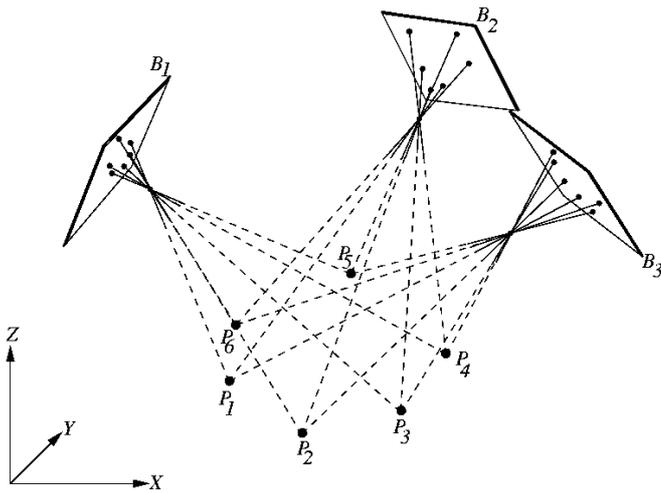


Figure 3: Coordinate determination of object points  $P_i$  by triangulating bundles of observation rays from different image planes  $B_i$

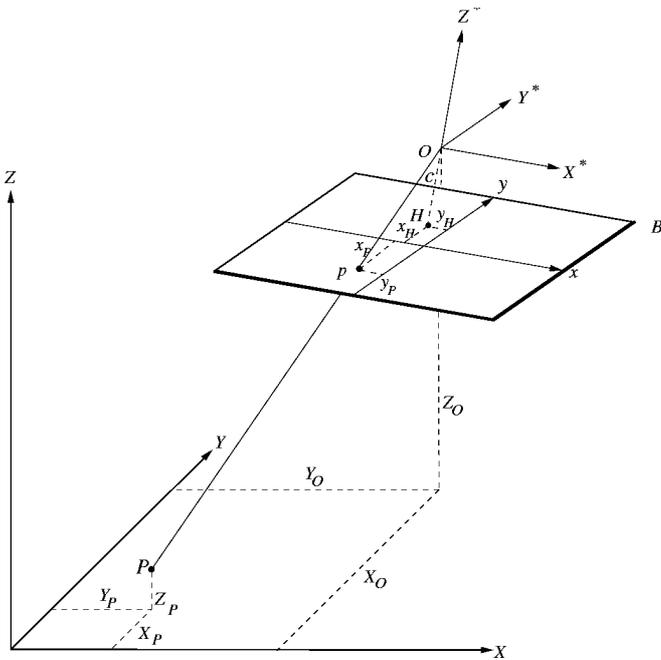


Figure 4: Central projection

- $B$  - Image plane
- $c$  - principle distance
- $x, y$  - image coordinate system
- $x_H, y_H$  - image coordinates of the principle point
- $x_P, y_P$  - image coordinates of the projected object point  $P$
- $X, Y, Z$  - object coordinate system

- $X^*, Y^*, Z^*$  - support coordinate systems
- $X_O, Y_O, Z_O$  - Object coordinates of the projection center  $O$
- $X_P, Y_P, Z_P$  - Object coordinates of the observed object point  $P$

The relationship between object and image coordinates can be described mathematically according to the collinear assumption

$$\begin{bmatrix} x_P \\ y_P \end{bmatrix} = \frac{-c}{Z_P^*} \cdot \begin{bmatrix} X_P^* \\ Y_P^* \end{bmatrix} + \begin{bmatrix} x_H \\ y_H \end{bmatrix} + \begin{bmatrix} dx \\ dy \end{bmatrix}$$

with

$$\begin{bmatrix} X_P^* \\ Y_P^* \\ Z_P^* \end{bmatrix} = R \cdot \begin{bmatrix} X_P - X_O \\ Y_P - Y_O \\ Z_P - Z_O \end{bmatrix}$$

- $X_P^*, Y_P^*, Z_P^*$  - support coordinates of the object point  $P$
- $dx, dy$  - lens distortions
- $R$  - rotation matrix

The camera parameters like the principle distance  $c$ , the coordinates of the principle point  $(x_H, y_H)$  and the elements to describe the lens distortions  $(dx, dy)$  are called inner orientations. The values for the projection center  $(X_O, Y_O, Z_O)$  and the rotation matrix  $R$ , which depends upon the camera position in the global coordinate system, establish the outer orientation.

The orthonormal rotation matrix is used for the transformation of global coordinates into support coordinates.

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

### Bundle adjustment

The bundle adjustment is used to determine the unknown object coordinates and additionally the parameters of the detecting arrangement. For this, multiple observations from different directions are required, with a partially overlapping image area. Furthermore it is necessary that all desired object points exist in more than one observation. A minimum of two observations of one object point is required to create enough equations for the derivation of its position.

The image coordinates together with the appropriate project center define bundles of projection rays as illustrated in figure 3.

The goal of the bundle adjustment is to determine the unknown parameter in such a way that the collinear assumptions are met as good as possible. The equation can typically not be solved exactly, as more observations than unknown parameters exist and the observations have errors related to the detection process. An iterative process is needed for the approximation of these system of equations.

If all parameters of the detection setup are unknown, seven additional degrees of freedom exist in the equation system. Three of them describe a translation, three a rotation and one the scale. These degrees of freedom, which are called additional observations have to be restricted.

#### ADDITIONAL OBSERVATIONS

For the transformation of the calculated point coordinates  $X_{P_i}, Y_{P_i}, Z_{P_i}$  from the model coordinate system to  $X'_{P_i}, Y'_{P_i}, Z'_{P_i}$  of the reference coordinate system, restricted additional observations are needed.

For a definition of the reference coordinate system without contradiction, the introduction of the following additional observations is typical.

- Definition of a plane

Restriction of the  $Z$ -coordinate  $Z'_{P_1}, Z'_{P_2}, Z'_{P_3}$  of three object points  $P'_1, P'_2, P'_3$  in the reference coordinate system.

- Definition of a direction

Restriction of the  $Y$ -coordinate  $Y'_{P_1}, Y'_{P_2}$  of two object points  $P'_1, P'_2$  in the reference coordinate system.

- Definition of a coordinate

Restriction of the  $X$ -coordinate  $X'_{P_1}$  of one object point  $P'_1$  in the reference coordinate system

For the use of these observations for the adjustment calculation, the detection setup has to be transformed from the model coordinate system into the reference coordinate system which is defined by the additional observations.

In case of a definition of the position of the reference coordinate system without contradiction, the transformation takes place as follows.

- Scaling

The scaling can be derived based upon the relationship between the measured distance  $S$  in the model coordinate system and the pre-defined distance  $S'$  in the reference coordinate system

- Transformation of the three fixed  $Z$ -coordinates
- Transformation of the two fixed  $Y$ -coordinates
- Transformation of the one fixed  $X$ -coordinate

#### CIRCULAR MARKERS

To characterize the image points in the camera image, so called reference targets are used, which are applied onto the object's surface or the surrounding area.

The following criteria should be taken in consideration for the choice of these markers:

- High accuracy concerning determination of the position
- Ability to be identified automatically
- Easy production and handling

In photogrammetry, typically circular markers are used as they meet these criteria.

#### Identification of circular markers

For the coordinate determination of the reference targets using the bundle adjustment, the circular markers have to be identified uniquely in the different images, to make sure that they can be related to each other.

The goal is to have an automated identification to eliminate a time consuming and erroneous manual procedure.

#### Ring coding of circular markers

For the unique identification of the circular markers a special ring coding was developed. The code is next to the circle and corresponds to a binary coding.

Thus, a rotation invariant identification of the reference targets is realized.

#### Identification of non-coded circular markers

The disadvantage of the ring code is the larger area which they are covering in comparison to the non-coded circles. It is then necessary to have less coded reference targets and to identify the remaining non-coded targets based upon their relationship to the coded ones.

#### Material of the reference targets

The material of circular markers is an important factor for the ease of use of such a photogrammetric system. It is typical to use a retro reflective material. These targets

can be easily identified in the images as they appear bright and the rest of the image black.

For the actual accident research, retro reflective targets cause some disadvantages as in the black images, details like scars or blood marks are not recognizable.

The TRITOP photogrammetry system also utilizes plane white targets. Their advantage is that they can easily be produced on a standard laser printer and in addition, the image itself is still visible. Thus the image can still be used for some further processing and even color images can be used. Using some advanced search algorithms, the time to identify plain white targets is now on the same level as for retro reflective targets and the identification accuracy even exceeds that of the retro reflective targets.

## MEASUREMENT PROCEDURE

The steps of a photogrammetric measurement are:

1. Applying the non-coded markers at the required measurement positions
2. Applying some coded markers
3. Positioning of scale length
4. Taking images
5. Automatic processing of all images and automated calculation of the 3D coordinates of all markers
6. Transformation of the results into a distinct coordinate position.

## VERIFICATION OF ACCURACY

When a photogrammetric system is applied for any measurement task, the user has to be sure the efficiency of the used system is adequate. The VDI/VDE guideline 2634 part 1 introduces a standardized way of determining the length measuring deviation as stated in the ISO 10360-2.

Inspection and monitoring of photogrammetric measurement systems are performed by measuring calibrated test-specimen. Here one-dimensional length standards are used which are calibrated with a coordinate measuring machine.

The length measuring deviation has to be tested in the complete measurement volume. For this, seven different measurement lines of the test-specimen are evaluated. Along these measuring lines, the specimen should be positioned. Five test lengths have to be measured along one measurement line as shown in figure 5. The longest test length has to be as long as the measurement volume. The specimen should be positioned as shown in figure 6.

The deviation between the calibrated and the measured length is determined and leads to the length measuring deviation of the photogrammetric setup.

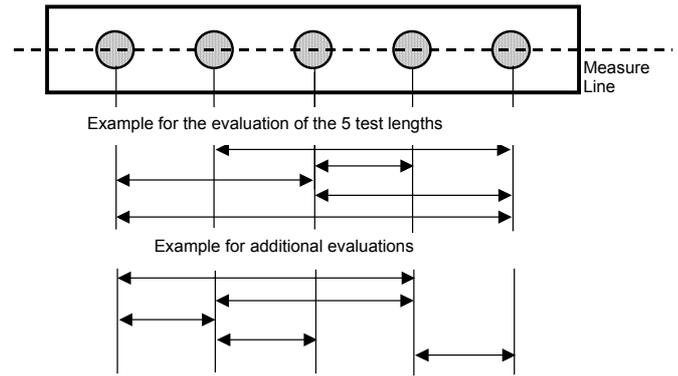


Figure 5: Test lengths

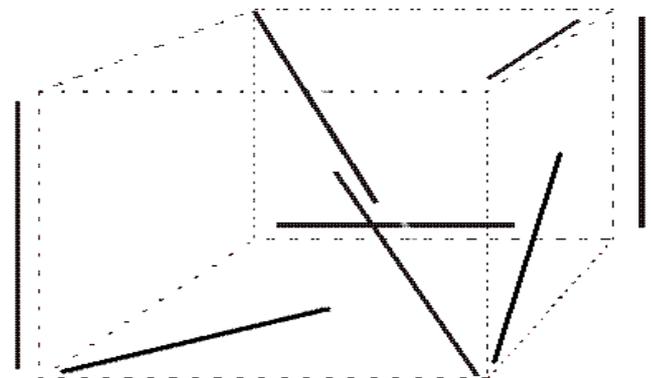


Figure 6: Recommendations for the positioning of the test specimen during the determination of the length measuring deviation

## DETERMINATION OF 3D DISPLACEMENTS IN ACCIDENT INVESTIGATIONS

### MEASUREMENT

For the measurement of accident vehicles, the position of measurement targets of an undeformed vehicle is defined. A map of targets will be created which allows a precise positioning of the targets on the deformed vehicle. To create such a reference setup, a vehicle which is completely equipped with targets is measured on a coordinate measuring machine. Thus the position of the reference points in the vehicle coordinate position are determined. This reference will be used to position the measurement results in the TRITOP software into the vehicle coordinate system.

For the measurement of a vehicle, some coded reference targets are positioned on the vehicle. It is important that these targets are positioned carefully as they are used for the coordinate transformation.

The deformed areas are marked with non-coded reference targets to make these areas available for the later analysis. Additional coded targets are positioned around the vehicle on the floor to support the photogrammetric calculation. These targets have no importance for the evaluation of the deformation. Two scale bars are used for the scaling of the setup.



Figure 7: Photogrammetric preparation of a crash vehicle

The next step is the recording of the vehicle using a digital camera. The camera is positioned in a bell shape around the vehicle.

The images are processed in the photogrammetric software TRITOP. All images are read into the PC and the position of the reference targets in the images and then in 3D space will be determined automatically.

#### FURTHER PROCESSING AND ANALYSIS OF THE MEASUREMENT RESULTS

The correctly scaled point cloud is now located in a randomly chosen coordinate position, see figure 8. For the further processing it has to be transformed into the vehicle coordinate position.

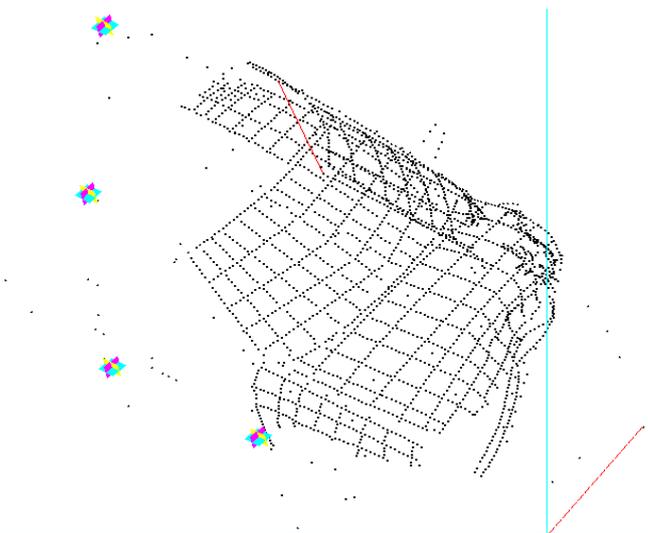


Figure 8: Cloud of 3D points in a random coordinate system

This transformation takes place using the reference targets that are placed at pre-measured positions with the coordinate measuring machine. The following steps are necessary for the transformation: At first, the coded targets on the vehicle have to be examined whether they are positioned in a deformed or undeformed area of the vehicle. The quality of the transformation with the targets

in the undeformed areas will be evaluated to determine the four targets which lead to smallest deviation to the reference data. They are used to create a basic transformation into a support coordinate system. The result is a positioning of the measurement data with an acceptable accuracy. To further improve the transformation, all coded reference markers in undeformed areas are used to minimize the sum of single positioning deviations.

The final result of the transformation steps is a good positioning of the point cloud into the vehicle coordinate system, figure 9.

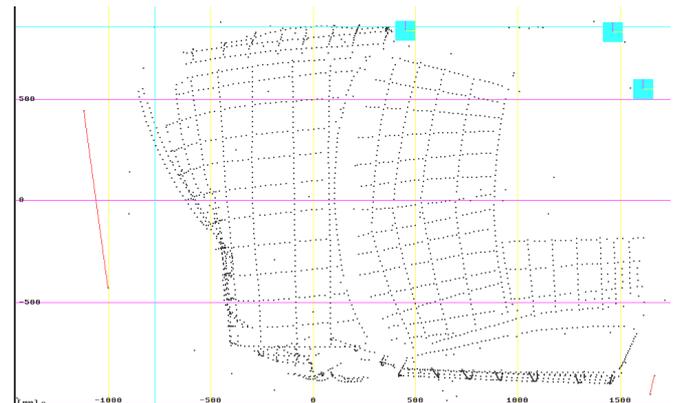


Figure 9: Cloud of 3D points in vehicle coordinate system

#### VISUALIZATION OF CRASH RESULTS

The photogrammetric measured 3D points are positioned in the vehicle coordinate system. Now they can be compared to the CAD model of the vehicle. Simply importing the 3D coordinates into a CAD viewer allows to quickly visualize the crash results, figure 10. This helps the crash analyst to estimate the degree of deformation.

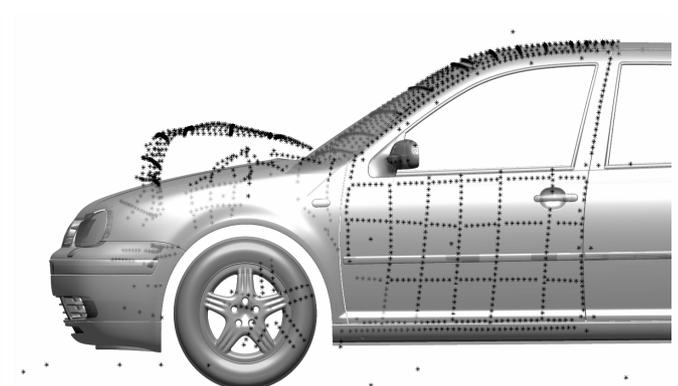


Figure 10: Direct comparison of 3D coordinates of the crash vehicle with the CAD model.

In a second step, the 3D coordinates can be used to create a surface model of the deformed vehicle. The goal is a shaded view of the accident vehicle to better visualize the measurement results, see figure 11.

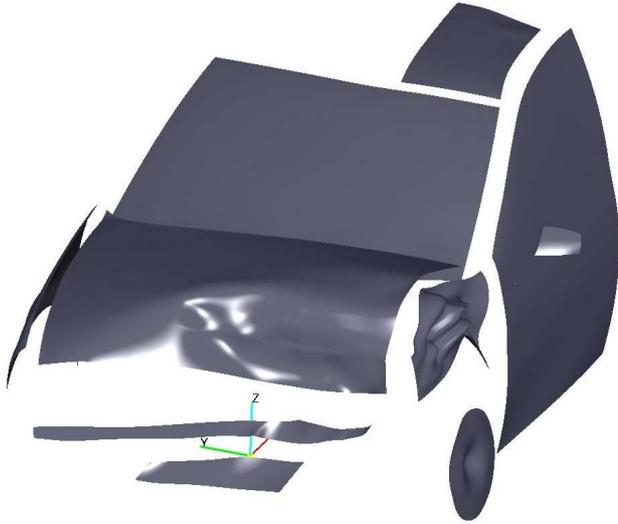


Figure 11: Surface model of the deformed vehicle based upon the photogrammetrically measured 3D points.

The surface data can be compared with the vehicle CAD data as shown in figure 12 and 13.

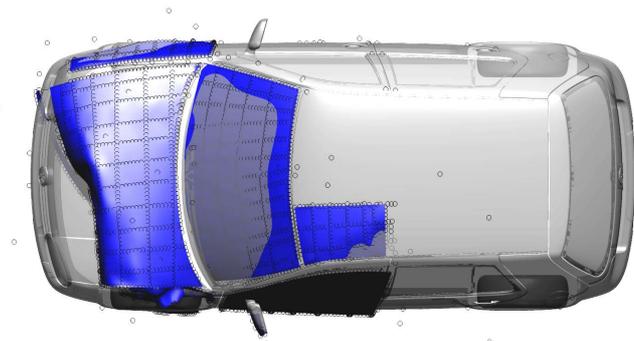


Figure 12: CAD data and surface model of the deformed vehicle.

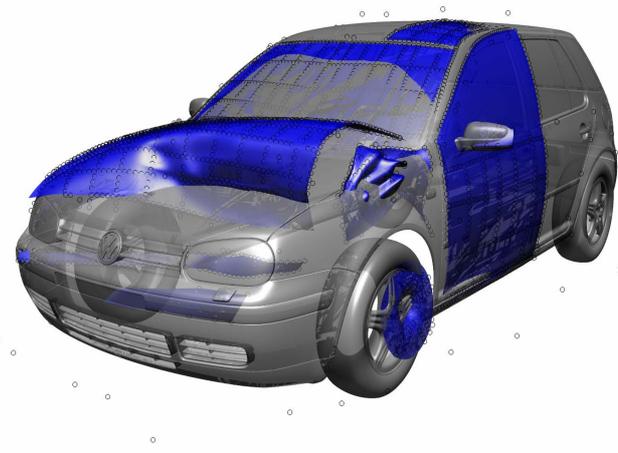


Figure 13: CAD data and surface model of the deformed vehicle.

Now by having available a surface model of the deformation, a lot of different ways of evaluating the crash are possible. Sections through the surface data and the CAD data can be used to view and measure certain areas. These sections can subsequently be used

for the determination of the actual crash angle, in vehicle-to-vehicle crashes. The Finite Element Method can also be applied to the deformation model to evaluate crash energies.

## CONCLUSION

The described method for the determination of 3D coordinates for accident reconstruction delivers a measurement accuracy that can hardly be achieved by tools nowadays in use. In addition most of the known methods are very time consuming. In comparison: the subject photogrammetry discussed here is able to perform an evaluation of a complete vehicle with up to 5000 measurement points in less than two hours.

A clear advantage of the photogrammetric method is the ability to further process the once photographed vehicles. Whenever needed, the measurement can be refined and extended. It is also possible to establish a data base of accident vehicles to allow a comparable examination.

Evaluating the direction of the measurement point displacement caused by the deformation, allows to determine the direction of the impact's forces. These analysis methods are new and possible, only with the help of the subject photogrammetry. This method is most beneficial for the evaluation of real life traffic accidents. Thus the base of information is extended to further improve vehicle safety.

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