A flexible vehicle measurement system for modern automobile production

by

Thilo Lichtenberg Dipl.-Ing.(FH)

A dissertation submitted in full satisfaction of the requirements for the degree of Magister Technologiae Mechanical Engineering in the Faculty of Engineering, the Built Environment and Information Technology of the Nelson Mandela Metropolitan University

Promoters: Prof. Dr.-Ing. T.I. van Niekerk
Prof. Dr.-Ing. H. Holdack-Janssen

December 2006
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III Abstract

To stay competitive and to be able to sell high-class products in the modern automobile production it is absolutely necessary to check the quality standard of a manufactured vehicle. The normal measurement strategy to check the quality standard of a completely assembled car is through a complex measurement strategy whilst the vehicle is in the actual series production. This is an immensely time and money consuming process. Furthermore, measurement systems are fixed within a certain position and the flexible measurement of a produced vehicle is very difficult to realize. This project presents a measurement system compliant to all quality guidelines, with which it is possible to measure any mounted component from a completely assembled vehicle wherever and whenever required. For the first time it is possible to measure the vehicle quality and dimensional standard from the first body in white prototype assembled in production up to the completely assembled vehicle delivered to the customer. The result of this project is a measurement system that consists of a hardware tool and a specially programmed software add-on. The complete system could easily be carried to the vehicle that must be analysed. This gives a lot of advantages. Furthermore it is possible to use this developed technology for the whole Volkswagen Company including the other brands like Audi, Skoda and Seat.
IV Acknowledgments

I want to acknowledge the contributions by the following people and institutions:

• My promoters, Prof Theo van Niekerk and Prof Hinrich Holdack-Janssen, for their support, guidance and encouragement;
• All the team members from the University-Industry Cooperation CarMetric Project for their assistance during the whole project;
• The staff of the GOM mbh in Braunschweig Germany, in particular Dr.-Ing. Jan Thesing, for assisting with measurement related problems and for the use of a high-end measurement system;
• The Institute of vehicle construction in Wolfsburg, for creating research opportunities at the University of Applied Sciences;
• The Volkswagen Company, especially to the staff of the departments of product optimisation (PWA-V) and quality assurance (GQA);
• My parents and my girlfriend for their love and support throughout the duration of this research project.
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Chapter 1

Introduction to Current Measurement Systems

The automotive industry is placing an ever increasing demand on dimensional tolerances, with environmental, comfort, safety and especially the quality requirements of the customer constantly rising, whilst vehicles tend to consist of more and more parts and components. Component development and implementation times have become shorter with engineering and production costs rising annually.

In order to guarantee a safe series production, the correct locations of all attachments have to be examined and verified, whilst equipment out of tolerance in the car body has to be corrected, right from inception. To meet this requirement the measurement of the completely assembled vehicle during the product development process is absolutely necessary as a quality assurance requirement. In addition, the need for a measurement system to perform vehicle dimensional analysis as part of an after-sales service has been identified. Any problems or errors in the product can be identified and analysed at the customers convenience.
Current measurement procedures are complex and use measurement data from the respective vehicle parts and compare it to recorded CAD data and part information obtained from the construction. Errors are detected in direction, position and size. Traditionally these measurements are carried out with systems which are based on a complex and expensive tactile procedure. This kind of measurement is inflexible as the completely assembled vehicle is stretched on measurement fixtures to create a basis for this analysis.

Through innovative improvements, a new, flexible procedure for production measurement methods is required and errors need to be eradicated more easily and cost effectively. An integrated process consisting of the creation of a complete picture of the vehicle as it is constructed, using as many complex measurements from assembly, is proposed as a future development. To enable this technology the respective parts or the entire body have to be correlated and aligned to different measurement photographs. Together the individual measurements create a complete picture of the entire vehicle. This overall view consists of a large set of integrated data.

Another requirement for flexibility is that the vehicles should not have to be lifted from the ground. This will enable test results to be more realistic. When the weight of the vehicle does not rest on the wheels, complex procedures of comparison ratios in the tested body are required which are time consuming and costly. Current measurement procedures are limited by the surrounding space available for measuring of the respective parts. It has been impossible
up to now to realize a flexible measurement system of an assembled car while standing on the ground, as it was a requirement within the current guidelines of the Volkswagen Company.

The Reference Point System (RPS) and the so called RPS-Points form the basis of every kind of measurement, as the coordinates of an object (part) is aligned to them in 3-D space. The RPS points are the basis of the coordinate system and the object-orientated system is placed as a reference over the entire vehicle with every point having a known position in relation to the constructed CAD. These basic RPS points of an assembled automobile are situated in the front and rear chassis rails of the vehicle and are invisible to every kind of measurement. It is not possible to measure a completely assembled vehicle in a flexible way, while it stands on the ground. With current measurement systems it is not possible to locate the hidden points in the chassis rails when the vehicle stands in a realistic condition on its wheels.

For this reason the work requires a hardware tool enabling flexible and complete measurement of the vehicle in a realistic condition in accordance with current standards from the Volkswagen Company. The integration of this hardware tool into the existing quality assurance software is achieved through programming additional geometrical calculations.

This chapter starts with a brief description of the current measurement guidelines of the Volkswagen Company, hence it explains the geometrical fundamentals with reference to the vehicles which are used in this project.
The actual measuring strategy currently used within modern automobile production is clearly explained.

1.1 RPS Standard of the Volkswagen Company

For the detailed determination of the main reference points, the current guideline VW 0 10 55 is essential as within it all procedures and scopes of VW measurement strategies and quality standards are declared. The Reference Point System in the Volkswagen Company is officially called RPS. A copy of this document is included in the Appendix B.

The intention and application range of the RPS-Standard is declared as:

“*The standard VW 0 10 55 applies for the dimensioning, fabrication and inspection of individual parts as well as complete assemblies in every phase of the product development process, for the consistent positioning, as well as the coverage of the same dimensional benefits.*” [11]

By an early determination of the main reference-points, the position in the three dimensional space of the respective vehicle part - in this case the completely assembled vehicle - is appointed clearly and without ambiguity. An object orientated coordinate system must be used for this. Every point of the object gets a definite position coordinate relative to the constructed CAD. A reference-point has got several functions. On the one hand these points are the location points for a measurement process. On the other hand the RPS- points are the check points in the quality assurance procedure. These
points also provide the basis for the tool fittings (jigs and fixture) as used within the production process.

With the points the whole body is fixed within the 3-degrees of freedom. Figure 1.1 indicates possible directions of movement.

![Degrees of freedom in the 3D-Space](image)

**Figure 1.1: Degrees of freedom in the 3D-Space**

To implement the so called 3-2-1 rule is used, with which a well-defined fixing in space is possible. This rule appoints the following arrangement of pick up points in the different indicated directions:

- 3 pick-up points in z-direction
- 2 pick-up points in y-direction
- 1 pick-up point in x-direction

That means that every component part is fixed with three attachment points in z-direction, two attachment points in the y-direction and one attachment point in x-direction, so that the object is aligned in an object orientated coordinate system in an accurate way.
The RPS points for the definite fixing of the vehicle must be defined early to establish a reference for the multidisciplinary provision interworking or so called SE-teams (simultaneous engineering teams). Through a thorough inspection of the function and tolerances from the respective part, the SE-team configures the best positions of the RPS-points, early in the construction phase. These points should ideally lie in the strongest parts of the object and should be distributed extensively over the object. After that the constructing engineers adds these points in the dimension sheets.

For every single part and also for the whole vehicle as an assembly, the basis is a global coordinate system (also called mathematic coordinate system) that is used for the unique dimensioning. For a complete vehicle the point of origin of the object orientated coordinate system is situated centrally and level with the front axle as shown in Figure 1.2. From that origin, the coordinate system could be mounted over the entire vehicle with axially parallel ruled lines in every coordinate direction, placed a distance of 100 mm apart.
Using these lines every existing part within the completely assembled vehicle can be assigned and assessed. The x-axis runs over the entire length of the vehicle, the y-axis runs through the vehicle width and the z-axis gives the vehicle height. Because of the position from the zero point, there are positive and negative directions for every coordinate direction.

In the guideline VW 0 10 55, it is explained in which way the RPS-points must be shown and appointed in the technical drawings. This input description is shown in Figure 1.3. The complete Volkswagen guideline can be found in the Appendix B.
Figure 1.3: RPS description

RPS 1 Hxy Fz

- **Geometry of the survey**: F = flat (Fläche)
  - Fixing direction: z-axis

- **Geometry of the survey**: H = hole (Loch/Stift)
  - Fixing direction: x- and y-axis

**RPS** = Reference point system

Reference point number: 1
1.2 Golf A5 Test Vehicle

To be able to compare and judge the measurements that will be done in this project, a pre-assembled Golf A5 was allocated by Volkswagen AG. This vehicle is the test object. A flexible measurement of the whole car should be realized in this project for the first time.

This car was measured with a conventional system before the project started. These measurement results provide the basis for further measurements and provide the obtainable coordinates for future comparisons. The complete test report from the Volkswagen Company is included in Appendix C. Additionally, a body of a Golf A5 (in white) shown in Figure 1.5, was allocated, especially for the adaptation of the constructed hardware.
The Volkswagen Golf A5 which is built on the PQ 35 platform by the Volkswagen Company, has precise positions of the main reference-points for the complete vehicle as shown in Figure 1.7 and 1.8 (assembly underbody). From these drawings it is clear, that the RPS-points are situated on the bottom side of the front and rear chassis rails. For the clarification, only a single section from the underbody is shown.
Figure 1.7: RPS-Situation PQ 35, front end, underbody, down view [12]
The 3-2-1 rule is applied as follows:

RPS1 is situated on the right front side and fixes the vehicle in x, y, and z directions. RPS2 is located on the right rear side and fixes the y and z directions. RPS3 fixes the z direction and is situated on the left rear side of the underbody. RPS4 is a so called “assist reference-point”. The coordinates
of these points are the basis for the alignment and for every kind of measurement.

The reference-points “RPS1 HxyFz” and “RPS4 fz” are defined via a 30mm round hole and the lower contact surface of the front chassis rails as shown in Figure 1.10.

The reference-points “RPS2 HyFz” and “RPS3 Fz” are defined by an elongated hole and the corresponding flats in the rear chassis rails.

Admittedly, the CAD-plane of the RPS-points on the rear chassis rails are defined inside the sheet plate on the chassis rails. Because it is impossible to locate the inside plane of the rails, the outside of the chassis rails must be used. Therefore, in a measurement it is necessary to integrate an offset with a sheet thickness of 2 mm as shown in Figure 1.11.
Figure 1.10: Section “-370x” over RPS1 HxyFz (PQ35), front [12]

Figure 1.11: Section “2975x” over RPS2 HyFz (PQ35), rear
Figure 1.12: RPS2 of PQ35 platform, rear, down view [12]
1.3 Actual Measuring

Traditionally the procedure to check the quality standard of the produced vehicle is to measure with systems which are based on a tactile localisation. In the following section two systems are shown, with which a common measurement is carried out. These tactile systems are superordinated when compared to non-contact systems. Because of the fact that these tactile systems are related and fixed to a certain position, they are not applicable for flexible measurements in quality assurance. However, in the area of the production and manufacturing, these tactile systems cannot be replaced by contactless systems in the near future.

1.3.1 Underfloor Coordinate Measurement Instrument

This kind of tactile coordinate measurement instrument (Figure 1.13) offers the possibility to measure the produced vehicle from the top as well as from the bottom of the vehicle. With this system it is important to maintain the coordinates of the RPS-points which are accessible only from underneath the vehicle. It is possible to align the object in the object orientated coordinate system, by conforming to standards when the car stands on the ground on its wheels. One of the problems with this system is that such a measuring machine is mounted stationary on a baseplate, so mobile measurement is impossible. Furthermore the complete system is very expensive.
Figure 1.13: Underfloor coordinate measurement instrument

The method of localising the buried RPS-Points in the chassis rails with the underfloor coordinate measurement instrument is by driving the vehicle over a cavity. The whole system consists of three tactile sensors. In this cavity is one of the tactile sensors with which it is possible to obtain the necessary coordinates of the RPS-Points from the bottom side of the vehicle. The measurement procedure is to detect the coordinates of the RPS-Points with the sensor from under the vehicle first. The result is that the positions of the RPS-Points are entered in the machine-orientated coordinate system. The whole car is then aligned in the three-dimensional space, and the object orientated coordinate system can be mounted. In this coordinate system every point in and outside the vehicle has an exact precise position. Every point of interest can be measured with the two tactile sensors outside the cavity, and compared with the CAD coordinates.

This measurement strategy takes up to 1.5 days for a Golf A5 when a normal analysis is carried out, and the complete underfloor coordinate measurement instrument costs around 700,000,-€.
1.3.2 Measuring Fixture

Another strategy to measure a completely assembled vehicle, is to stretch the car on a measurement fixture using the RPS-points in the chassis rails. In Figure 1.14 the basic principle is illustrated. By holding and clamping the car body directly in the RPS-holes, the position of the object orientated coordinate system is established (comparable with CAD). A measurement confirming the standards in the necessary coordinate system is then possible, because the positions of the RPS-coordinates are known for the measurement system and for the alignment.

![Figure 1.14: Golf A5 fixed on a measuring fixture](image)

The problem with this kind of measurement is that the actual stress condition of the car body does not occur in this way when the vehicle stands on the ground on its own wheels. There are different positions of the parts, like the doors or the hatchback, and such a measurement gives no realistic results. Furthermore, when the vehicle is measured on such a tool it is not in the
condition in which the customer receives the vehicle. The biggest problem with this measurement fixture is to measure open-topped vehicles. These cars are delicate concerning the torsion of the car body when the vehicle is clamped on the fixture.

1.4 Disadvantages of Current Measurement Tools

The current measurement strategies are approved methods to check the car within the production process, however there are some disadvantages, namely:

- extremely time consuming process
- interruption of the production process
- stationary process
- necessity of large rooms
- vehicle must be disassembled
- vehicle is fixed on a tool in an unrealistic condition
- cost-intensive fixtures necessary
- no continuous measurement in the whole process from the first prototype up to the finished product at the customer possible

Generally it is very complicated to do a continuous measurement of the entire process from the first prototype up to the finished product. In modern automobile production it is absolutely necessary to have a benchmark for the whole vehicle to meet the current guidelines wherever and whenever it is required.
Chapter 2

A Flexible Measurement Concept

In this chapter the basic concept and system for flexible vehicle measurement as applied within modern automobile production and as used in this project, is described.

2.1 Main Principle

To realize flexible measurement wherever and whenever you want, the basic concept lies in the mechanical dislocation of the relevant invisible points required for the measurement, thereby establishing a system that links to other observable points outside the vehicle. These external points have a known relation to the invisible RPS-Point embedded in the chassis rails. With this relation it is possible to locate and connect the required component coordinates and the main reference points. This system which is built in cooperation with the Volkswagen Company Wolfsburg, Germany, is referred to as “FlexMess”. The author can proudly announce that the measurement
strategy of the FlexMess System as developed in this masters project has been filed for a patent by the Volkswagen Company.

![FlexMess Logo](image)

*Figure 2.1: Brand name, trademark and logo from the FlexMess system*

The name FlexMess is a proprietary identification for the whole system. The development cycle is shown in the following chapters. A patent document from VW is included in Appendix F.

![FlexMess Diagram](image)

*Figure 2.2: Basic principle of the FlexMess*

With a self-centring chuck it is possible to attach all reference hardware components of the FlexMess under the car, as shown in Figure 2.2. For every RPS-Point there is a single component composed of a chuck and two carbon tubes that can be placed directly into the holes of the chassis rails. The principle of FlexMess is that you have several external points on the
carbon tubes which you can see when the hardware is fixed under the assembled car. These points have a known relation to the invisible RPS-Points in the chassis rails, as shown in Figure 2.3.

The following subsections will describe the fundamental principles of non-contact measurement and indicate the techniques employed with the FlexMess system. Finally it will describe existing photographic technology TRITOP used to implement the FlexMess system.

2.2 Alternative Measurement Systems

The coordinate measurement systems with mechanical feelers that are normally used, are not very applicable in production-related inspections. Even in the observation of complex geometrical surfaces, non-contact measurement and inspection systems provide a positive alternative. Furthermore the flexibility of the measurement system is one of the main demands why non-mobile systems have remained out of consideration. The system that will be used in this project must fulfil the following requirements:
- It must be a portable system that is able to work at different places and on cars.
- It must have an accuracy of less than 0.5 mm for a measurement volume of around 5 meters.
- It must be a competitive system to reach a cost effective solution.
- The system software must have the capability to allow for add-ons, and to enable continuative applications.
- The system must be based on non-contact measurement principles.

Fundamentally, all non-contact measuring methods are based on the interpretation of electro-magnetic waves with different wave lengths. The popular strategies are shown in the following diagram in Figure 2.4.

![Classification of non-contact measuring methods](image)

**Figure 2.4: Classification of non-contact measuring methods**
Because of the high demands for accuracy in automobile production, only the analysis of light waves with a congruently small wave length is acceptable. An example of the use of wide wave lengths is the echo-sounder, the sonar or locating with radio waves.

In this project the non-contact measuring of vehicles is selected as a method to solve the problem. Because of the dimensions of the whole vehicle and the required accuracy for this application, (close-range) photogrammetry is the best procedure. An alternative to this is to apply laser-scanning systems or to consider combinations of non-contact and flexible tactile systems, but these are relatively expensive options.

2.3 History of Photogrammetry

The fundamental principle used by photogrammetry is triangulation. By taking photographs from at least two different locations, so-called "lines of sight" can be developed from each camera to points on the object. These lines of sight (sometimes called rays, owing to their optical nature) are mathematically intersected to produce the 3-dimensional coordinates of the points of interest. Triangulation is also the way the eyes work together to gauge distance (called depth perception).

Photogrammetry is defined as:

\begin{quote}
Photogrammetry is the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images or patterns of electromagnetic radiant energy and other phenomena.
\end{quote}
The concepts of photogrammetry go back to the period of Leonardo da Vinci in 1492, when he began investigating perspective and central projections. Many other scientists continued da Vinci’s work mathematically and the first great step in the formal creation of the Science of Photogrammetry was in 1759 when a scientist Johann Heinrich Lambert, in a treatise “Perspectiva Liber” (The Free Perspective), developed the mathematical principles of a perspective image using resection to find the point in space where the image was created.[23]

![Figure 2.5: Leonardo da Vinci (left) and Johan Heinrich Lambert (right) [20]](image)

The first ever photograph required over eight hours exposure, N.J.Niépce composed the diapositive image created. Jacques Mandé Daguerre, in 1837, using a method known as the Daguerreotype, obtained the first practical photograph. By 1840 scientists were beginning to use the technical term “photogrammetry”. Dominique François Jean Arago, a French geodesist, proposed the use of photogrammetry in front of the French Arts and Science Academy. From 1850, photogrammetry has followed four key development cycles (Konecny, 1985). Each of these cycles are approximately 50 years long, namely:
1. Plane table photogrammetry, from ~ 1850 to 1900.
2. Analog photogrammetry, from ~ 1900 to 1960.
3. Analytical photogrammetry, from ~ 1960 to present.
4. Digital Photogrammetry, which is beginning to show a strong presence in the photogrammetric industry. [21]

Before each cycle a basic invention is present. One of the most important personalities in photogrammetry is Aimé Laussedat, widely referred to as the “Father of Photogrammetry”. In 1849 he was the first person to use terrestrial photographs for topographic mapping. In 1858 he began experimenting with aerial photography and by 1862 he had managed to get the use of photography for mapping accepted by the Science Academy of Madrid and so the science of photogrammetry was born. To take photogrammetry to the next phase of development, namely analog photogrammetry, two inventions were required. The stereo plotter and the aeroplane, to provide a better platform for cameras. The first stereo-planigraph, a stereo plotting instrument, was invented in 1896 by Edouard Deville, Surveyor General of the Dominion, however this instrument was extremely complicated and
resulted in little use. It wasn’t until 9 years later in 1907 that, in Germany, Ritter von Orel, helped develop the first stereoautograph with a small emerging company known as Zeiss. These were still incredibly complex devices even after 50 years development. It wasn’t until 1941 and the invention of the computer by Zure in Germany and independently by Aitken in the US in 1943, that enabled significant advances in photogrammetry possible. The primary scientist responsible for taking this phase of development on is Dr Hellmut Schmid, who in 1953 developed the principles of multi-station analytical photogrammetry using matrix notation, and the least squares solution. The man responsible for the invention of the analytical plotter however is Uuno (Uki) Vilho Helava. While working at the National Research Council in Canada he developed the analytical plotter in 1957. This instrument was the first to be servo controlled as opposed to optically or mechanically constructed. A computer drove the instrument around the stereo model as well as digitally transforming image-map coordinates. Helava continued to play a key role in the current phase of photogrammetry, digital photogrammetry. He helped to develop a digital photogrammetric workstation for the Defence Mapping Agency (now NIMA). The company Helava formed, Helava Associates has now been acquired by LH Systems, a subsidiary of Leica Geosystems. The current state, even with the developments in digital photogrammetry, analytical photogrammetry and film based photogrammetry still play major roles in aerial photogrammetry. This is mainly due to the familiarity with the format but also due to the extremely high costs of high resolution aerial cameras. When it comes to close range photogrammetry the digital technique has now become a dominant media,
mainly due to the reduced cost of digital cameras and the speed at which data can be obtained. As with film cameras, digital cameras need to be carefully calibrated. It can produce equivalent or better results due to the lack of data loss occurring in transferring the film data to digital format. [3] [6]

2.4 The Principle of Photogrammetry

Close-range photogrammetry relies on the reconstruction of the object from several images from different perspectives / positions to ensure a suitable and accurate geometrical construction of intersecting rays. The images are stationed free in object space as the photogrammetric network is reconstructed from the bundle of rays. The object coordinates, the exterior orientations and the interior orientation of the camera are estimated simultaneously in a common process called bundle adjustment. Bundle adjustment is the program that processes the photographic measurements to produce the final XYZ coordinates of all the measured points. In order to do this, it must triangulate the target points, resect the pictures and self-calibrate the camera. It is critical that at least one picture is positioned at an angle of approximately 90° differently to the others. If you do not, you cannot self-calibrate the camera. Instead, you will have to rely on an existing calibration that is less reliable and less accurate. The bundle adjustment process is called STAR, which stands for Self-Calibration, Triangulation and Resection. The real power of the bundle adjustment is that it is able to do all three of these things simultaneously. In order to triangulate the measured points, the orientation of the pictures must be known. However, in order to orientate the
pictures, the coordinates of the measured points must be known. The bundle adjustment has the capability to determine both simultaneously and to self-calibrate the camera as well. This is where the name bundle adjustment comes from because it bundles all these things together and solves them all at the same time. When the bundle adjustment is finished, it produces the following [2]:

1. The XYZ coordinates (and accuracy estimates) for each point.

2. The XYZ coordinates and 3 aiming angles (and accuracy estimates) for each picture.

3. The camera calibration parameters (and their accuracy estimates). [1]

Requirements for successful application of photogrammetry as illustrated in Figure 2.7 are:

- Ensure that the photos has been taken from a central projection of the 3D object points in every single image
- No or little scattering of light rays passing through the lens (point PC) of the camera.
- The image medium at the focal plane of the camera must be a rigid
The mathematical relationship between the 3D object and the image is known as the principle of collinearity, as shown in Figure 2.8 and described in the following subsections. The principle of collinearity embraces the six degrees of freedom of the camera: three translations and three rotations. Departures from the central projection can be modelled as systematic errors in the collinearity condition.

### 2.5 The Collinearity Condition

The collinearity condition defines that a point in an object space, the corresponding point on the plane, and the projection center are on one line. An ideal image geometry is assumed. Real cameras do not have the characteristics of an ideal pinhole camera. Consequently, some deviations from this ideal model are expected. For the purpose of photogrammetry, the
principle of the pinhole camera has been modified with correctional measures. These measures correct lens distortion, scale differences, and the errors arising when two 'normal' planes do not meet at a right angle. The mathematical principle is shown in Figure 2.8.

\[ y = c + \lambda R x \]

Where the following principles define the relations:

- \( y \) = the object space vector to the object point
- \( c \) = the object space vector to the photograph perspective centre
- \( \lambda \) = a variable scale factor
- \( R \) = an orthogonal three dimensional rotation matrix
- \( x \) = the image space vector to the image point
the collinearity equations:

\[
x = -f \frac{r_{11}(x-x_0) + r_{21}(y-y_0) + r_{31}(z-z_0)}{r_{13}(x-x_0) + r_{23}(y-y_0) + r_{33}(z-z_0)}
\]

(Eq. 1) [22]

\[
y = -f \frac{r_{12}(x-x_0) + r_{22}(y-y_0) + r_{32}(z-z_0)}{r_{13}(x-x_0) + r_{23}(y-y_0) + r_{33}(z-z_0)}
\]

(Eq. 2) [22]

\(x, y\) = coordinates of the image point

\(f\) = focal length of the camera

\(r_{ij}\) = element \(i\ j\) of the rotation matrix \(R\)

\(r_{ij} = f_{ij}(\omega, \phi, \kappa)\)

\(\omega, \phi, \kappa\) = rotations of the camera relative to the object space

With this collinearity condition, it is warranted that the real point in an object space, the corresponding point on the plane, and the projection center are on one line.

2.6 Advantages & Disadvantages of Photogrammetry

The use of photogrammetry has many advantages. But there are also some disadvantages.

Advantages:

- non-contact process
- 2D or 3D information options
- high density of measurements possible
- photographs are a permanent record
- measurements are made in the laboratory
- re-measurement is possible
Disadvantages:

- photographic coverage is limited
- dead ground precludes measurement
- photographic processing delays
- measurement and analysis delays
- efficient only for large data sets

The above subsections formed the basic knowledge used to search and select a qualified system that meets the criteria and to support the FlexMess measurement system. This was found in the GOM Tritop system described in the next section.

2.7 GOM Tritop

A system that is very applicable for this kind of measurement is TRITOP from the GOM Company, Braunschweig / Germany. TRITOP is an industrial optical measurement system which is used for non-contact measurement of 3D-coordinates and discrete object points. It is a mobile system based on photogrammetry. Relevant object points are identified with markers, adapters or markings. The object, in this case a completely assembled vehicle, is recorded by a high-resolution photogrammetric camera from different directions and angles. System components are shown in Figure 2.9.
Based on digital images, the TRITOP-Software automatically calculates the 3D coordinates of the adhesive markers and adapters, as shown in Figure 2.10.

In addition object features can be defined. TRITOP is used for objects up to and over 20m. The system achieves measuring accuracies of 0.02mm per 1m object size. The TRITOP Software can handle several thousand measuring points and allows the use of different recording devices.
2.7.1 Workflow of TRITOP

Generally a measurement with the TRITOP system is divided into four parts, the steps are as follows:

1. **Marking:**

   The object – in this case the completely assembled vehicle – must be placed between the two measuring sticks. With this action the software gets a known relation for the appointment of lengths and distances. The object is then marked with adhesive circular markers, adapters or features for those locations of interest. Single markers or combinations of markers can be used. Furthermore so called coded markers must be distributed on the object. With these coded markers the software is able to generate an interconnection from all the photos that will be done in the measurement.

![Preparation / gluing the circular markers](image)

Figure 2.11: Preparation / gluing the circular markers [15]

2. **Recording:**

   The prepared object is recorded freestyle by the digital photogrammetric camera from different directions. Photos should be taken in different areas and in a kind of a socket around the vehicle.
3. Automatic Computation:

After taking enough photos of the object (the number of photos that must be taken is based on experience) it can be sent directly to a computer which has the TRITOP software installed. Based upon the digital images, the TRITOP software automatically calculates the image-coordinates, the camera positions and the object-coordinates of the measuring points. The system is self-controlled and allows a statistical estimation of the measurement uncertainty.
4. Results:

The 3D coordinates of the measuring points, (the green points on Figure 2.14) and features of the camera positions (yellow points) are visualized in the TRITOP software. Additionally, the measuring points can be compared to CAD data or additional stages, exported in typical standard formats or used directly in continuative software types.

![Figure 2.14: Exposition of camera positions and measurement points [15]](image)

2.7.2 Typical Result and Datasheet

To be able to compare and to make use of a measurement that was done with the TRITOP system a test report must be displayed. A typical test report is shown in Figure 2.15. By using a colour image chart, it is possible to localise which sections on the analysed object are in a different position in comparison to the CAD data. The scale and the colour from that test report could be changed manually. Furthermore special points are shown with the nominal values from the CAD data and the actual values (measured) in a table.
Figure 2.15: Typical result of a measurement with TRITOP [15]

The measurement system TRITOP meets all the requirements for a successful measurement strategy, and integration with FlexMess. The datasheet is provided in Figure 2.16.

Using TRITOP, objects of up to some 20 m can be measured. Depending on the measuring task, different camera systems are available.

All TRITOP systems are self-calibrating and self-checking.

<table>
<thead>
<tr>
<th>System Configurations</th>
<th>HR / Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera Resolution</td>
<td>up to 12 million pixels</td>
</tr>
<tr>
<td>Data Transfer</td>
<td>wireless or flash card</td>
</tr>
</tbody>
</table>
| Measuring Area        | 0.1 x 0.1 to >> 10 x 10 m²  
                        | 4 x 4 to >> 400 x 400 inch² |
| Calibration           | self-calibrating |
| Certification         | according to VDI 2634/1 |
| Operating Temperature | -40 to 120°C  
                        | -40 to 250 °F |

Figure 2.16: Datasheet of TRITOP [15]
In this chapter it was shown that photogrammetry is a technology that could be used very well for this measurement project. Furthermore it was shown that the system TRITOP from the GOM Company is a system with which it is possible to integrate the FlexMess adapters and to enable a flexible measurement wherever and whenever it is required.

The company GOM placed a complete high-end system for this project to the author’s disposal, so a practical strategy could be developed and realized. This action is shown in the following chapters.
Chapter 3

FlexMess Hardware Technology

In this chapter the developed hardware for a flexible vehicle measurement is shown. At first the prototype phase is explained and after that the construction of a second version, purpose-built for this project, is shown.

3.1 The First Prototype

The basic principle proposed in this project is the mechanical dislocation of the relevant invisible points for the measurement. The basic concept was developed with the help of a prototype. This flexible measurement fixture consists of two rigid aluminium telescope profiles as shown in Figure 3.1. On the ends are orthogonally placed aluminium beams on which reference-globes are mounted. On each fixture two centring-pins are fixed with which the hardware can be mounted directly to the RPS-holes in the chassis rails.
When the hardware is fixed under the car, there are two reference-globes that are visible outside the car for every RPS-point, as shown in Figure 3.2.

It is possible to maintain the necessary coordinates of the invisible RPS-points using the visible points from the FlexMess outside the vehicle. After the prototype was fixed in a safe and reproducible way, the development of
the integrated measurement strategy with the TRITOP system could start. This operation is shown in detail in Chapter 4.

With this prototype the first method of flexible vehicle measurement was realized, the hardware showed great advancement potential. The demands on the next version of a measurement fixture for the project included:

- Lightweight construction
  
  *with this demand an uncomplicated mounting and carrying by a single person should be realized.*

- Safe and reliable fixing to the vehicle
  
  *it must be guaranteed that the hardware is fixed in a safe and stable way, that the hardware is mounted planar to the RPS-plane on the underside of the chassis rails.*

- Inherently stable material
  
  *it must be ensured that the hardware may not be deformed by crushes or temperature differences.*

- Modular concept
  
  *firstly a style with a modular concept is required that the installation in the RPS holes becomes easier and secondly that there is the possibility to store the whole hardware in a case for transport*
With these demands a new layout of the hardware was developed and constructed in a CAD-data.

### 3.2 FlexMess

One of the biggest modifications is the modular concept. Now there is a measurement fixture for every RPS-point that is constructed in a dismountable way.

![Figure 3.3: CAD of one of the four measuring fixtures](image)

Every single part from the FlexMess is described in the following subsections and shown in Figure 3.4. Additionally in Figure 3.5 a photograph of one of the FlexMess adapters without the carbon extensions is shown.
Figure 3.4: Exploded drawing of one of the FlexMess adapters

Figure 3.5: Photograph of one FlexMess adapters without the extensions
3.2.1 Collet Chuck

The RPS-chucks are based on a commercially available product form the company WITTE from Lüneburg / Germany. On these chucks, which are normally used to fix hoses and tubes, special clamping jaws are installed as shown in Figure 3.6. These clamping jaws should centre the hardware in the bore sight of the RPS-hole and thereby fixing and centring the hardware in the x- and y-direction. Furthermore the jaws must fix the hardware in the z-direction. This is realized by a bevel on the clamping jaws. With this bevel all the hardware is pulling on the underside of the chassis rails and assures a positive fixing in the horizontal plane (z-direction).

![Collet chucks with clamping jaws front (left) and rear (right)](image)

By rotating the scroller of the chuck, the chops are straddling apart. With this configuration it is possible to erect the hardware in the RPS-holes. By rotating the scroller, the clamping jaws clamp the hardware in the hole and press the hardware directly onto the RPS-plane.
Because of the fact that two of the RPS-points are located in round holes, and the other two RPS-points are located in elongated holes (cp. Chapter 1.2), different kinds of chucks must be used. For the round holes in the front chassis rails (RPS1 HxyFz and RPS4 fz) a three jaw chuck, and for the elongated holes in the rear rails (RPS2 HyFz and RPS3 Fz) a six jaw chuck is used. In Figure 3.7 this procedure is shown with one of the clamping jaws in the RPS-hole.

![Diagram](image_url)

Figure 3.7: One of the clamping jaws in the RPS-hole
3.2.2 Extensions

After testing different materials for the extensions it was decided, that carbon is the most suitable material for this use. The advantages of carbon are:

- low weight with high strength
- extremely corrosion-resistant / no rottenness
- beat and shock-proof
- heat-proof and cold-resistant
- high durability

After testing different types of carbon tubes, the best suitable dimension is a 1 meter length of tube with a wall thickness of 0.5 mm and a diameter of 23 mm was easily handled, shown in Figure 3.8.

Figure 3.8: Carbon tubes [18]

This kind of tube which is produced by the company, Carbon-Team, Reutlingen / Germany, has a weight of only 52 grams and is normally used for extension arms of helicopters. There must be measurement targets on these carbon tubes which the measurement system can localise when the
FlexMess is fixed under the vehicle. For this purpose, there are two uncoded markers that could be used in the TRITOP system, as shown in Figure 3.9. With a black-white contrast the software can realize the coordinates of the benchmarks on the carbon extensions.

Because of the fact that the developed hardware is not only intended for use with the TRITOP system in the future, extensions with other features were developed at the same time. These extensions are not equipped with gage marks which could be found by a camera, but are equipped with gage balls, as shown in Figure 3.10.
Many scanning systems are not able to localise two dimensional markers or points. They need three dimensional geometrical objects to be able to localise coordinates in a measurement procedure. These systems with which a measurement in communication with the FlexMess hardware is scheduled for future projects, can use four gage balls for every RPS-hole, as shown in Figure 3.11.

All other parts of the FlexMess can be used in the same way as it is working with the current TRITOP software system.
3.2.3 Joining Technology for the single Parts

To realize a reproducible connection between the shank and the carbon extensions, special threaded sleeves have been developed that are laminated into the carbon tubes. The notches in the sleeves, as seen in Figure 3.12, ensure that the markers on the tubes are always in a parallel ratio to the horizontal level.

![Figure 3.12: Thread sleeve with fit-in key](image)

In this way the measurement system TRITOP can localise the position of the markers in every case. The CFK tubes are mounted on the base of the FlexMess by using a M8 screw with a star head that can be screwed into the threaded sleeves in the carbon extensions.

![Figure 3.13: Reliable connection CFK-extensions with M8 star handle screw](image)
The connection between the shank core and the base of the FlexMess is realized in a similar way, shown in Figure 3.14. Because of the fit-in key on the end of the shank core, there is only one position in which the hardware could be assembled. All the single parts of the FlexMess were constructed in CAD (ProEngineer-Wildfire 2.0), so that it is possible to duplicate or improve on the hardware whenever it is needed. All drawings are included in the Appendix A.

Figure 3.14: “Save from twist” connection between shank core and base

3.2.4 Calibration Plate

Because of the fact that the FlexMess is dismountable – it means that you can screw off the carbon tubes from the chuck for transport. The hardware must be calibrated before mounting the FlexMess under the vehicle and starting the measurement. This is done with a special calibration plate. On this plate you can mount the 4 components of the FlexMess when they are assembled, like it is shown in Figure 3.15 and 3.16.
Figure 3.15: All the 4 components of the FlexMess on calibrate plate

Then some photos are taken with the TRITOP camera (this procedure is shown in Chapter 4). For the calibration, a special macro was programmed into the TRITOP software (Chapter 4.2), which is able to locate the actual position from the points on the tubes in relation to the point in the chucks. After the calibration, the ratio between all the points on the hardware is determined. The 4 components can then be mounted directly into the RPS holes in the chassis rails under the car.

Figure 3.16: Build up of the FlexMess ready for calibration
3.3 Complete Package of the FlexMess

To realize a flexible measurement it is necessary to be able to carry all the necessary hardware of the FlexMess to any place where an analysis of a produced vehicle is required. Because of this, from the start of the construction phase it was observed that all hardware components could be placed into a case for transport. For this request a special case was developed and built for the hardware, shown in Figure 3.17.

![Figure 3.17: FlexMess system in transport case](image)

In the expanded material of the case special milled grooves are integrated into which every part of the FlexMess can be placed. Thus a safe and shock-proof transport of the system is assured. The completely equipped case has a weight of approx 22kg. The case has special wheels on the back so that it can be transported by one person. The case has the following dimensions:

- Length: ca. 1400mm
- Width: ca. 500mm
- Height: ca. 200mm
Furthermore all the hardware in the case is not only for the mentioned PQ 35 platform. During this measurement project it became apparent, that it is also crucial to enable flexible measurements of completely assembled vehicles that are built on other platforms by the Volkswagen Company. This thesis is not dealing with the adaptation of the hardware to other VW-platforms. The adaptation and the integration of the FlexMess hardware to every VW-platform is a point for the future work. All the hardware for the PQ35 and for the PQ24 platform is placed in the special case. All drawings, graphs, data-sheets and a complete bill of materials of the constructed FlexMess is included in the Appendix A.

This hardware guarantees a safe and reliable fixing on the vehicle and because of the modular concept, all hardware can be carried by a single person to the vehicle that must be analysed. The next step is to integrate the connection between the visible points on the extensions to the invisible RPS point on the chassis rail into the TRITOP software. This integration within the preparation of a special software add-on is shown in the following chapter.
Chapter 4

GOM TRITOP Software and FlexMess Interface

This chapter starts with a general description of the measurement system GOM TRITOP as used in this project, with software components developed and added to enable the illustrated FlexMess. The programming and recording of measurement macros which were specifically developed for the FlexMess is presented by way of an operation instruction as it would be used for the teaching and training of a normal TRITOP user.

4.1 TRITOP Photogrammetry Software Interface

The measurement system GOM TRITOP and the workflow are described in Chapter 2.3. The following part gives a description of the software operations, a brief introduction to the TRITOP system, and describes TRITOP application software.

The basic idea of photogrammetry (Chapter 2.2) is to look at reference points from different directions and to calculate the 3D coordinates from the images
or point rays obtained. The visible reference points in an image have a fixed relation to each other. Therefore, using images constructed from other angles it is possible to calculate the camera location using the reference point relations. During the acquisition of a set of images it is the goal to record reference points from multiple different directions ideally with large angles between images. It is the task of the TRITOP software to precisely determine ellipses (a perspective view of reference points) in all images of the set as well as their 3D orientation. The TRITOP software interprets the images and generates 3D measuring data. The measuring data can be evaluated in the TRITOP system (CAD comparison and inspection) or made available to subsequent systems. Some of the most important TRITOP features include:

• Optical 3D coordinate measuring machine.
• Coordinate measurements of drilled holes, edges, lines, patterns and freehand lines on surfaces.
• Optional measuring adapters for edges, holes, threads, cones, cylinders, spheres and surfaces with automatic identification.
• Measuring of flexible objects.
• Mobility by using a standard notebook PC.
• Flexible object sizes from 0.1 m to some 20 m.
• Easy and quick image acquisition.
• Optional wireless image transfer (WLAN) to the computer.
• Automatic computation of the digital images.
• Automatic 3D coordinate measurement of reference points.
• Precise measurement of 3D coordinates.
• Definition of a coordinate system, e.g. using the 3-2-1 rule, best-fit or pass points.

• Comparison of the measuring data to CAD or measuring plans.

• Direct interface to the ATOS software.

• Point export in standard formats.

• ASCII, HTML and Open Office export of measuring results.

• Clear and easy user interface. [15]

Main Hardware and Software components of the TRITOP system include:

• High-resolution digital camera with interchangeable lenses of fixed focal length.

• Storage medium (Compact Flash, PCMCIA, microdrive) for transporting data from the camera to the PC or optional image transmission via WLAN.

• Camera flash, in order to optimally light the measuring object.

• Coded reference point families (sets of 100, 300 or 420, consisting of a center dot and a surrounding ring code). Each point has its own ID no. in order to generate an image set that can be automatically evaluated in TRITOP and to allow for calculating the camera positions.

• Uncoded reference points, to get 3D coordinates of the measuring relevant parts of the object to be measured.

• Certified scale bars for scaling the TRITOP measuring results. They have ultra-precisely measured reference points for determining their length.
• High-performance PC or laptop.
• TRITOP application software TRITOP v6 for analyzing and evaluating the image sets and measuring results.
• GOM Linux operating system as of version 7.
• One of the following computers: Dual Core Opteron (64 bit), Dual Opteron (64 bit) Dual Xeon (32 bit), or one of the following notebooks: Dell Precision M70, Dell Latitude D800, Dell Inspiron 8200. [15]

4.1.1 Application of TRITOP Software

It is possible to start the software in two ways:

a) Using the KDE menu
Click on the KDE start icon and select the software from the directory GOM-v6.0.0. This directory is the master version and is automatically linked to the current software version \((GOM-v6.0.0-xx)\) installed on a computer.

b) Using the software icon
Simply click on the respective icon in the KDE tool bar. In case the icon is not available, click on the desired software in the master directory \(GOM-v6.0.0\), keep the left mouse button pressed and drag the icon onto the tool bar.
Figure 4.1 shows a screenshot of the main user interface of TRITOP, whilst Figure 4.2 gives an explanation into the options.
Figure 4.2: Explanation screen elements [15]

The following paragraphs relate to various settings and options supplied by the TRITOP software and are important to understand so as to develop and integrate auxiliary systems like FlexMess.
• **TRITOP image points**

TRITOP generally distinguishes between image points and object points. Image points are automatically identified 2D points (reference points) or points manually set in the 2D images. Object points are 3D points that were created based on 2D image points. In addition, the system distinguishes between exact points that are used for bundling and less exact points that are excluded from the bundling process (computation). Less exact points are the so-called outliers and feature points. Outliers are image points having a higher inaccuracy compared to the standard deviation. Feature points are 3D points added to the measuring project manually or points identified as feature points because of unfavourable point rays, for example, 3 rays in one plane.

In the point list (tabs Object Points, Image Points and Images at the bottom right), different icons may be displayed. The following table informs about these icons.

<table>
<thead>
<tr>
<th>Icon</th>
<th>Description</th>
<th>Display in the tab:</th>
<th>Used for bundling?</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Ellipse-based feature point" /></td>
<td>The 3D object point of which was deleted while maintaining the 2D image points or which was created in just one image.</td>
<td>Object points: yes, Image points: no</td>
<td>no</td>
</tr>
<tr>
<td><img src="image" alt="Line point (feature point)" /></td>
<td>Defined manually in at least 2 different images which results in a 3D object point.</td>
<td>Object points: yes, Image points: yes</td>
<td>no</td>
</tr>
<tr>
<td><img src="image" alt="Line point (feature point)" /></td>
<td>The 3D object point of which was deleted while maintaining the 2D image points.</td>
<td>Object points: no, Image points: yes</td>
<td>no</td>
</tr>
<tr>
<td><img src="image" alt="Pattern matching point (feature point)" /></td>
<td>Defined manually in at least 2 different images by using pattern recognition.</td>
<td>Object points: yes, Image points: yes</td>
<td>no</td>
</tr>
<tr>
<td><img src="image" alt="Pattern matching point (feature point)" /></td>
<td>The 3D object point of which was deleted while maintaining the 2D image points.</td>
<td>Object points: no, Image points: yes</td>
<td>no</td>
</tr>
<tr>
<td><img src="image" alt="Pixel point (feature point)" /></td>
<td>Defined manually in at least 2 images.</td>
<td>Object points: yes, Image points: yes</td>
<td>no</td>
</tr>
<tr>
<td><img src="image" alt="Pixel point (feature point)" /></td>
<td>The 3D object point of which was deleted while maintaining the 2D image points.</td>
<td>Object points: no, Image points: yes</td>
<td>no</td>
</tr>
<tr>
<td><img src="image" alt="If later you deactivate an image in the explorer using the right mouse button command ignore Image, the image appears in the list of points as ignored as well." /></td>
<td>no, no, yes</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Image point in project mode set to Ignore Image Point using the right mouse button menu." /></td>
<td>no, no, yes</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>
Table: Overview point types and icons

<table>
<thead>
<tr>
<th>Icon</th>
<th>Description</th>
<th>Display in the tab:</th>
<th>Used for bundling?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coded reference point resulting in a 3D object point because it was found in</td>
<td>Object points: yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>at least 5 images.</td>
<td>Image points: yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Images: yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Coded reference point not resulting in a 3D object point because it was</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>found in less than 5 images.</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Untouched reference point resulting in a 3D object point because it was</td>
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<td>yes</td>
</tr>
<tr>
<td></td>
<td>found in at least 3 images.</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
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</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>found in less than 3 images.</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>3D points that were created with File ➤ Import ➤ Import Project from</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Reference Points.</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Option: Coded reference point was set as pass point in the object points</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>list by clicking with the right mouse button. In the images of the</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>evaluation image group the points thus defined are assumed to have not</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>changed and the images are oriented in space according to these points.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Option: Untouched reference point was set as pass point in the object points</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>list by clicking with the right mouse button. In the images of the</td>
<td></td>
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<td>evaluation image group the points thus defined are assumed to have not</td>
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<tr>
<td></td>
<td>changed and the images are oriented in space according to these points.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Option: 3D points that were created with File ➤ Import ➤ Import Project</td>
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<td>no</td>
</tr>
<tr>
<td></td>
<td>from Reference Points. As a default, these points are set as pass points.</td>
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</tr>
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<td>Coded reference point identified as outlier resulting in a 3D object point.</td>
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</tr>
<tr>
<td></td>
<td>This point was identified with a higher inaccuracy.</td>
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<td>no</td>
</tr>
<tr>
<td></td>
<td>Untouched reference point identified as outlier resulting in a 3D object</td>
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<td>yes</td>
</tr>
<tr>
<td></td>
<td>point.</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Untouched reference point identified as feature point resulting in a 3D</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>object point because it was found in at least 2 images.</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

Figure 4.3: Overview point types and icons [15]

- **Camera Parameters**

The following table shows all the most important specifications and settings of the standard cameras that can be used with the TRITOP system.

In this measurement project the camera Fuji S1 Pro and the camera Nikon D1X are the used as standard cameras in communication with the TRITOP software.
Figure 4.4: Camera parameters [15]

- **Reference Points**

For a successful measurement with TRITOP different reference points must be used. There are two kinds of points, namely the coded reference points and the uncoded reference points. Coded reference points ensure an image set that can be evaluated and allow for automatic calculation of the camera positions. Uncoded reference points are used to determine the 3D coordinates and are identified automatically by TRITOP.

**a) coded Reference Points**

When recording an image, it is the goal to see as many reference points spread over the entire object as possible (e.g. from front to rear side) in order to achieve a high measuring accuracy. Generally, coded reference points, as shown in Figure 4.5 are not used for determining the 3D coordinates of the
object to be measured. TRITOP can work with 100 (10 bit), 300 (12 bit) and 420 (15 bit) reference point sets. A 100 reference point set, for example, means that the set consists of 100 reference points with the defined identification numbers 0 to 99. Around its central circle, each coded reference point has a so called ring code. The ring code consists of regular white ring segments which contain, in coded form, the identification number of the point. For 10 bit reference point sets the ring code consists of 10 regular ring segments, for 12 bit it is 12 and for 14 bit it is 14 ring segments.

![Figure 4.5: Coded reference points](image)

In addition, so-called orientation crosses, shown in Figure 4.6, are available which are factory-equipped with several coded points. The orientation crosses allow for easy and fast application of points to the measuring object.

![Figure 4.6: Orientation crosses](image)
b) uncoded Reference points

Position the uncoded reference points on the object, the measuring system then determines the position of these points.

![Figure 4.7: Uncoded reference points](image)

The size of the reference points need to be adapted to the camera resolution (image pixels) and to the lens setting. The optimum reference point diameter is 10 image pixels. As an example for a good camera view of a reference point, an uncoded reference point is shown in Figure 4.8. The factual relations also apply to coded reference points.

![Figure 4.8: Good camera view on an uncoded point](image)

Here, the minimum diameter of the ellipse is approximately 10 pixels. As an example of a poor camera view of a reference point, an uncoded reference point is shown below in the same way.
Here, the minimum diameter of the ellipse is approximately 3 pixels.

- **Scale Bars**

In each TRITOP measuring project, the scale bars are the reference for determining the dimensions. If you create a measuring project in the TRITOP software, you are prompted to enter the scale bar parameters or to click on the respective scale bar if it is already included in the list of the calibration options. It is absolutely necessary to ensure that the selected scale bar in the software (calibration object) and its scale bar parameters are identical to the real scale bar. On each GOM scale bar you will find the scale bar parameters.
Ideally, the scale bars fit 1:1 to the measuring object (e.g. the longest extension of the object is approx. 1 m and the length of the scale bars is approximately 1 m as well). This way the scale bars and objects totally fill the format of at least one image. Generally, two scale bars are used. The advantage is that the software checks the scale bars with respect to each other (discrepancy), and wrong scale bar parameters are noticed better. Basically, the position of the scale bars can be arranged at random, however it should be chosen such that the scale bars are completely or partly shown in the images and do not lie directly next to each other. In this project the yellow invar scale bars will be used.

- **Measuring Setup and Shooting Techniques**

In order for the TRITOP application software to be able to evaluate reference points and image sets reliably and precisely some basic requirements need to be observed:

- In each image at least 5 coded reference points must be visible because TRITOP needs at least this number to compute the camera positions precisely. It is useful to apply sufficient coded reference points to the measuring object at positions well visible, to ensure that this requirement is always complied with. However, do not clutter the measuring setup with coded reference points. That will not achieve a higher accuracy and each unnecessary point burdens the computation process.

- Typically, the diameter of the reference points should correspond to 10 image pixels (minimum ellipse diameter) in the image reference.
• Do not overexpose or underexpose the reference points. TRITOP identifies reference points (ellipses seen from a perspective view) precisely if the reference points are clean and the light-to-dark transition consists of many grey levels.
• The reference point must be visible in at least three different images so that TRITOP can automatically and precisely determine the 3D coordinates of an uncoded reference point.
• While shooting a group of images do not change the camera settings like aperture, shutter speed, sensor sensitivity and focus. Protect the camera from changing it unintentionally, e.g. by vibrations.
• From a central camera position record four calibrating images each of which is rotated by 90° around the optical axis.
• An image set consists of many overlapping images recorded in succession, e.g. images of a measuring object, recorded at an angle of 45° clockwise all around. This shooting technique also requires images that – seen from above – combine the right and the left side as well as the front and the rear side in order to avoid accumulated errors within an image set.
• Set the parameters of the used scale bars and the coded reference points correctly in the TRITOP software.

• Camera movement for a 3D-Object
At the beginning of every measurement it is necessary to record the four calibration images from the top first. The object view from the top is not mandatory but desirable. Otherwise a position must be selected out of which
as many coded reference points as possible can be recorded that are well spread out across the image.

The calibrating images are always at the beginning of an image group. These four calibrating images are needed for computing the optical distortion of the lens and the position of the principle point. Calibrating images are images recorded from a central camera position each turned by 90° (along the optical camera axis), as shown in Figure 4.11. A camera position should be selected out of which as many coded reference points as possible that are well spread out across the image can be recorded.

For all around measurement of the three-dimensional object the camera must be held at a medium object height (level 0), then walk around the object and record images at a distance of 45° from each other. Record the same number of images from below (level -1) and finally from above (level +1).

![Figure 4.11: Camera movement](image-url)
After recording enough photos, all images can be sent directly to the computer. Figure 4.13 shows, in what way the TRITOP software illustrates a normal photo. In the upper section the normal photo in *.jpg-format, below the same photo is shown in the TRITOP software.
When all images are sent to the computer the computation starts automatically. During this computation, so-called outliers will also be marked. Outliers are image points that would deteriorate the measuring results. Generally, they are reference points in the 2D images that are largely distorted in perspective. After successful computation, the following results are available:

- Camera images are displayed with a green checkmark in the explorer.
- Reference points are shown in the 2D view with IDs and ellipses.
- Point explorer contains data (Object Points, Image Points, Images, Selection Image).
- The 3D view, the calculated 3D points are visible.

Figure 4.14: Display of Ellipses in the 2D Camera Window after computation [15]
• **Checking and Correcting the Result of the Measuring Project**

In the explorer window it must be checked under “image group” if the images have been orientated (green check mark). If they are largely not orientated (red signs) further images must be added to the measuring project. The average deviation in the complete measuring project (remaining residual error) depends on the size of the measuring project. For a car (1:1) which was recorded according to the "tiling" method, this value should be less than 0.1 pixel. If the value is larger than 0.08 or 0.1 pixel, the individual images of the image set must be checked if an image shows a considerably higher value, e.g. 4 times larger than the average. Then, this image needs to be switched off.

![Figure 4.15: Check marks and average deviation](image)

Furthermore at least one scale bar needs to be identified, as shown in Figure 4.15 and 4.16. For two identified scale bars the discrepancy between specified and actual length should be less than 0.1 mm. Additionally it must be checked if all required uncoded reference points have been identified.
Important unidentified reference points should be added manually. Check whether just real reference points have been identified.

- **Display of the deviation**

In the display of deviation the quality of a measurement that was done could be checked in a simple way. As shown in Figure 4.16, the quality and the deviations from the single parameters are displayed in that window.

![Screenshot deviation](image)

**Figure 4.16: Screenshot deviation**

1. Here, the ellipse quality is described which results from the gray values in the camera images. Continuous gray value gradients of the reference points with no sharp jumps result in a good quality.

2. Here, the deviation is described which results when the software calculates from a 3D point back to its 2D position again. If, for example, a reference point moved during the measurement, this is clearly visible here.

3. Average mean deviation of all points in a camera image based on the values of 2. Only those points are considered that have been used in the bundling process.

4. Deviation of specified and actual value of scale bars in mm. The specified value is the scale bar value entered during the product definition.

5. Average mean deviation of all points in a measuring project based on the values of 2. Only those points are considered that have been used in the bundling process.

**Figure 4.17: Explanation of deviations [15]**
• Macros

The TRITOP software allows for recording macro scripts based on Python. Thus, automation of individual processing steps is possible. All macros are saved in the "hidden directory" /home/demo/.gom/[software version number]/scripts-tritop. You may easily generate a new macro by creating a new, empty macro, start recording, carry out the desired operating steps, stop recording and save the macro (Chapter 4.2.2). You may modify macros in the editor at any time using the context menu of the right mouse button on the respective macro. If you have the necessary knowledge, you may also change the macro script directly in the script syntax. In addition, you may include a macro into another macro.

Finally, a main automation application is the evaluation of TRITOP series measurements. For example, the coded reference points in TRITOP may well be used for evaluations as they are always clear in all measurements.

4.2 Calibration and Measurement Macro

The following subsection is written as an operating instruction guide. It explains the working of a macro and the complete development of the macro that was specifically programmed for the FlexMess adapters. With that macro the FlexMess can be used in the TRITOP software in an automated way.
4.2.1 Basics about Macros

Marcos are commands which are completed by a program after selecting the macro. You can use macros to automate daily tasks. By performing the needed steps across the program, macros can be recorded with a macro recorder. A macro can include nearly all commands which can be called by the mouse and the keyboard. Marcos can be linked with certain events for example with the opening or closing of a document. They are completed automatically when these events occurs. You can edit the macro manually with an editor, but for this you need some previous knowledge and experience. [4]

Another possibility to create activities in a macro is the insertion of standard operations or pop-up windows which are shown in the macro display window when clicking the right mouse button.

Furthermore it is possible to insert other macros or lecture notes in a macro to make clear the function of macros. You can execute a macro simply by choosing the wanted object in the tab “macro”. It may be necessary to engage in the dialogues which are included in a macro.

4.2.2 Socket Adapter

The RPS-points of a vehicle which are needed for measuring are not visible if the vehicle is not raised. So with the TRITOP-System or any other system you cannot measure a vehicle standing on the ground. But by raising the vehicle, the results can be falsified because it deforms itself. The FlexMess-System allows the recording from the RPS-points without raising the vehicle, Figure 4.18 shows this relation.
Figure 4.18: FlexMess in installation position on the rear left chassis rail

To identify the RPS-point, depending on the FlexMess adapter, you have to create this point virtually by using a socket adapter. Socket adapters are adapters for the FlexMess-chuck. They are fixed and adapted to the chuckcones, and are specifically constructed and deposited in the software for the calibration of the hardware.

Figure 4.19: FlexMess socket adapter
The RPS-point is simulated by the socket adapter while the hardware is standing on the calibration plate. When defining the position of the RPS-point, depending on the points on the FlexMess adapter, you can use these points as RPS-points.

Figure 4.20: Appointment of the resulting point from the calibration socket

The socket adapter allows the creation of the virtual RPS-points and consequently the creation of the FlexMess adapter in the TRITOP.
Since the calibration has to be repeated frequently, (after each disassembly of the system) the work can be simplified by automating this calibration.

TRITOP complies excellently with the requirements. The following steps help to create a macro:

1. Creating the socket adapter
2. Creating a deformation project
3. Writing a subprogram for the Flex adapter
4. Writing a main program for user structure

To create a macro you need an explanation which will be changed into a step by step instruction later for documentation purposes.
In order not to mix up the socket adapters they have to be marked with the position they will take over the FlexMess (FR, RR, RL, FL). Four measuring points (uncoded reference points cp. Chapter 4.1) have to be stuck on the top and the bottom side. Now the socket adapter will be recorded with the Tritop and a reference point cloud will be created. The next step includes scanning the sockets with the Atos-System and generating them as a 3D-object. Atos is an industrial 3D-Scanner which is based on the strip projection technology and triangulation principle. With this system, which is also developed by the GOM Company, it is possible to measure the complete surface of an object and to generate many kinds of CAD-files.

![Socket scanned by GOM Atos](image)

Figure 4.22: Socket scanned by GOM Atos

When being scanned you have to open a new Tritop-project and import the sockets. Then the virtual RPS-point on the bottom of the sockets can be created. The first step is shown in Figure 4.23.
While creating the socket adapter the four points from the top sample for the points to identify the RPS-points. The four points from the bottom have to be cancelled. These points are only for the purpose of defining the under plane of the socket while the scanning process takes place. The complete creation of the virtual socket adapters is described in Chapter 4.2.5. After creating the socket adapter in Tritop, the FlexMess adapter for the macro can be created as explained in the next subsection.
4.2.3 Compiling the Macro

The FlexMess-System is assembled and put on the calibration plate, as shown in Figure 4.24.

Figure 4.24: FlexMess ready for calibration (1: calibration plate; 2: virtual coordinate system of the calibration plate; 3: calibration sockets; 4: Tritop scale bars; 5: orientation crosses)

This built-on system is recorded with the measuring camera. All points are recorded because they are needed for analysis in Tritop.

Figure 4.25: Four calibration photos
The first step is to take four photos, each turned at an angle from 90°, as shown in Figure 4.25. The complete built-on system is then recorded by the camera in two levels, as shown in Figure 4.26.

![Figure 4.26: Camera movement while calibration](image)

**4.2.4 Preparing the Macro**

Before creating the macro you need to create a new deformation project in Tritop. This is used to record activities with the macro recorder for which the elements have to be available. Create a new step as a reference for the calibration called calib-ref for the recorded pictures. The four big points on the calibration plate are placed as "global transformation points". Realise a 3-2-1 transformation to mount a coordinate system and select the step (calib-ref) as a reference to load a second picture formation as a further step (calib). This step has to be transformed over the global points on the calibration plate and the points have to be renumbered.
For the actual macros you first have to create a new group into which it is possible to create new lecture notes. To assign the points on the FlexMess adapter to the socket adapter you use the lecture note recorder.

- **Main Program**

The step “calib” will be deleted completely while you delete by the “calib-ref” the feature elements and the project will be closed. A new step will be created in the group which has been created during the last step. To record the opening of the project you use the lecture notes recorder and insert an interruption, this interruption is used to delete old FlexMess adapters. In the next interruption you will be called to record a new group of pictures. With the aid of the lecture notes recorder you record how to create a new step (calib). This step will be transformed over the global points on the calibration plate, the points will be renumbered and the adapter has to be identified while the recorder is on. Now you have to insert the group that was created in the first step into the lecture notes. In the end you have to delete the step “calib” and delete by the “calib-ref” the feature elements and the project will be closed.

The creation of the the marco is finished.
4.2.5 Instruction Book

This detailed instruction was written for use in practice. Because of paying attention to all details while compiling the instruction users only have to execute the steps one after another.

The first step is to create the socket adapters to be able to simulate the RPS-point in a measurement, while the FlexMess hardware is standing on the calibration plate.

- **Compiling the Socket Adapter**

  1. Provide sockets with 8 uncoded reference points (4 on the bottom, 4 on the top), label sockets with their position on the FlexMess.
  2. Take measuring images of the sockets and open them with TRITOP.
3. Create reference point cloud.
4. Scan sockets with ATOS.
5. Remove bottom points from sockets.
6. Create TRITOP project.
7. Specify the sockets (z.B.: fr_socket.c3D).
8. Import Project from reference points (chose file: “.ref”).
9. Load ATOS Scan’s (.c3D).
10. Create des RPS- point as shown in Figure 4.29.
10.1 Create planes as in Step 1.
10.2 Select surface.

→ (Without uncoded points).

→ Best fit plane
→ Create plane Step 2.

For the Creation of a plane the best-fit method is a strategy, that is explained in Figure 4.28.

10.2 Selecting cylinder with the planes (exterior wall)

→ selecting plane
Figure 4.29: Steps for creation of the RPS point on the socket

➔ best fit plane

➔ primitives: “cylinder” Step 3.

11. Create an intersection point out of plane and cylinder Step 4. The relation is shown in Figure 4.30.

Figure 4.30: Result point

12. Cancel reference points without the points on the top
13. Save the Session (fr)

14. Create Adapter

14.1 „Adapter“: „edit Adapter“: „add“ (FR_socket)

15. Save the session

Repeat the steps for each socket.

- **Compiling the Macro**

  0. Assemble the FlexMess on calibration plate.

     Pay attention on the order of the single adapters on the plate. The programmed software is only working, when this order is assembled. The correct position from every FlexMess adapter is shown in Figure 4.32.

     ![Figure 4.31: positions of the single adapters on the plate (PQ35)](image)

     Figure 4.31: positions of the single adapters on the plate (PQ35)

  1. Scale bars 1000mm and coded reference points

  2. Assemble sockets on FlexMess
3. Photograph the calibrating assembly (look out for the points on the calibrating plate because they are necessary to build a coordinate system)

4. Create new deformation-projekt in TRITOP („File“, „Deformation-projekt“)
   4.1 Create new folder („calibrating-FlexMess“)
   4.2 Create file „Deform-ref“ in folder „calibrating-FlexMess“
   4.3 Radius for renumbering: 50mm
   4.4 Transformation mode: automatically by distance
   4.5 Complete

5. In menu „Stage“: „new stage“: „new stage from pictures“
   5.1 Name of the stage: „Kalib-Ref“
   5.2 Identify adapter: switch of
   5.3 „Erase the pictures on memory card“ activate on demand
   5.4 Look out for right adjustment of scale bars („1000“)
   5.5 Complete

6. It is necessary to check if all uncoded points on calibrating plate are identified

7. Select the 4 „big points“ on calibration plate (deselect all, right click with mouse, select single point)
8. Set the object points as global transformation points

9. Project: Projecttransformation: 3-2-1 Transformation

9.1 3-2-1 Modus: ZZZ-YY-X

9.2 Select 3 of the 4 big uncoded points as plane (ZZZ)

9.3 Select 2 uncoded points on the long side of the plate as line (YY)

9.4 Select 1 uncoded point on the short side of the plate as point (X)

9.5 Take care for the right determination of the coordinate system

(illustration on calibrate plate)

9.6 Result: 0mm, complete
10. Select the Measurement „Kalib-Ref“ in the left window as reference
   (right click with mouse, choose)

11. Record a second image group

12. Stage: new stage: new stage from pictures
   12.1 Name of the stage: „Kalib“
   12.2 Identify adapter: switch of
   12.3 Look out for right adjustment of scale bars („1000“)
   12.4 Complete

13. In the left window: selecting the Measurement „Kalib“: stage-
    transformation: transform stage by global points

14. „Kalib“: „identify“: „renumber points“
   14.1 Renumber radius: 50mm
   14.2 Complete

15. Take care that the points reassigned right. An example for checking is
    shown in Figure 4.35

<table>
<thead>
<tr>
<th>front</th>
<th>Left</th>
<th>1003</th>
<th>1016</th>
<th>right</th>
<th>1025</th>
<th>1040</th>
</tr>
</thead>
<tbody>
<tr>
<td>right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>front</td>
<td>Left</td>
<td>1002</td>
<td>1014</td>
<td>right</td>
<td>1024</td>
<td>1020</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rear</td>
<td>Left</td>
<td>1015</td>
<td>1012</td>
<td>right</td>
<td>1023</td>
<td>1019</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rear</td>
<td>Left</td>
<td>1013</td>
<td>1038</td>
<td>right</td>
<td>1022</td>
<td>1041</td>
</tr>
<tr>
<td>left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.34: Possibility of point numbers

16. „Adapter“: „Adapter identify“ (in all stages)
4.2.6 Subprogram for Compiling the Flex Adapter

17. „macro“: „edit script “

18. „new“: „new script“: „add group“ (blank sheet left above)
   18.1 Declare the name of the new script
   18.2 OK

19. Assign the stage “Kalib” in the menu left

20. Activate the record button (red dot left below)

21. „Adapter“: „create adapter“
   21.1 Specify name (name_Flex_fr)
   21.2 In array “geometry” (red triangle) (keep key Strg) dial socket adapter (for example: socket_XX)
   21.3 Dial „points for intentification“ and the appendant points (on pipes), keep Strg and dial (on pictures), press ok

22. Repeat step 21 for the remaining 3 adapter

23. „Record“ off, save the sub programm with the disk symbol up right

24. Close

- Macro main Program

25. Delete the second step “Kalib”

26. Delete the “feature elements” in step “Kalib-ref”

27. Close all (do not close TRITOP)

28. „macro“: „edit macro“: „new“
   28.1 In window: „new script“: label the main program and select the group,
   28.2 Klick “ok”
28.3 Switch „record“ on

29. „file“: „open“
29.1 „deform-ref“: „deform-ref.dyn“, „ok“

30. Switch „Record“ off, click right on prompt in macro editor
30.1 Paste break: title: delete adapter
30.2 In description field: call on to delete the old flex adapter

31. Paste another break: recording a image group (scale bars “1000”), connect memory card with pc

32. „stage“ „new stage from pictures“
32.1 Name „Kalib“
32.2 Ok
32.3 Look out for right scale bars and right temperature, complete

33. Switch „Record“ on

34. Select „Kalib“, click right on prompt in macro editor, stage-transformation: transform stage by global points

35. „Record“: select „Kalib“, click right on Kalib, „Identify“: „renumber points“
35.1 Radius for renumbering: 50mm, OK

36. „Record“, „Adapter“: „Adapter identify“ (all stages)
36.1 Click right on prompt in macro editor, paste: scripts: generate-flex-script

37. „Record“, select „Kalib-Ref“, delete feature elements (important: only in selected stages, “malfunction”: „ignore error“.)
   Alternative: include another break and call on to delete the feature elements in stage „Kalib-Ref“. 
38. Select „Kalib“, click right, delete stage

39. „Record“ on, „file“, close all

40. Complete

In this section it was shown how to generate the macro for the FlexMess adapters in the TRITOP software. Is this macro programmed and installed, a normal TRITOP user is able to work with the FlexMess adapters. This macro is to calibrate the FlexMess after assembling the components in an automatic way. Because of the commands which are programmed in the macro the user gets all orders and commands which are needed for the calibration in every time. After calibration in a normal measurement TRITOP will identify every single adapter automatically and after localisation the adapters the calculated position of the calibrated resulting points in the chucks are shown with all coordinates in the machine based coordinate system.

So the first flexible measurement of a complete assembled vehicle could be processed. This action is shown in the following chapter.
Chapter 5

Measurement with the FlexMess

This chapter deals with the first measurement of a vehicle using the inaccessible RPS-points with the developed FlexMess adapters. The necessary preparations of the vehicle and the complete measurement procedure are shown in this section. As mentioned before, this was the first time that the Volkswagen Company measured a completely assembled vehicle in a flexible way according to new guidelines.

5.1 Preparations of the Vehicle

To be able to mount the FlexMess adapters directly into the RPS holes, some parts must be removed from under the car. Because of security and aerodynamic requirements, the underside of the vehicle is covered with plastic covers.

The preparation for the measurement as it is shown in Figure 5.1 is applied to a front drive VW Golf A5 with a 1.6liter petrol engine without parking heating. The preparation of the vehicle could be different when the car is
equipped with different parts or components and especially with different engines. To maintain the necessary accessibility to the RPS holes the following demounting has to be done:

1. demount the front right wheel house trim panel
2. demount the front left wheel house trim panel
3. demount the engine cover
4. disconnect the exhaust clamp from the rear chassis rail
5. disconnect the heat protection plate above the exhaust

Figure 5.1: Step 1+2 demounting of the front right wheel house trim panel [12]

(1. wheel house trim panel, 2. screw nut, 3. crosshead screw, 4. snap nut)
Figure 5.2: Demounting the engine cover [12]

(1. engine cover, 2. crosshead screw, 3. screw nut, 4. slotted screw)

FlexMess was then enabled and mounted to the vehicle using the following steps.

**Step 1:**
Mount all four adapters without the extensions on the calibration plate. Follow the caption on the adapters and on the plate to ensure the right order.
### Step 2:
Place the screws with the chucks in the designated drilled holes.

### Step 3:
Assemble the carbon extensions to the base of the FlexMess adapters. As shown in the picture it is necessary that the points on the tubes are showing upward.

### Step 4:
Put the calibration sockets on the chuck of every adapter (follow the caption). Fix the sockets stalwart on the chuck by turning on the chucks. Measure the geometrical connection between the points and the RPS. **Attention! Don not untwist the collet chucks to the end. It could be possible that the clamping jaws can fall out of the guideway.**

### Step 5:
After the calibration in Step4 the adapters of the FlexMess can be mounted directly into the RPS holes on the vehicle.
Step 6:
After mounting all components into the RPS-holes, the coordinates of the RPS-points are localised using TRITOP and the programmed macro, the car is aligned in 3D space.

Figure 5.3: Assembly guideline

If there are any problems or in case of doubt it is advisable to mount only the FlexMess adapters without the extensions into the RPS holes first. Then check the correct location of the chuck and the relation to the RPS plane on the chassis rails. The chucks must be mounted backlash-free and the plane of the jaws must fit closely to the underside of the chassis rail (RPS plane). There may not be a visible gap between the jaws and the rail, the correct installation is shown in Figure 5.4.

Figure 5.4: Correct contact between chuck/jaw and chassis rail (RPS-Plane)
5.2 Taking Photos of the complete Vehicle Platform

When the hardware is calibrated and each one of the four adapters is mounted into the RPS holes, the measurement may start. First it is necessary to place and assign the points of interest with adapters or tapelines on the surface on or in the vehicle, and that the scale bars and the coded reference points are also placed as described. The normal experimental setup is shown in Figure 5.5.

If it is possible to use the orientation crosses with coded reference points, these crosses must ideally be placed around the car as shown in Figure 5.6. This procedure is a timesaving action as it is a simple action to place at least 11 crosses around the car instead of allocating many single coded reference points onto and around the vehicle.
The photographic session can now be conducted. The first step is to take four calibration photos, each at right angles to each other. The building of a complete set of pictures must be done in two planes from different directions and at different angles around the whole vehicle. From the entire set of single images the software is able to generate a calculable group of pictures. On every image at least one orientation cross needs to be seen. The best camera positions for a complete measurement are shown in Figure 5.7.
To ensure identification of the relevant geometrical elements, detailed photos of the parts where the FlexMess adapters are mounted need to be taken. The number of photos that must be taken depends on the quantity and the complexity of the points and geometrical elements of the point of interest. Based on practical experiences a group of picture to analyze for example some points on the doors and the hatchback requires around 150-200 pictures.

After the successful recording of the pictures, it can be sent to a computer where the Tritop software is installed.
5.3 Comparison with Tactile Measurement

After sending the complete group of pictures to the computer it must be checked if all four FlexMess adapters were identified in the software. This step is automatic as it was programmed into the macro. Furthermore the two scale bars and the marked points of interest must be identified. The system is able to find pictures that are unusable and shows them with a red sign in the initial evaluation.

When all FlexMess adapters are identified by the software, the RPS coordinates from every RPS point is shown directly in the program, shown in Figure 5.9. Now the alignment of the vehicle orientated coordinate system takes place. The standard alignment is done by using the 3-2-1 rule (Chapter 1). The identified coordinates from the RPS points (actual value) will be aligned with debit coordinates (nominal values) from the CAD file. In that way the x-, y- and z-coordinates from the RPS 1 will be compared with the nominal values. In RPS 2 the y- and z-coordinate and in RPS 3 the z-coordinate will be put on a level with the nominal values. Now the vehicle is aligned in the 3D space and every measured point or complete surface on and inside the vehicle can be compared to the CAD. The position of the vehicle coordinate system is known by the RPS points. The deviations from every measured point to that of the CAD could be shown directly in software. The deviations from the actual to the nominal RPS are in the respective fixation direction to zero in.

In the evaluation of the measurement, the points of interest lead to obtaining values in a precise x, y and z coordinate system.
With this it is possible to compare these measured points on the vehicle with the CAD or with measurements of the same object that were done earlier. For evaluation purposes the identified coordinates are compared to previous measurement. The test vehicle was measured with a conventional measuring system (Chapter 1.3). The complete test report of the measurement that was done with a tactile system is included in Appendix C. Some of the nominal values are shown in Figure 5.8. In this measurement twelve points on the surface and inside the vehicle, and the four RPS-points in the chassis rails were localised and compared to the former benchmark. Figure 5.9 gives the identified cloud of points, which was localised by the TRITOP system. The blue points are the RPS points after mounting the object orientated coordinate system. The green points are measuring points which were localized by the system. Furthermore, the figure shows the camera positions from which every image was recorded while building the complete group of pictures. Here the comparisons between actual and nominal values are clearly identified.
Figure 5.9: Test report with actual and nominal values
5.4 Discussion and Conclusion

Generally the overall result of the measurement is very positive because it was possible to localize the buried RPS-points using the FlexMess and the programmed macro. There were no problems in the alignment of the vehicle in the 3D space, and therefore the main tasks were carried out successfully. Every point of interest was found with an average deviation of around 0.6mm, in comparison to the measurement of the same points with the tactile system.

It was clearly demonstrated that the developed measurement tool FlexMess, in collaboration with the programmed software add-ons in Tritop, works excellently. It is therefore possible to analyse a produced vehicle with this system wherever and whenever it is required.

However some points were found in a higher deviation which is caused by different factors.

Due to the fact that the test vehicle was measured at Volkswagen around 6 months ago, before these measurements were done, it could be possible that there are some deformations on the car which were caused by external influences. Over that period the test vehicle was transported several times, and especially in the adaptation phase from the first rigid prototype (Chapter 3.1) deformations could have occurred. For the simple reason that some points are lying in the area of the engine bonnet and the hatchback it is possible, that these points where deformed at indiscernible distances while relocating the vehicle. Furthermore the position of single points that were
localized can cause deviations between the nominal and the actual value.

Because some points are lying in round areas, a plane of reference for this point must be built. In this step the measurement engineer has a big influence on the result because he can choose the position of the plane freehand. It is therefore possible that these planes of reference were built differently in the measurement at Volkswagen in comparison to the measurements done with the FlexMess system.

Additionally the huge measurement volume determines higher deviations because no present measurement system is able to work in such a big volume without causing internal deviations.
Chapter 6

Testing and Data Analysis

In this chapter the necessary analysis of the reproducibility of the FlexMess Hardware in collaboration with the TRITOP system is performed. Before a realistic measurement on a completely assembled vehicle can start commercially, the whole system needs to be analysed to see if it is working in a repeatable way. Without the analysis it could happen that the coordinates for the alignment of the object in the 3D-Space are nonfactual, or are lying in a stray field. Firstly a theoretical calculation of errors is required. Additionally a test series with the system has been carried out, to analyse the systems internal measurement noise.

6.1 Calculation of Errors

The following paragraphs refer to Figure 6.10 where all theoretically determined errors which are caused by different factors are shown and combined. For every factor the worst case is assumed. In the last three columns of the table the deviations of the identification of the RPS-Points in
all three directions in space results from the theoretical factors are diagrammed. For every column, declarations with detailed drawings are provided.

The theoretical calculations can be compared to the results of a measurement and give an indication of the total accuracy of the system.

### 6.1.1 Column 1: Errors in point localisation in x, y-direction caused by TRITOP uncertainty

The TRITOP photogrammetric system is able to identify points in the 3D-Space with accuracy of ±0,05mm. In the worst case it is possible, that one of the points on the extensions is drifting in the maximum positive direction and the second point on the extension is drifting in the maximum negative direction when TRITOP is detecting the points. Thereby a false theoretically position of the carbon extension gives a higher deviation in the identification of the RPS coordinates. The geometrical correlation is shown in Figure 6.1.

![Figure 6.1: Largest deviation in y-direction](image-url)
The resulting deviation in x-direction, that could occur on the sidewise extensions is behaving the same. The deviation in the three space directions that is caused by the described circumstances is only ascertainable with a vectorial error analysis. This was done with an evaluation that is shown in the following pages, with the results of the analysis shown in Figure 6.10.

6.1.2 Column 2: *Errors in point localisation in z-direction caused by TRITOP uncertainty*

The measurement uncertainty that occurs while detecting the points on the extensions with the TRITOP system which is described in column 1, also recurs in the z-direction. Because of the fact that the extensions are standing orthogonal to the shank, there is an analog measurement deviation not only a deviation in the z-direction but also in the respectively perpendicular coordinate axis (x,y). In the following figures this fact is illustrated.

Figure 6.2: Largest deviation in y- and z-direction
To be able to identify all FlexMess adapters with the TRITOP system, the points on the extensions are indicated with different distances. The coherence between the two points on the extension and the coherence from every single point to the RPS-point is different on every carbon tube. The TRITOP-software is able to distinguish between every extension and therefore between every complete FlexMess adapter. In Figure 6.4 the different distances are shown.

<table>
<thead>
<tr>
<th>Tube Nr.</th>
<th>Dimension a [mm]</th>
<th>Dimension b [mm]</th>
<th>possible deviation/adjustment in the RPS point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deviation z [mm]</td>
</tr>
<tr>
<td>1</td>
<td>23</td>
<td>470</td>
<td>0,169</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>430</td>
<td>0,190</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>410</td>
<td>0,199</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>415</td>
<td>0,209</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>390</td>
<td>0,222</td>
</tr>
<tr>
<td>6</td>
<td>85</td>
<td>410</td>
<td>0,232</td>
</tr>
<tr>
<td>7</td>
<td>55</td>
<td>365</td>
<td>0,255</td>
</tr>
<tr>
<td>8</td>
<td>45</td>
<td>330</td>
<td>0,285</td>
</tr>
</tbody>
</table>

Figure 6.3: Largest deviation in x- and z-direction

Figure 6.4: Overview about point positions on every extension
The deviations of the localisation of the RPS-point that are described in 6.1.1 and 6.1.2 will be at its worst when both points on the extensions are lying close to each other. In that aspect the tube number 8 (cp. Figure 6.4) is the worst case configuration of the position of the points on the tube. Because of that, all the following calculations are made with the data from tube number 8.

![Figure 6.5: Relevant dimensions for the uncertainty estimation](image)

The dimension c results from the length of the tube and half the length of the base of the FlexMess adapter. This dimension is 1020mm. The maximum dimension of d is 355mm. With these geometrical coherences the possible deviation in the RPS-point localisation was calculated for every tube. The results are also shown in Figure 6.10.
To be able to calculate the deviations in the three directions (x,y,z) caused by TRITOP uncertainty, the geometrical coherences of the FlexMess adapters must be known. The relations between the parts of one adapter are shown in Figure 6.6. With this relationship the following system of equations was build, to calculate the deviations.

**Geometrical coherences:**

The dimensions a,b,c and d are shown in Figure 6.5, the geometrical situation is shown in Figure 6.6.

**Angle $\alpha$ in relation to the measurement inaccuracy TRITOP in z-direction**

\[
\tan \alpha = \frac{2 \cdot \Delta z_{(gagemark)}}{b - a}
\]  
(6.1)

**Coordinate deviation from RPS in z-direction**

\[
\Delta z_{(RPS)} = \sin \alpha \cdot l
\]  
with

\[
l = c - \frac{b - a}{2} - a
\]  
(6.2)

**Coordinate deviation from RPS in x-direction**

\[
\Delta x_{(RPS)} = \tan \alpha \cdot (d - \Delta z)
\]  
(6.3)
From the evaluation it becomes apparent that the largest deviation could be theoretically caused by tube number 8. In column 1 and 2 in table 6.10 these deviations are indicated to maintain the theoretical deviations for the worst case.

**Example calculation for tube 8**

\[
\tan \alpha = \frac{2 \cdot \Delta z_{(gagemark)}}{b - a} = \frac{2 \cdot 0,05\text{mm}}{330\text{mm} - 45\text{mm}} \Rightarrow \alpha_8 = 0,02^0 \quad (6.1)
\]

\[
\Delta z_{(RPS)} = \sin \alpha \cdot 1
\]

with

\[
l_8 = c - \frac{b - a}{2} - a = 1020\text{mm} - \frac{330\text{mm} - 45\text{mm}}{2} - 45\text{mm} = 832,5\text{mm} \quad (6.2)
\]

\[
\Rightarrow \Delta z_{(RPS)} = \sin 0,02^0 \cdot 832,5\text{mm} = 0,29\text{mm}
\]

\[
\Delta x_{(RPS)} = \tan \alpha \cdot (d - \Delta z) = \tan 0,02^0 \cdot (355\text{mm} - 0,29\text{mm}) = 0,13\text{mm} \quad (6.3)
\]
6.1.3 Column 3: *Point adjustment because of bending*

The calibration of the FlexMess adapters takes place when the adapters are standing on their bases (cp. chapter 4.2). Because of the fact that the adapters are hanging under the vehicle when they are mounted directly in the RPS holes, it is possible that there is a bending moment in the shank because of the extensions. By using the Software MDESIGN mec 9.2 from the company TEDATA a statatical evaluation for that case was performed.

![Figure 6.7: Bending of the shank caused by uniform load carbon tube](image)

The result is that the deviation from the determined RPS-point to the real RPS position in x- and y-direction is 0.03 mm and in z-direction 0.07 mm. These deviations are also shown in Figure 6.10. The complete strength behaviour that was calculated with the help from the MDESIGN Software is included in the Appendix D.
6.1.4 Column 4: *Deformation in the shank*

Because of the different burdens between the calibration when the adapters are standing on their bases and the measurement when the adapters hang under the vehicle, it is possible that there could be a slight deformation in the shank. This case was also calculated in the software MDESIGN mec 9.2. The result of this statistical analysis is that there is no changing in the geometry of the FlexMess adapters that is relevant. Because of that the deviations that could be caused by this situation are negligible.

6.1.5 Column 5: *Manufacturing tolerance of the clamping jaws*

As a result of the complex geometry of the clamping jaws a detailed evaluation concerning the deviation in the mold alignment is realizable, but difficult. In the present situation the eccentricity of the clamping jaws is
estimated at 0,2 mm for the x- and y-direction. In the z-direction the deviation is estimated at 0,1 mm.

### 6.1.6 Column 6: Unevenness of the RPS flange hole

Because of the complex tension in the RPS hole, a detailed localisation of the contact surfaces inside the hole is impossible. On the basis of the tolerances from the geometry of the clamping jaws and the tension, a maximum deviation in x- and y-direction is accepted to be 0,5 mm (conform to the manufacturing tolerance of the hole).

The deviation in z-direction is 0 mm because the clamping jaws are pressing the hardware directly on the surface of the chassis rail (RPS-plane).

![Figure 6.9: Tension situation of one clamping jaw in the RPS hole](image)

**6.1.7 Column 7: Errors while the calibration is performed**

The measurement inaccuracy of the TRITOP system is also considerable when the calibration of the FlexMess adapters takes place. From experience the total uncertainty for the calibration can be estimated at 0,2 mm in every direction.
6.1.8 Combined theoretical Calculation of Errors

In the following table all the theoretical deviations that are calculated in the prior sections are shown and are added to provide a maximum total deviation. In every point the worst case (highest deviation) is used. Because of this the theoretical deviation is much higher than the real deviation that is determined in a practical measurement against a superior system. All the statements that are in grey fields are relying on estimations.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Description</th>
<th>Deviation in RPS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x [mm]  y [mm]  z [mm]</td>
</tr>
<tr>
<td>1</td>
<td>Point localisation in x-, and y- direction with TRITOP uncertainty 0,05mm</td>
<td>0,29  0,29  0</td>
</tr>
<tr>
<td>2</td>
<td>Point localisation in z- direction with TRITOP uncertainty 0,05mm</td>
<td>0,13  0,13  0,29</td>
</tr>
<tr>
<td>3</td>
<td>Point adjustment because of bending</td>
<td>0,03  0,03  0,07</td>
</tr>
<tr>
<td>4</td>
<td>Upsetting deformation in the shank (acceptance)</td>
<td>0  0  0</td>
</tr>
<tr>
<td>5</td>
<td>Manufacturing tolerance form the clamping jaws (estimation)</td>
<td>0,20  0,20  0,10</td>
</tr>
<tr>
<td>6</td>
<td>Unevenness of the RPS flange hole (estimation)</td>
<td>0,50  0,50  0</td>
</tr>
<tr>
<td>7</td>
<td>Errors while the calibration is performed (calibration) (estimation)</td>
<td>0,20  0,20  0,20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>∑</td>
<td>maxima (linear determined)</td>
<td>1,35  1,35  0,66</td>
</tr>
<tr>
<td>∑</td>
<td>maxima (quadratic/ Gauss)</td>
<td>0,66  0,66  0,37</td>
</tr>
</tbody>
</table>

Figure 6.10: Combined theoretical calculation of errors

With the theoretical calculation the complete system will have an inaccuracy of ± 0,7 mm. After the theoretical calculation, a practical measurement must be performed to determine the repeating accuracy and the real deviation. The first step for this is to analyse the system on its own.
6.2 Internal Measurement Noise

To be able to judge, to compare and to make use of the results of the measurements that will be done with the FlexMess system, the statistical analysis with an average value and the standard deviation is used. With this strategy that is normally used in the Volkswagen Company, a data specification of the accuracy and the informal value of the developed system is possible.

The benchmark test of the new system to maintain the internal measurement noise, is divided into three groups. The first part is that one point on the test vehicle (cp. Chapter 1.2) was measured ten times with the FlexMess hardware and the TRITOP system without disassembling the hardware from the vehicle. The next step is that the same point was measured ten times with disassembly of the hardware from the vehicle but without calibration before the hardware was remounted in the RPS holes. The last step is that the same point was measured ten times but with disassembly of the hardware from the vehicle and with a new calibration of the adapters before every one of the ten measurements.

Necessary formulas:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>single measurand $x_j$</td>
<td></td>
</tr>
<tr>
<td>arithmetic average value $\bar{x}$</td>
<td></td>
</tr>
<tr>
<td>standard deviation from single measurand $s$</td>
<td></td>
</tr>
<tr>
<td>standard deviation from average value $s(\bar{x})$</td>
<td></td>
</tr>
<tr>
<td>methodical error $u_s$</td>
<td></td>
</tr>
</tbody>
</table>
accidental error $u_z$

confidence interval $\mathcal{I}$

confidence level $\gamma$

Coherences [16]

$$\bar{x} = \frac{1}{n} \cdot \sum_{j=1}^{n} x_j$$

(6.4)

$$s = \sqrt{\frac{1}{(n-1)} \sum_{j=1}^{n} (x_j - \bar{x})^2}$$

(6.5)

$$s(\bar{x}) = \frac{s}{\sqrt{n}}$$

(6.6)

$$\mathcal{I} = t \cdot s(\bar{x})$$

(6.7)

Standard deviation $s$ from single measurands = variation of the single value.

The standard deviation is an indication of the reliability and accuracy of a single measurement. It declares the variation of the measurands around the average value. With the use of the standard deviation it is possible to give an interval, where the single value lies with a certainty of a 68, 95 or 99% probability.

Consequently the standard deviation gives an interval, into which 95 out of 100 collected values will theoretically lie, when this interval is declared with for example $\pm 2s$.

$$\pm 1s \triangleq 68\%$$

$$\pm 2s \triangleq 95\%$$

$$\pm 3s \triangleq 99\%$$
The standard deviation from the average value $s(\bar{x})$ indicates the accuracy of the average value by declaring its spreading.

By using $s(\bar{x})$, an interval could be declared with an appointed probability $\gamma$, where the average value from another measurement series of the same measurement point will lie. This interval is called confidence interval $\vartheta$.

The confidence interval is dependent on $\gamma$ and on the number of measurements $n$.

The values for this interval can be found in Figure 6.11.

A typical value for $\gamma = 95\%$ when 10 measurements are processed is 2,26.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$\gamma = 68,3%$</th>
<th>$\gamma = 90%$</th>
<th>$\gamma = 95%$</th>
<th>$\gamma = 99%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1,32</td>
<td>2,92</td>
<td>4,3</td>
<td>9,93</td>
</tr>
<tr>
<td>5</td>
<td>1,15</td>
<td>2,13</td>
<td>2,78</td>
<td>4,60</td>
</tr>
<tr>
<td>10</td>
<td>1,06</td>
<td>1,83</td>
<td>2,26</td>
<td>3,25</td>
</tr>
<tr>
<td>50</td>
<td>1,01</td>
<td>1,68</td>
<td>2,01</td>
<td>2,68</td>
</tr>
<tr>
<td>100</td>
<td>1,00</td>
<td>1,66</td>
<td>1,98</td>
<td>2,63</td>
</tr>
</tbody>
</table>

Figure 6.11: Values for the confidence interval [16]

The result of a measurement series is generally declared in the form $X = \bar{x} \pm (u_s + u_z)$. The methodical error $u_s$ is the measurement inaccuracy from the instrument $\Rightarrow u_s = 0,2 \text{mm}$ . The accidental error is the confidence interval $\vartheta$.

If after the application of the standard deviation only one value is measured, it is possible to declare that in a range of $n \cdot s$ (with $n \in [1,2,3]$) this value lies with in a range of the true value. In that case it takes effect that $u_z = n \cdot s$ and consequently $X = x_j \pm (u_s + u_z)$.
In the following subsections different test series are declared. The results are shown in different charts and diagrams. One of the results is the density function from every test series, also called probability function. A probability density function is non-negative everywhere and its integral from $-\infty$ to $+\infty$ is equal to 1. If a probability distribution has density $f(x)$, then intuitively the infinitesimal interval $[x, x + dx]$ has probability $f(x) \, dx$. A probability density function can be seen as a "smoothed out" version of a histogram: if one empirically measures values of a continuous random variable repeatedly and produces a histogram depicting relative frequencies of output ranges, then this histogram will resemble the random variable's probability density (assuming that the variable is sampled sufficiently often and the output ranges are sufficiently narrow).

**Coherences Density function:**

\[
\text{Definition: } f(x) = \frac{1}{s\sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x - \mu}{s} \right)^2}
\]  

(6.8)

The area below the density function within an interval $[a, b]$ gives the probability with which a constant random variable lies in this interval.

\[
\int_{-\infty}^{\infty} f(x) \, dx = 1
\]

The probability that a random value lies in the interval $\pm \infty$ is 100%. The total area under the graph is 1

\[
\lim_{k \to \infty} \int_{-k}^{k} f(x) \, dx = 0
\]

The probability that a random value gets a specific value is at zero. 95% probability with $\pm 2\sigma$

\[
\int_{-2\sigma}^{+2\sigma} f(x) \, dx \approx 0.95
\]
6.2.1 Dismounting the Adapters from the vehicle

Measurement series PQ35 point R3; 10 single measurands.

Composition 1 with demounting from the vehicle but without calibration and without disassembling the FlexMess adapters. All numeric values are shown in mm, if it is not otherwise declared. Test reports of the processed measurements are included in the Appendix E.

<table>
<thead>
<tr>
<th>values</th>
<th>$x_j$</th>
<th>$y_j$</th>
<th>$z_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1539.22</td>
<td>712.65</td>
<td>826.20</td>
</tr>
<tr>
<td>2</td>
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<td>826.26</td>
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<td>826.28</td>
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<td>1539.42</td>
<td>712.82</td>
<td>826.32</td>
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<td>1539.43</td>
<td>712.84</td>
<td>826.36</td>
</tr>
<tr>
<td>10</td>
<td>1539.44</td>
<td>712.87</td>
<td>826.37</td>
</tr>
</tbody>
</table>

$\bar{x}$ 1539.368 712.761 826.278

$s$ 0.068 0.069 0.060

$2s$ 0.136 0.137 0.121

$s(\bar{x})$ 0.021 0.022 0.019

$t$ 0.049 0.049 0.043

Figure 6.12: Results series 1

<table>
<thead>
<tr>
<th>Example calculation X (measurement series)</th>
<th>Example calculation X (single measurement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma = 95%$ → $t = 2,26$</td>
<td>$95%$ → $2s$</td>
</tr>
<tr>
<td>$u_z = 0,0485 mm$</td>
<td>$u_{ze} = 0,136mm$</td>
</tr>
<tr>
<td>$u_x = 0,2 mm$</td>
<td>$u_{xe} = 0,2 mm$</td>
</tr>
<tr>
<td>consequently $X = (1539.37 \pm 0,2485) mm$</td>
<td>consequently $X_i = (1539.22 \pm 0,336) mm$</td>
</tr>
</tbody>
</table>

Figure 6.13: Exemplary results series 1
True values of the measurement series:

\[ Y = (712.76 \pm 0.2491) \text{mm} \]
\[ Z = (826.28 \pm 0.2431) \text{mm} \]
\[ X = (1539.37 \pm 0.2485) \text{mm} \]

Measurement value for the single value \( x_i, y_i, z_i \):

\[ x = (x_i \pm 0.336) \text{mm} \]
\[ y = (y_i \pm 0.337) \text{mm} \]
\[ z = (z_i \pm 0.321) \text{mm} \]

In single measurements this value lies maximal \( \Delta x = u_x + u_w \) from the true value. In the following figures the charts of the density function for every test series is shown. The area below the density gives the probability with which a constant random variable lies in this interval.

![Figure 6.14: Chart density function series 1](image-url)
6.2.2 Test Series without dismounting the Adapters from the Vehicle

Measurement series PQ35 point R3; 10 single measurands.

Composition 2 without demounting from the vehicle, without disassembling the hardware and without calibration

<table>
<thead>
<tr>
<th>values</th>
<th>$x_i$</th>
<th>$y_i$</th>
<th>$z_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1539,29</td>
<td>712,68</td>
<td>826,23</td>
</tr>
<tr>
<td>2</td>
<td>1539,38</td>
<td>712,80</td>
<td>826,33</td>
</tr>
<tr>
<td>3</td>
<td>1539,33</td>
<td>712,65</td>
<td>826,24</td>
</tr>
<tr>
<td>4</td>
<td>1539,35</td>
<td>712,63</td>
<td>826,31</td>
</tr>
<tr>
<td>5</td>
<td>1539,34</td>
<td>712,67</td>
<td>826,23</td>
</tr>
<tr>
<td>6</td>
<td>1539,36</td>
<td>712,70</td>
<td>826,29</td>
</tr>
<tr>
<td>7</td>
<td>1539,30</td>
<td>712,70</td>
<td>826,26</td>
</tr>
<tr>
<td>8</td>
<td>1539,27</td>
<td>712,74</td>
<td>826,29</td>
</tr>
<tr>
<td>9</td>
<td>1539,33</td>
<td>712,69</td>
<td>826,21</td>
</tr>
<tr>
<td>10</td>
<td>1539,34</td>
<td>712,67</td>
<td>826,31</td>
</tr>
<tr>
<td>$\bar{x}$</td>
<td>1539,329</td>
<td>712,693</td>
<td>826,270</td>
</tr>
<tr>
<td>$s$</td>
<td>0,033</td>
<td>0,048</td>
<td>0,041</td>
</tr>
<tr>
<td>$2 \cdot s$</td>
<td>0,067</td>
<td>0,096</td>
<td>0,083</td>
</tr>
<tr>
<td>$s(\bar{x})$</td>
<td>0,021</td>
<td>0,030</td>
<td>0,026</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>0,048</td>
<td>0,069</td>
<td>0,059</td>
</tr>
</tbody>
</table>

Figure 6.15: Results series 2

True values of the measurement series:

$$X = (1539,33 \pm 0,221) \, mm$$

$$Y = (712,69 \pm 0,230) \, mm$$

$$Z = (826,27 \pm 0,226) \, mm$$

Measurement value for the single value $x_i, y_i, z_i$:

$$x = (x_i \pm 0,267) \, mm$$

$$y = (y_i \pm 0,296) \, mm$$

$$z = (z_i \pm 0,283) \, mm$$
6.2.3 Test series with dismounting the adapters from the vehicle, with disassembling the hardware and with calibration

Measurement series PQ35 point R3; 10 single measurands
Composition 3 with demounting from the vehicle, with disassembling the hardware and with calibration

\[
\begin{array}{ccc}
\text{values} & x_i & y_i & z_i \\
1 & 1539.53 & 712.28 & 826.07 \\
2 & 1539.51 & 712.33 & 825.93 \\
3 & 1539.55 & 712.33 & 825.97 \\
4 & 1539.58 & 712.36 & 825.90 \\
5 & 1539.77 & 712.24 & 825.99 \\
6 & 1539.64 & 712.38 & 825.94 \\
7 & 1539.78 & 712.37 & 826.05 \\
8 & 1539.77 & 712.24 & 825.99 \\
9 & 1539.69 & 712.37 & 826.11 \\
10 & 1539.60 & 712.30 & 826.07 \\
\hline
\bar{x} & 1539.642 & 712.320 & 826.002
\end{array}
\]
True values of the measurement series:

\[ X = (1539.33 \pm 0.349) \, mm \]

\[ Y = (712.69 \pm 0.276) \, mm \]

\[ Z = (826.27 \pm 0.300) \, mm \]

Measurement value for the single value \( x_i, y_i, z_i \):

\[ x = (x_i \pm 0.409) \, mm \]

\[ y = (y_i \pm 0.306) \, mm \]

\[ z = (z_i \pm 0.340) \, mm \]
6.3 Total Deviation in the 3D-Space

Because of the fact that the measured point is placed in the three dimensional space, the measured value has an inaccuracy in all three space directions. To be able to maintain the maximum distance (deviation) to the real point, the absolute value of the single instability factors is generated. The maximum deviation is affected by the methodical measurement inaccuracy, because the big factors have a bigger influence on the calculation.

Composition 1

Measurement series: \[ d = \sqrt[3]{\Delta X^2 + \Delta Y^2 + \Delta Z^2} = 0,568 \text{mm} \] (6.9)

without \( u_s \) d=0,188

Single measurement: \[ d = \sqrt[3]{\Delta x^2 + \Delta y^2 + \Delta z^2} = 0,691 \text{mm} \] (6.10)

without \( u_s \) d=0,373

Composition 2

Measurement series: \[ d = \sqrt[3]{\Delta X^2 + \Delta Y^2 + \Delta Z^2} = 0,559 \text{mm} \]

Single measurement: \[ d = \sqrt[3]{\Delta x^2 + \Delta y^2 + \Delta z^2} = 0,535 \text{mm} \]

Composition 3

Measurement series: \[ d = \sqrt[3]{\Delta X^2 + \Delta Y^2 + \Delta Z^2} = 0,612 \text{mm} \]

Single measurement: \[ d = \sqrt[3]{\Delta x^2 + \Delta y^2 + \Delta z^2} = 0,570 \text{mm} \]
6.4 Discussion of Results and Conclusion

The measurement series composition 3 (with demounting from the vehicle, with disassembling the adapters and with calibration) was processed on a different day than the other measurement series. The difference from the average value of about 0.04 mm may be caused by the difference in measurement temperature. (comparison difference between composition 1 and composition 2 is around 0.005 mm).

As expected the standard deviation $s$ is smallest in composition 2. Here are no annoying external influences affecting the measuring arrangement. The difference in this case is the internal measurement noise.

In the measurement with composition 1 the standard deviation is almost twice as high as in composition 2. Here an inaccuracy comes in because of the minimal different tensions while de- and remounting the hardware in the RPS-holes. The highest standard deviation was established while demounting the FlexMess from the vehicle, with disassembling the hardware and with a new calibration before the hardware was remounted in the RPS holes and the next measurement was processed. This is caused by the new calibration. There the inaccuracy from the instrument ($u_i = 0.2mm$) occurs two times – first while the assembled hardware is calibrated on the calibration plate and in the second place while the real measurement on the vehicle is processed.

It is a consideration to be as accurate as possible, to use the calibration only when it is absolutely necessary. But it must be warranted that other external
influences like differences in the temperature which could be compensated by the calibration are not causing a higher inaccuracy.
Chapter 7

Certification of System

This chapter deals with the official certification that was done at Volkswagen, to obtain the permission for using the developed system in the construction and production process. The complete system must be accredited by an official micro-inspection department called inspection equipment monitoring. The result from that action is a certificate. The complete system with every influencing variable that can cause errors in the result of a measurement are shown explicitly. For that request further measurements with the FlexMess system in comparison to a superior system were done. The hardware was checked if it is rugged and reproducible.

7.1 Mechanical Investigation

To examine mechanical stability and reproducibility of the collet chuck and the carbon extensions as a single system, three different measurement series were carried out. The used measurement machine for these series
was a Leitz PMM (tactile system) with an internal measurement accuracy U3 1.5 µm.

7.1.1 Chuck centring Accuracy

The accuracy of the chuck centring including clamping jaws in the RPS hole was measured in standalone condition in five different fixed positions, each five times. Before every measurement the clamping jaw was opened and closed. To realize the fixture position bolts with different diameters (5 mm, 10 mm, 15 mm and 20 mm) were used. The position “0 mm” was measured on the closed chuck. In every measurement the center of a circle from the chuck (green points in Figure 7.1) was measured to define the condition. As a reference for the height, the upper plane of the chuck was measured (red points).

![Measuring reference (schematic)](image)

- Red → z-plane
- Green → x / y condition (center of a circle)

Figure 7.1: Measuring strategy

The centring of the chuck was determined by measuring every single clamping jaw on the chuck with a circle calculation. This procedure is shown with green arrows in Figure 7.2. Tilting of the jaws was determined with a measurement of three planes on the upper plane on every jaw (red points / plane in Figure 7.2).
Figure 7.2: Centring and tilting from the chuck and the jaws

With this measurement series the tilting of every single jaw and the centring of the complete chuck was ascertained. The results are shown in the following tables (all single values from the five series are included in the Appendix F).

**Messung Spannstift 0mm: Zentrierung**

<table>
<thead>
<tr>
<th></th>
<th>X [mm]</th>
<th>Y [mm]</th>
<th>Z [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mittel</td>
<td>0,0006</td>
<td>0,0038</td>
<td>0,0036</td>
</tr>
<tr>
<td>StdAbw</td>
<td>0,0008</td>
<td>0,0019</td>
<td>0,0015</td>
</tr>
<tr>
<td>Spanne</td>
<td>0,0019</td>
<td>0,0051</td>
<td>0,0053</td>
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</table>

**Messung Spannstift 5mm: Zentrierung**

<table>
<thead>
<tr>
<th></th>
<th>X [mm]</th>
<th>Y [mm]</th>
<th>Z [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mittel</td>
<td>-0,0100</td>
<td>0,0026</td>
<td>0,0105</td>
</tr>
<tr>
<td>StdAbw</td>
<td>0,0049</td>
<td>0,0020</td>
<td>0,0045</td>
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<tr>
<td>Spanne</td>
<td>0,0150</td>
<td>0,0047</td>
<td>0,0153</td>
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</tbody>
</table>

**Ebenenverkippung**

<table>
<thead>
<tr>
<th></th>
<th>PXZ1</th>
<th>PXZ1</th>
<th>PXZ2</th>
<th>PXZ2</th>
<th>PXZ3</th>
<th>PXZ3</th>
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</thead>
<tbody>
<tr>
<td>Mittel</td>
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<td>0,00146</td>
<td>0,00222</td>
<td>-0,00340</td>
<td>0,00194</td>
<td>0,00292</td>
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<tr>
<td>StdAbw</td>
<td>0,00777</td>
<td>0,00285</td>
<td>0,00453</td>
<td>0,00474</td>
<td>0,00236</td>
<td>0,00543</td>
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<tr>
<td>Spanne</td>
<td>0,01861</td>
<td>0,00694</td>
<td>0,01083</td>
<td>0,01139</td>
<td>0,00556</td>
<td>0,01306</td>
</tr>
</tbody>
</table>

**Ebenenverkippung**

<table>
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<tr>
<th></th>
<th>PXZ1</th>
<th>PXZ1</th>
<th>PXZ2</th>
<th>PXZ2</th>
<th>PXZ3</th>
<th>PXZ3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mittel</td>
<td>-0,01028</td>
<td>-0,01139</td>
<td>0,00236</td>
<td>-0,01208</td>
<td>0,00736</td>
<td>0,01097</td>
</tr>
<tr>
<td>StdAbw</td>
<td>0,00483</td>
<td>0,00219</td>
<td>0,00416</td>
<td>0,00450</td>
<td>0,00179</td>
<td>0,00381</td>
</tr>
<tr>
<td>Spanne</td>
<td>0,01566</td>
<td>0,01389</td>
<td>0,00917</td>
<td>0,01583</td>
<td>0,00944</td>
<td>0,01417</td>
</tr>
</tbody>
</table>
In conclusion the mechanical stability from the collet chuck with the clamping jaws is very well. On average there is a centring accuracy from 8.3µm and a tilting from the jaws from 0.0058°.

### 7.1.2 Repeating Mounting Accuracy

To determine the reproducibility of the mounting process and the position in the RPS hole, the centring of the chuck in the RPS hole was measured on a sliced chassis rail to get access to the inside of the chassis rail. For this the jaws of the chuck were measured in mounted position in the hole at the outside of every jaw (blue points in Figure 7.4) and a circle around these points was build. The center of this circle gives the centring position of the chuck. In this way the chuck was measured five times – before every
measurement the chuck was removed from the chassis rail and was then mounted into the hole again.

![Circle measuring on the outside from the jaws in implemented condition](image)

**Figure 7.4: Circle measuring on the outside from the jaws in implemented condition**

### Results

<table>
<thead>
<tr>
<th>Zentrierung</th>
<th>x [mm]</th>
<th>y [mm]</th>
<th>z [mm]</th>
<th>D [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>-0.0964</td>
<td>-0.0217</td>
<td>-1.0073</td>
<td>1.2411</td>
</tr>
<tr>
<td>2)</td>
<td>-0.0970</td>
<td>-0.1957</td>
<td>-1.0072</td>
<td>1.2404</td>
</tr>
<tr>
<td>3)</td>
<td>-0.0965</td>
<td>-0.1992</td>
<td>-1.0073</td>
<td>1.2407</td>
</tr>
<tr>
<td>4)</td>
<td>-0.0954</td>
<td>-0.2025</td>
<td>-1.0072</td>
<td>1.2407</td>
</tr>
<tr>
<td>5)</td>
<td>-0.0966</td>
<td>-0.2051</td>
<td>-1.0072</td>
<td>1.2417</td>
</tr>
</tbody>
</table>

**Mittelwert**  
-0.0964  -0.2008  -1.0073  1.2409

<table>
<thead>
<tr>
<th>Abweichungen</th>
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<th>0,0009</th>
<th>0,0000</th>
<th>0,0009</th>
</tr>
</thead>
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<td>1)</td>
<td>-0,0006</td>
<td>0,0051</td>
<td>0,0001</td>
<td>0,0052</td>
</tr>
<tr>
<td>2)</td>
<td>-0,0001</td>
<td>0,0016</td>
<td>0,0000</td>
<td>0,0016</td>
</tr>
<tr>
<td>3)</td>
<td>0,0010</td>
<td>-0,0017</td>
<td>0,0000</td>
<td>0,0019</td>
</tr>
<tr>
<td>4)</td>
<td>-0,0002</td>
<td>-0,0043</td>
<td>0,0001</td>
<td>0,0043</td>
</tr>
</tbody>
</table>

| Standardabweichung | 0,0006  | 0,0036  | 0,0001  | 0,0018  |
| Spanne         | 0,0016  | 0,0034  | 0,0001  | 0,0043  |

**Figure 7.5: Mounting repeating accuracy**

In this measurement series it was shown, that the repeated mounting accuracy is around 0,005 mm. Especially in z direction a mounting of the FlexMess adapters is repeatable in a range from around 0,0001 mm.
A graphical description from the centring of the chuck in mounted position is shown in Figure 7.6 (all values in mm).

Figure 7.6: Centring from the chuck in the hole in x & y direction

**The repeating accuracy of the mounting process from the FlexMess adapter in the RPS holes is also very well with a spread of under 5 μm.**

### 7.1.3 Mechanical Stability

For a further evaluation it was checked if the adapter has dimension accuracy between the removable carbon extensions and the shaft of the FlexMess adapter. For this evaluation the distance from the center of the
chuck in the RPS hole to the reference points on the extensions was measured five times, as shown in Figure 7.7.

![Figure 7.7: Measuring assembly for the stability from the adapter](image)

Before each of these five measurements were done, the hardware was removed from the chassis rail.

<table>
<thead>
<tr>
<th>Strecken</th>
<th>[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>554,7585</td>
</tr>
<tr>
<td>2)</td>
<td>554,7554</td>
</tr>
<tr>
<td>3)</td>
<td>554,7495</td>
</tr>
<tr>
<td>4)</td>
<td>554,7798</td>
</tr>
<tr>
<td>5)</td>
<td>554,7499</td>
</tr>
</tbody>
</table>

| Mittel   | 554,7586 |

<table>
<thead>
<tr>
<th>Abweichungen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) -0,0001</td>
</tr>
<tr>
<td>2) -0,0032</td>
</tr>
<tr>
<td>3) -0,0091</td>
</tr>
<tr>
<td>4) 0,0211</td>
</tr>
<tr>
<td>5) -0,0088</td>
</tr>
</tbody>
</table>

| Standardabw. | 0,0124 |
| Spanne       | 0,0302 |

![Figure 7.8: Mechanical stability from the FlexMess adapter](image)

The mechanical stability of every FlexMess adapter within one calibration interval is in a range of 0,03 mm
7.2 Absolute Accuracy

To be able to give an indication of the absolute accuracy of the FlexMess system, a measurement series with a superior system must be carried out. For the appointment of the absolute accuracy of the whole FlexMess system, a separate coordinate system was built up, which can be localised by both systems. The superior measurement system for this measurement series was a Zeiss KMG USMC, and the tested system was the GOM TRITOP in collaboration with the FlexMess adapters. The chassis rail that was used for this test series was built up on the KMG like it is shown in Figure 7.9.

![Figure 7.9: Measuring setup from the chassis rail for the absolute accuracy](image)

For the realization of the coordinate system, special aluminium cubes were produced, on which uncoded reference points for the TRITOP system were fixed. With both systems three planes on these cubes were appointed, and the intercepting points of these planes are the reference points for the coordinate system in this test series. With this strategy it is warranted, that
both systems are using the same coordinate system as reference and that there are no variances in the accuracy while comparing results.

![Figure 7.10: One of the three aluminium cubes for the reference coordinate system](image)

After measuring the three cubes with the KMG, the coordinates of the three resulting points were appointed. With a CNC program the position of the RPS hole could be defined. In several repeated measurements with the KMG it was shown that the repeatable accuracy of the KMG for the RPS position was less than 0,01 mm. The precise position from the RPS coordinate in the chassis rail is known in relation to the mounted coordinate system. Because of the cubes, the TRITOP system was also able to build up the same coordinate system as in the tactile measurement before.

![Figure 7.11: One FlexMess adapter on chassis rail](image)
After the mounting of the coordinate system using the planes on the three cubes, the TRITOP was able to localise the RPS coordinates using the four points on the carbon extensions from the FlexMess.

Figure 7.12: Tactile system (left) and FlexMess adapter (right) in the RPS hole

This procedure was repeated five times, with the FlexMess adapter being removed from the chassis rail before every localisation from the RPS coordinate. The results of the five measurements could be compared to the result of the tactile procedure. The result is shown in Figure 7.13 (all values in mm).

<table>
<thead>
<tr>
<th>Messung</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>0.06</td>
<td>0.08</td>
<td>0.01</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Y</td>
<td>0.36</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.38</td>
</tr>
<tr>
<td>Z</td>
<td>0.01</td>
<td>0.04</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 7.13: Results / deviations from the comparison to the tactile procedure

The variation of the RPS localisation with the FlexMess is in a diffusion of less than 0.1 mm. The result of the comparison with the superior tactile procedure is that the x- and z-coordinate was localized by the FlexMess with very little deviation to the tactile procedure. In the y-direction there is a systematic deviation from around 0.4 mm. Also with a new calibration and different mounting positions of the FlexMess adapter in the hole there were no appreciable alterations in the y-coordinate. This fact was already
mentioned in the theoretical calculation of errors in Chapter 6.1.6. The height of the RPS holes in the chassis rails is tolerated with ±0,5 mm like it is shown in Figure 7.14.

![Figure 7.14: Tolerance in the height from the RPS hole](image)

A measurement of the z-plane directly in the hole confirmed this fact. The variance of the z-coordinates in the hole was 0,64 mm. The result of this measurement is also included in Appendix F. Because of the 45° bevel on the chucks, this tolerance can cause a deviation in x- or y- direction in expected dimension.

The analysis of the absolute accuracy in a practically relevant measurement volume gives a maximum deviation from < 0,4mm.

Additionally, the FlexMess was compared to the superior tactile system, the underfloor-coordinate measurement instrument (cp. Chapter 1.3). In Figure 7.15 this action is shown. The result of this comparison confirmed all the tests and results that were done before. It was possible to localise all the points that were measured with the tactile instrument with an accuracy of under 0,35 mm by using the developed FlexMess system.
7.3 Summary and Conclusion

The examination of the chuck concerning the mechanical stability had shown that the results are in a variation of under 0.01 mm. Therewith the influence of the chuck on the accuracy of the end result is negligible.

The repeatability accuracy from the FlexMess adapters in a practically relevant assignment is less than 0.1 mm, well inside the normal accuracy of the measurement system TRITOP.

Because of the irregular geometry of the RPS hole, the clamping jaws have the only influence on the accuracy of the total FlexMess system.

The FlexMess system fulfils the requirements to enable a flexible measurement system with an accuracy of under 1 mm.

The total accuracy of the FlexMess system in combination with the photogrammetric system TRITOP is ±0.35 mm.
Chapter 8

Summary and Future Development Goals

The purpose of this study was to enable a flexible measurement of a completely assembled vehicle in the modern automobile production for the first time. For that request a hardware tool was developed and constructed. An acceptable measurement system for this kind of measurement was searched and encountered and special programs in the existing software of this system were programmed and applied. The new system was tested in different kind of measurements and a theoretical calculation of errors was done. Because of the high potential of this developed strategy the Volkswagen Company applied for a patent for the complete system. Additionally, the complete system was certified by the measurement department and the quality assurance team of VW. The author is authorized to use this measurement system with the developed hardware in every phase of the product development process, also in the real production of the whole Volkswagen Company. Furthermore, it now is possible to use the system directly at the customer or in the after sales business. Because of this master project, it has become possible to measure a completely assembled vehicle
wherever and whenever it is required in conformance with current guidelines. With two persons it is possible to carry the whole system to the vehicle that must be analysed. The total accuracy while analysing a direct point by using the FlexMess system is under 0.5 mm. An overview of the complete system is shown in the Figure 8.1.

Additionally it was tested where it is possible to use the developed system. The FlexMess was applied both indoors and outdoors. Indoors you can use the patent FlexMess everywhere. Even in the adverse ambience directly in the production it was possible to do a usable measurement. Because of this, the integration of this technology in the whole Volkswagen Company was started at the end of the project.
The measurements that were done outdoors were also as successful as in closed rooms. The only problem was caused by the wind and the sun. When it is very windy, it could happen that the carbon extensions are swinging in the wind, and the programmed software is not able to indicate the correct locations of the reference points on the carbon extensions. The sun can cause a problem when one of the two points on an extension lies in the shadow and the other lies directly in the sun. It is very difficult to detect both points because they have not the same black / white contrast. But when every point lies in shadow and there is not too much wind outside it is also possible to do a measurement conforming to current guidelines without any problems. With no present measurement system this kind of measurement was possible up to now.
8.1 Advantages

The advantages of the developed measurement strategy are as follows:

- Fast availability of the results on site
- Simple handling
- High mobility
- Space saving
- Flexible with minor transport volume
- Alignment of the car by the use of the 3-2-1 rule $\rightarrow$ no Best-Fit
- Vehicle must be minimally disassembled
- Humble make-ready time
- Realistic statement about the actual position of the vehicle
- Continuous measurement from the body making up to the customer
- No cost intensive measurement fixture necessary
- Possibility for the assignment in after-sales service
- Useful for every platform (VW, Audi, Skoda, Seat)
- Torsion consistence from a convertible car (Eos) is analysable
- Also adaptable for external cars for benchmarks and comparisons

*high quality product simultaneous with less capital expenditure*
8.2 Financial facts

Money saving potential in comparison to the traditional measurement technologies for this kind of analysis are shown below.

All costs are based on real offers and calculations from the respective company.

**FlexMess:**

Hardware:
15.000€ for 4 adapters incl. vehicle/platform specific clamping jaws for one platform

Measurementsystem incl. Software (High End configuration):
65.000€ (Camera, Notebook, Software, Scale Bars, Adapters, coded & uncoded reference points....)

→ **80.000€**

**Underfloor coordinate measurement system:**

2xtactile measurement machine:
350.000€ (incl. operating system)

Tactile undefloorsensor + sensor range of products:
155.000€

Basement:
100.000€

Measurement plate for the machine:
60.000€

Vehicle specific measurement fixture:
35.000€

→ **700.000€**
8.3 Analysed cars

Additional to the Golf A5 / PQ35, at the end of this thesis the developed FlexMess was adapted to several vehicles from the Volkswagen Company. Therewith it also becomes possible to measure and to analyse following cars using the developed system FlexMess:

- VW Passat B6 station wagon & limousine
- Scoda Octavia station wagon & limousine
- VW Polo 9N
- VW Golf5 Plus
- VW Eos
- Skoda Fabia
- VW Suran
- VW Fox
- Audi A3 & Sportback with Quattro

Figure 8.4: FlexMess adapted on several vehicles
8.4 Future Work

For the developed system to become usable for more future projects, it needs to be adapted for every platform from the Volkswagen Company in which also Audi, Seat and Skoda is included. For this complete adaptation most of the work was done in this project. Now it is only necessary to check the dimension of the RPS holes of the other platforms and vehicles. Only the clamping jaws from the FlexMess adapters need to be new for the other products. The rest of the developed FlexMess is the same on every platform. The next step is to make an enquiry with other OEMs in the automobile industry regarding in what way these companies are using RPS points for the alignment of objects in the 3D space.

Furthermore a very important work for the future is the integration of this technology in the whole VW Company worldwide. For that request some information documents must be written, and a “promotion tour” to every VW factory must take place. To promote sales and integrations of the system a journal paper was written. Because of the application for a patent, the author
is not authorized up to now, to present this system to the publicity. But when
the patent situation is accepted, the journal paper can be used for the
promotion of the FlexMess system. This paper is included in Appendix G.
Furthermore it is necessary to construct an efficient user manual for the
whole System FlexMess in collaboration with the GOM TRITOP system.
Some points for a user manual were already done in this project. Especially
the programming of the macros (Chapter 4.2) can be used for a user manual.
Additionally, it must be clarified which companies additional to the
Volkswagen AG are allowed to use the patent FlexMess. Especially the
Company GOM and the Company WITTE are interested in buying the licence
of the FlexMess patent, to be authorized to use the developed technology.
Another important point for future projects is the integration of the FlexMess
system directly into the production line. It would be possible to install the
adapters fixed into the process, and to analyse every produced vehicle in an
automated way.

Steps for future work:

1. adapting FlexMess for every VW platform
2. enquiry with other OEMs concerning the use of RPS
3. creating an user manual
4. “promotion tour” to every VW factory → presenting to the publicity

Independent of the FlexMess adapters it is absolutely necessary to integrate
more and more non-contact measurement systems in the production and
development process, to enable more flexibility and to be able to react to
every measurement and analysis problem in a fast and efficient way.
Chapter 9

Bibliography


http://www.geomsoft.com, created 14.08.1998


# Chapter 10

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Drawings and Bill of Materials for the FlexMess Hardware

up to date 18.10.2006

**Design Engineer:**
Dipl. Ing. Thilo Lichtenberg
Institut für Fahrzeugbau Wolfsburg
Tel.: 05361/831299
Mobil: 0176 21210305
Mail: thilo.lichtenberg@fh-wolfsburg.de
## Bill of Materials FlexMess for PQ 35

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**Bill of Materials**

**FlexMess**

**Flaring for PQ 24**

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**Norm**

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**Zust**

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<th>Name</th>
<th>Urspr.</th>
<th>Ers. für</th>
<th>Ers. durch</th>
</tr>
</thead>
</table>

---

**Thilo Lichtenberg**
DIN 7188 mittel

Werkstoff: Al

Datum Name
Bearb. 30.08.2006 Lichtenberg
Gepr.
Norm

Thilo Lichtenberg

CM/FM3/DRW0004

6.3

Alle Fasen 1.5x45°

Maßstab: 1:2
Werkstoff: Al

Turning Handle

<table>
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<th>Änderung</th>
<th>Datum</th>
<th>Name</th>
<th>Urspr.</th>
<th>Ers. für</th>
<th>Ers. durch</th>
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6 von 66
Screw Cap

Datum Name
Bearb. 16.05.2006 Lichtenberg
Gepr
Norm

Thilo Lichtenberg
CM/FM3/DRW0008
Blatt: 1
Maßstab: DIN 7168 mittel

Werkstoff: Al

Turning Handle Chuck 50mm

Datum: 04.09.2006
Name: Thilo Lichtenberg
Bearb.
Gepr.
Norm

CM/FM3/DRW0009 Blatt:
Maßstab: Allgemeintoleranz DIN 7168 mittel

Werkstoff: Al

Datum: 04.09.2006

Bearb.: Thilo Lichtenberg

Gepr.: Lichtenberg

Norm:

S Shank Core Chuck 50mm

Durchmesser: 22-0.5

Länge: 254

M8 Gewinde

Fase 1.5x45°

97 Oberflächenränder

Chapter A Drawings FlexMess

CM/FM3/DRW0010

Thilo Lichtenberg

9 von 66
Maßstab: 1:5

Allgemeintoleranz

Werkstoff:

Datum: Name: Bearb.

08.06.2006: Lichtenberg

Gepr.

Norm

Thilo Lichtenberg

CM/FM3/DRW0012

Blatt: 1

Zust. Änderung Datum Name Urspr. Ers. für Ers. Durch

Chapter A Drawings FlexMess

4x Sackloch Ø 6+0,2 t=5

DIN 66-8

40 120 120 120

R=10

142

20

250

600

41

10

75

90
Maßstab: 1:1

Datum Name
Bearb. 04.09.2006 Lichtenberg

Werkstoff: 9 S Mn 28 K

Calibrationadapter

Alle Fasen 1x45
Maßstab: 1:1

Werkstoff: PA

Datum: 04.09.2006

Lichtenberg

Gepr

Norm

Thilo Lichtenberg

CM/FM3/DRW0014

Blatt: 1

Holder for Referencepoint
Maßstab: 2:1

Allgemeintoleranz DIN 7168 mittel

Datum Name
Bearb. 04.09.2006 Lichtenberg
Gepr
Norm

Thilo Lichtenberg CM/FM3/DRW0016

Alle Fasen 0.5x45°

Threaded Bolt M8
Maßstab: 5:1

Allgemeintoleranz
DIN 7168 mittel

Datum Name
04.09.200 Lichtenberg

Werkstoff:

Dowel Pin

Zust. Änderung Datum Name Urspr. Ers. für Ers. durch

Thilo Lichtenberg CM/FM3/DRW0017

Maßstab: 1:1

Allgemeintoleranz
DIN 7168 mittel

Werkstoff: Al

Calibrationsocket 1 PQ35
Maßstab: 1:1

Allgemeintoleranz
DIN 7168 mittel

Werkstoff: Al

Calibrationsocket 2 PQ35

Thilo Lichtenberg
CM/FM3/DRW0019

Zust. Änderung Datum Name Urspr. Ers. für Ers. durch
Maßstab: 1:1
Werkstoff: Al

Kalibrationssockel 3 PQ35

Datum | Name
---|---

Bearb. | Lichtenberg
Gepr. | 
Norm | 

Thilo Lichtenberg CM/FM3/DRW0020

Zust. | Änderung | Datum | Name | Urspr. | Ers. für | Ers. durch
4x Ausfräsung Ø 11 t=1

Maßstab: 1:1
Werkstoff: Al
Allgemeintoleranz DIN 7166 mittel

Datum Name
Bearb. 18.10.2006 Lichtenberg

Calibrationsocket 4 PQ35
Thilo Lichtenberg CM/FM3/DRW 0021

Zust. Änderung Datum Name Urspr. Ers. für Ers. durch
4x Ausfräsung Ø11 t=1

1.5x45°

Ø45

Ø60

Calibrationsocket 5 PQ24
4x Ausfrä sung \( \Phi 11 t=1 \)

1.5x 45°

\( \Phi 45 \)

\( \Phi 60 \)

**Allgemeintoleranz**

DIN 7168 mittel

**Maßstab:** 1:1

**Werkstoff:** Al

**Datum Name**

Bearb. 18.10.2006

Lichtenberg

**Norm**

**Calibration socket 6 PQ24**

Thilo Lichtenberg

CM/FM3/DRW0023

Zust. Änderung Datum Name Urspr. Ers. für Ers. durch
Alle Passnute gefast 2x45°
Alle Außenkonten gefast 2x45°

Allgemeintoleranz DIN 7168 mittel

Werkstoff: Al

Datum
Bearb.
Norm

Base of FlexMess

Thilo Lichtenberg
CMFM3D70001
1 Scope and Aim

This standard applies to dimensioning and to manufacturing and inspecting single parts or assemblies (ASSY) in all product creation phases for

- uniform positioning throughout the manufacturing and inspection areas
- assurance of identical dimensional references
2 Theoretical Principles

2.1 Component-Oriented Reference System

One of the basic ideas forming the basis for the reference point system is the component-oriented coordinate system according to VW 010 52.

A vehicle is dimensioned by means of a global coordinate system (mathematical vehicle coordinate system), the origin of which is defined to be in the center at the level of the front axle of a vehicle (see VW 010 59 Part 1; VW 010 52 is the binding reference for the vehicle coordinate system), Figure 1.

Starting from the axes of this coordinate system, grid lines are spread out parallel to the axes. These grid lines, spaced 100 mm apart, theoretically penetrate the vehicle. These grid lines serve to find all points on the vehicle. In other words, they help to determine the position of each vehicle component. Dimensioning is also performed with the aid of these grid lines.

The reference point system is based on a component-oriented reference system.

The origin of the component reference system is defined by the intersection point of three reference planes. The reference planes are formed via the RPS main mountings defined on the component.

When several parts are assembled, these parts are toleranced with respect to each other. After the parts are joined, the ASSY is described by a combined component-oriented reference system. This is formed

by adoption of one of the existing reference systems or
by forming a new reference system using the existing reference points.

The specification of the new reference system depends on the function of the ASSY.
2.2 Standard Sizes/Characteristics for RPS Mountings

Multiple-use location holes with high precision requirements must be adequately strong. In general, the standard sizes according to Table 1 and Table 2 shall be used. In case of holes in RPS surfaces, it must be ensured that the bearing surfaces are of adequate size and provide process assurance.

The specified dimensions shall be projected – parallel to the axes – onto the component.

Table 1. Recommended standard values

<table>
<thead>
<tr>
<th>Designation</th>
<th>Nominal dimension</th>
<th>Tol.</th>
<th>Graphical representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round hole</td>
<td>see VW 01077</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location holes, pluggable</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Square</td>
<td>15</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectangle</td>
<td>6 x 20</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 x 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 x 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circle</td>
<td>Ø 15</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ø 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ø 25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edges</td>
<td>10</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>Edge length &quot;a&quot;</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Recommended standard values

<table>
<thead>
<tr>
<th>Designation</th>
<th>Nominal dimension w x l</th>
<th>Tol.</th>
<th>Graphical representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long hole</td>
<td>see VW 01078</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long hole in angle position</td>
<td>see VW 01078</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3 The 3-2-1 Rule

Every rigid body possesses six degrees of freedom in three-dimensional space: three translational degrees parallel to the axes of a reference system and three rotatory degrees around the axes, Figure 2.

![Figure 2. The degrees of freedom in three-dimensional space](image)

In order to support a non-rotationally-symmetric body in a uniquely determinate manner, it must be fixed in all six possible directions of movement. The 3-2-1-rule provides for such unique fixing. It determines the following main-mounting distribution:

E.g. 3 mountings in z direction
     2 mountings in y direction
     1 mounting in x direction

Implementation of this rule is shown based on the following representation, Figure 3.

![Figure 3. Application of the 3-2-1 rule](image)

The three mountings in z direction restrict three degrees of freedom: translation in z direction and rotation around the x and y axes. The pin in the round hole prevents motion parallel to the axes in the x and y directions and, finally, the pin in the long hole prevents rotation around the z axis, Figure 3.

This rule applies equally to any other rigid component, even if its structure is much more complex. With a system of rigid bodies, the elements of which are interconnected by joints or guides, more than 6 degrees of freedom must be fixed using additional main mountings.

For non-rigid components, additional support points must be defined for supporting the components according to RPS aspects.

RPS 1 shall be the point that binds the most degrees of freedom.
4 Designation and Drawing Representation

4.1 RPS Designation

All RPS points must be included in the part drawing.

The designation is subdivided as follows:

- **Main mounting points** = Capitals
  - \( H \) = Hole
  - \( F \) = Surface
  - \( T \) = Theoretical point
    - is the mean of two support points

- **Support points** = Small letters
  - \( h \) = Hole
  - \( f \) = Surface
  - \( t \) = Theoretical point
    - is the mean of two support points

- **Mounting types**
  - Location holes/pins = Code letter \( H,h \)
  - Surfaces/edges/ball/tip = Code letter \( F,f \)
  - Theoretical point = Code letter \( T,t \)

- **Fixing directions** = Small letters
  - \( x, y, z \) for component-oriented reference systems parallel to the coordinate system
  - \( a, b, c \) for rotated, component-oriented reference systems

Examples of designation:

```
RPS 1 H xy F z
```

Fixing direction
Code letter for surface as main mounting
Fixing directions
Code letter for hole as main mounting
Designation with numbering

```
RPS 3 F z
```

Fixing direction
Code letter for surface as main mounting
Designation with numbering

```
RPS 5 f z
```

Fixing direction
Code letter for surface as support point
Designation with numbering

Numbering begins with the RPS 1 point for each single part and for each assembly.
4.2 Drawing Representation

Drawing representation takes place according to the valid drawing guidelines. The RPS surfaces shall be identified by means of cross-hatching.

If a part drawing does not exist yet, RPS Dimensions Sheet FE 515 \(^1\) shall be used.

As soon as the part drawing exists, the specifications from the RPS Dimensions Sheet are adopted directly in the drawing or adopted in text macro NO-F23 \(^2\). Administration of these specifications in the text macro is mandatory.

4.3 Procedure for Assemblies (ASSY) with Components with no Separate Drawing (ND):

The RPS points for components with no drawing (ND) must be identified by specifying the item number or part number.

A drawing exists for part 1; ND for parts 2 and 3, Figure 4.

\[\text{A} \quad \text{RPS 1 Hxy; RPS 1 Hxy for Item 3} \quad \text{S} \quad \text{RPS 2 Hx only for Item 3} \]
\[\text{D} \quad \text{RPS 1 Hxy only for Item 2} \quad \text{F} \quad \text{RPS 2 Hy; RPS 2 Hy for Item 2} \]

Fig. 4 ASSY with RPS points

Graphical representation, not adopted in drawing

---

\(^1\) Stored in design data administration system under FEO 000 515

\(^2\) Stored in design data administration system under NOF 000 023
5 Dimensioning and Tolerancing

5.1 General

Dimensions and tolerances can be entered directly in the drawing or via the table, Figure 5.

The starting point for dimensioning the components is generally the origin of the reference system.

Form and functional dimensions with tolerances shall always be referenced to the origin of the reference system.

Example: The holes within a hole group are dimensioned with respect to each other. The position of the hole group is dimensioned with respect to the reference planes.

In the fixing direction, the main mountings are positioned without tolerance with respect to the vehicle coordinate system / reference system.

The origin/reference point is shown in the drawing or table. If two or three fixing directions are bound at one point, tolerancing must be separated according to the hole or surface. In this case, the surface must be identified one line lower in the table. Here, the surface is set to zero in the tolerance zone. In the line in which the hole is set to zero, the tolerance zone for the surface shall be identified with a horizontal line, see the table in Figure 5.

The support-point tolerances shall be defined according to the requirements.

5.2 Component-Oriented Reference Systems Parallel to the Coordinate System

The origin of the reference system is defined without tolerances in the global vehicle coordinate system by means of a translation, Figure 5

5.3 Rotated, Component-Oriented Reference Systems

With rotated reference systems, the theoretical angles of rotation must be specified in RPS Dimensions Sheet FE 515 1) or in the drawing table text macro NO-F23 2).

If there are several angles of rotation, the angle specification and thus the sequence of rotations shall be obtained from the drawing. "See drawing" must be added to the table instead of the angle entry.

The position of the reference point is determined by means of its x, y and z coordinates in the global vehicle coordinate system.

Angles of rotation around the x, y and z axes are entered using mathematically positive or negative values. Positive angles are specified counterclockwise and negative angles clockwise.

In the coordinate system, the horizontal axis is assigned an angle of zero.

Nominal dimensions and tolerances are specified in a, b and c values in the RPS table. The fixing directions of the RPS points are specified as a, b and c values in the table and/or drawing, e.g. RPS 1 HabFc, Figure 6 and Figure 7.

1), 2) see page 6
<table>
<thead>
<tr>
<th>Feld</th>
<th>RPS</th>
<th>Globale Koordinaten</th>
<th>Aufnahmertyp/ Bemerkung</th>
<th>Bezugsquelle</th>
<th>x: 515</th>
<th>y: 275</th>
<th>z: 725</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sect.</td>
<td>Pkt./ Funct. point</td>
<td>x</td>
<td>y</td>
<td>z</td>
<td>Global coordinates</td>
<td>Mounting type/ note</td>
<td>Nominal sizes</td>
</tr>
<tr>
<td>1HxyFz</td>
<td>515 275 725</td>
<td>Hole Ø 14.5±0.2</td>
<td>0 0 0</td>
<td>0 0 –</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>. . .</td>
<td>. . .</td>
<td>Surface Ø 34.5+1</td>
<td>. . .</td>
<td>±1 ±1 0</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>2Hx . .</td>
<td>520 365 725</td>
<td>Long hole 13+0.2 x 26+0.4</td>
<td>5 90 0</td>
<td>0 ±0.5 .</td>
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<td>.</td>
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<tr>
<td>3F . . z</td>
<td>490 385 725</td>
<td>Surface 10+1 x 20+1</td>
<td>25 110 0</td>
<td>±1 ±1 0</td>
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<tr>
<td>4F . . z</td>
<td>600 380 725</td>
<td>Surface 10+1 x 20+1</td>
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<td>±1 ±1 0</td>
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<tr>
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<td>610 275 725</td>
<td>Surface 10+1 x 20+1</td>
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<td>±1 ±1 ±0.5</td>
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<tr>
<td>a 1</td>
<td>595 350 725</td>
<td>Hole Ø 8+0.2</td>
<td>. . .</td>
<td>. . 0.2</td>
<td>.</td>
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</table>

Fig. 5 Dimensioning with text macro NO–F23
**Fig. 6** Reference point is formed directly via RPS main mountings.
Fig. 7  Reference point is formed via RPS main mountings with defined distances.
6 Universal Use

6.1 General

The purpose of the RPS is to provide process assurance/capability and repeat accuracy for the procedures in order to make them independent of setting work performed by the worker. The reference points must be used in all manufacturing, assembly, inspection and installation processes.

In case of self-contained function sectors such as the side panel tank flap, a reference change in combination with functional dimensions to RPS planes is permissible.

Prior to the specification of RPS points, it is absolutely necessary to define the functions of the single part and the relevant assemblies with their required functional tolerances.

Reference points that were established at the beginning of a process must be kept for as long as possible. In order to avoid changes to arranged reference points, they are jointly defined – as early as possible in the design and development process – in consultation with all departments participating in the production process.

Reference points must be positioned at stable areas of a component that will remain unchanged even in further development and/or production processes.

Reference points on components that move relative to the body during driving operation can be considered according to the 3-2-1 rule only in the actual design position.

The RPS points on components that are used several times in vehicles and thus have multiple references to the global coordinate system can be shown without a global coordinate reference in the technical drawing.

The reference point system is equally oriented toward the production process, toward the function sectors and toward the strategic quality goals, e.g. audit, process capability.

6.2 Specification of Reference Points

Parallelism to the coordinate system (holes and surfaces) must be observed when entering the reference points. In the case of rotated systems, parallelism to the reference planes must be observed.

The RPS points must be produced in the tool sequence in which the greatest dimensional stability is attained.

Whenever possible, reference points must be produced with a standardized shape (hole, surface), which must be defined in detail.

If holes cannot be made in a component, surfaces or edges must be used to specify reference points.

In the case of COP parts (transfer parts), the respective reference-point positions arise in the ASSY.

6.3 Specification of Function Sectors

Use of the RPS on a complex portion of the vehicle such as the dashboard requires a structure that addresses the development and design engineering systems and includes all parts, single parts and assemblies.

A function sector includes all components in the visible and covered areas that directly affect their surroundings with their function points.

The specification of reference planes depends on the spatial and geometric position relationship of a component with its surroundings.

The reference planes are identical for a function sector. In other words, components or component groups and the surroundings have the same starting basis, Figure 8.
Fig. 8

7  Referenced Standards

VW 010 52
VW 010 59 T1
VW 010 77
VW 010 78
Vorgang:
Festhalten von Istwerten wenn das Fahrzeug nach den Haupt RPS Punkten aufgenommen wurde und mit der 3-2-1 Regel und nach der 4-2-1 Regel ausgerichtet wurde.

Grund:
Erprobung Fachhochschule Wob

Prüfergebnis:
Siehe Anlage.
# Teilbezeichnung: Kasten - Rohbau
# Teilnummer: 1K0.800.701
# Berichtsnummer: 574/04
# Fahrzeugtyp: VW 350

## Bereich: Ausrichtung

### Fahrzeug ID: 3-2-1 Regel

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<th>Soll</th>
<th>Ist</th>
<th>Abw.</th>
<th>TOL.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-370,0</td>
<td>-369,7</td>
<td>0,3</td>
</tr>
<tr>
<td>Y</td>
<td>-478,0</td>
<td>-479,0</td>
<td>-1,0</td>
</tr>
<tr>
<td>Z</td>
<td>150,0</td>
<td>150,4</td>
<td>0,4</td>
</tr>
</tbody>
</table>

RPS 4 fz

<table>
<thead>
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<th>Ist</th>
<th>Abw.</th>
<th>TOL.</th>
</tr>
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<tr>
<td>Y</td>
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<tr>
<td>Z</td>
<td>125,7</td>
<td>125,7</td>
<td>0,0</td>
</tr>
</tbody>
</table>

RPS 3 fz

## Zentrale Pilotheide
PM-Z11
Ersteller: B. Greinert

Meßdatum: 26.05.03
Prüfer(in): H. Nesser, H. Gaues

RPS
Seite 2 von 7
Deklarationsblatt 3 Zell Regel
**Bereich:**

**Fahrzeug ID:** 3-2-1 Regel

<table>
<thead>
<tr>
<th>SoS</th>
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<th>Abw.</th>
<th>TOL</th>
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<td>Z</td>
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**Lochung Federbeinaufnahme**

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<tr>
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<th>Ist</th>
<th>Abw.</th>
<th>TOL</th>
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<tbody>
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<td>Y</td>
<td>-240,2</td>
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<tr>
<td>Z</td>
<td>357,9</td>
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**Lochung Rahmen Montageplatte**

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**Loch Frontend KU**

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**Loch Frontend KL**

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**Zentrale Pilothalle**
PM-Z11. Kompetenz-Center Messtechnik
Ersteller: Meßdatum: 2002-09-25
Prüfer(in):

**PM - Z13**
WOB Halle 18
H.Gaede
Tel.: 05361-9 98346
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Lochung Bef Motorlager

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Lochung Montageplatte Stirnwend

---

**Zentrale Pilothalle**

PM-Z11 Kompetenz-Center Messtechnik

Ersteller:

Meßdatum: 2002-09-25

Prüfer(in):

Bleß

Seite 4 von 7

Datum: 22.09.2002

Fahrzeugtyp: VW350

Fahrzeug ID: 3-2-1 Regel

PM - Z13

WOB Halle 18

H. Gaede

Tel.: 05361-9 98346

© Volkswagen AG
**Teilbezeichnung:** Wagen fertig
**Teilnummer:** 1K4.000.000
**Berichtsnummer:** 574/04
**Fahrzeugtyp:** VW350

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**Tür vorn**

**Tür vorn**

**Tür vorn**

**Tür vorn**

**Tür vorn**

Zentrale Pilothele
PM-Z11, Kompetenz-Center Messtechnik
Ersteller:

**Messdatum:** 2002-09-25

**Prüfer(in):**
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Breitenpunkt Seitenteil

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Zentrale Pilothalle
PM-Z11, Kompetenz-Center Messtechnik
Ersteller:

Meßdatum: 2002-09-25
Prüfer(in):

Blatt04
Seite 6 von 7
Datum: Fachabteilung 3.1 Regel
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Zentrale Pilothele
PM-Z11, Kompetenz-Center Messtechnik
Ersteller:

Meßdatum: 2002-09-25
Prüfer(n):
Mit diesem Programm kann basierend auf der Finiten Elemente Methode der statische Festigkeitsnachweis von Trägern durchgeführt werden.

Der Geltungsbereich für das Berechnungsmodul Träger ist wie folgt definiert:

- **Belastungen:**
  - Axialkräfte (zentrisch, exzentrisch)
  - Radialkräfte
  - Streckenlasten
  - Biegemomente
  - Torsionsmomente

Bei der Berechnung des Trägers auf eingeschränkte Torsion gelten folgende Beschränkungen:

1. Der Träger soll einen konstanten Längsquerschnitt aufweisen.
2. Der Träger darf nicht mehr als eine Öffnung haben.
3. Als Stützen eines Trägers mit einer Öffnung können zwei Scharniere bzw. zwei Klemmen dienen.

- **Lagerstellen**
  - maximale Anzahl der Lager: 10
  - starre oder nachgiebige Lager (Vorgabe der Lagersteifigkeiten in den jeweiligen Freiheitsgraden)
  - Festlager, Loslager, Stütze, Feste Einspannung

- **Ermittlung der max. Durchbiegung**
- **Ermittlung der Neigungswinkel an den Lagerstellen**
- **optionale Berücksichtigung des Trägereigengewichts**
- **Ermittlung der Schnittgrößen für beliebige Trägerposition**
  (Momente, Spannungen, Durchbiegung, Neigungswinkel)
- **Ermittlung der statischen Sicherheit** $S_f$

- max. 50 Trägerabschnitte

**Verfügbare Trägerprofile:**

- DIN 1013 Ausgabe 11/1976 Warmgewalzter Rundstahl
- DIN 1025-1 Ausgabe 5/1995 Warmgewalzte schmale I-Träger
- DIN 1026 Ausgabe 10/1963 Warmgewalzter rundkantiger U-Stahl
Trägerberechnung

- DIN EN 10055 Ausgabe 12/95 Warmgewalzter gleichschenkliger T-Stahl
- DIN 1017 T1 Ausgabe 04/67 Warmgewalzter Flachstahl
- DIN 59410 Ausgabe 02/81 warmgefertigte rechteckige und quadratische Stahl-Hohlprofile
- DIN 2448 Ausgabe 02/81 nahtlose Stahlrohre
  - DIN 1013 Ausgabe 11/1976 Warmgewalzter Rundstahl
  - DIN 1025-1 Ausgabe 5/1995 Warmgewalzte schmale I-Träger
  - DIN 1026 Ausgabe 10/1963 Warmgewalzter rundkantiger U-Stahl
  - DIN EN 10055 Ausgabe 12/95 Warmgewalzter gleichschenkliger T-Stahl
  - DIN 1017, T1 Ausgabe 04/67 Warmgewalzter Flachstahl
  - DIN 59410 Ausgabe 02/81 warmgefertigte rechteckige und quadratische Stahl-Hohlprofile
  - DIN 2448 Ausgabe 02/81 nahtlose Stahlrohre

Eingabedaten:

- Werkstoffbezeichnung = AlMgMnF18
- Werkstoffnummer = 3.35
- Zugfestigkeit Rm = 180 N/mm²
- Streckgrenze Re = 80 N/mm²
- Elastizitätsmodul E = 70000 N/mm²
- Dichte ρ = 2.7 kg/dm³
- Berechnung der Durchbiegung für Stelle x = 320 mm
- Berücksichtigung Eigengewicht (nein/ja) nein
- Betriebstemperatur θ = 20 °C
Trägerberechnung

Trägerabschnitte

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<th>Wx cm³</th>
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Lager

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Axialkräfte Fax

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<th>Betrag Fax N</th>
<th>Radius r mm</th>
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<td>0.384</td>
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<tr>
<td>2</td>
<td>340</td>
<td>25</td>
<td>0</td>
</tr>
</tbody>
</table>

Ergebnisse:

Gesamtlänge der Träger \( l_g = 340.00 \) mm
Gesamtmasse der Träger \( m = 0.62 \) kg
Position des Schwerpunktes auf der x-Achse \( x_s = 201.550 \) mm

Verwendete Trägerprofile

Querschnitt - Nr. 1 = Rund 63 DIN 1013-AlMgMnF18
Querschnitt - Nr. 2 = Rund 22 DIN 1013-AlMgMnF18
Querschnitt - Nr. 3 = Flach DIN 1017-AlMgMnF18 - 40x40

Lagerreaktionskräfte

Radialkraft \( Y \)-Achse \( Fr, \) N = 0.0
Res. Axialkraft \( X \)-Achse \( Fax, \) N = -25.4
Neigungswinkel \( \alpha = 0.000000 \)

Belastungen

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</tr>
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<tbody>
<tr>
<td>Result. max. Biegemoment</td>
<td>( M_{bmax} = 0.384 ) Nm = 0.0 mm</td>
<td></td>
</tr>
<tr>
<td>Result. max. Biegespannung</td>
<td>( \sigma_{bmax} = 0.366 ) N/mm² = 8.0 mm</td>
<td></td>
</tr>
<tr>
<td>Result. max. Schubspannung</td>
<td>( \tau_{max} = 0.000 ) N/mm² = 8.0 mm</td>
<td></td>
</tr>
<tr>
<td>Result. max. Zug-Druckspan.</td>
<td>( \sigma_{zdmax} = 0.067 ) N/mm² = 8.0 mm</td>
<td></td>
</tr>
</tbody>
</table>
### Trägerberechnung

Result. max. Vergleichsspg. \[ \sigma_{\text{vmax}} = 0.433 \text{ N/mm}^2 = 8.0 \text{ mm} \]

Min. Sicherheit geg. Fließen \[ S_f = 185.0 = 8.0 \text{ mm} \]

Durchbiegung \[ y_{\text{max}} = -0.025350 \text{ mm} = 340.0 \text{ mm} \]

Winkel der max. Durchbiegung \[ = 0.007367^\circ = 340.0 \text{ mm} \]

Berechnungsergebnisse für Stelle \( x = 320 \text{ mm} \):

- Biegemoment \( M_{bx} = 0.384 \text{ Nm} \)
- Biegespannung \( \sigma_{bx} = 0.036 \text{ N/mm}^2 \)
- Schubspannung \( \tau_{tx} = 0.000 \text{ N/mm}^2 \)
- Zug-Druck-Spannung \( \sigma_{zd\text{x}} = 0.016 \text{ N/mm}^2 \)
- Vergleichsspannung \( \sigma_{vx} = 0.052 \text{ N/mm}^2 \)
- Sicherheit gegen Fließen \( S_{fx} = 1541.80 \)
- Durchbiegung \( y_x = -0.022778 \text{ mm} \)
- Winkel der Durchbiegung \( = 0.007367^\circ \)

### Berechnungsergebnisse für Querschnittsabschnitt:

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<th>Biegemoment</th>
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<td>( y )</td>
<td>( M_b )</td>
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<td>184.96</td>
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</table>

**Hinweise:**

- Mitteilungen bei der Berechnung auf die eingeschränkte Torsion:
  1) Der Träger soll einen konstanten Längsquerschnitt aufweisen;
  2) Der Träger darf nicht mehr als eine Stützweite haben;
  3) Als Stützen eines Trägers mit einer Stützweite können zwei Scharniere bzw. zwei Klemmen dienen.
Trägerberechnung

Querkraftverlauf X - Y - Ebene

Biegemomentenverlauf X - Y - Ebene
Trägerberechnung

Biegespannungsverlauf X - Y - Ebene

Schubspannungsverlauf (X - Y Ebene)
Trägerberechnung

Winkel der Durchbiegung X - Y - Ebene

Sicherheit gegen Fließen
(Ausschnitt: $S_f = 5 \times S_{f_{\text{min}}}$)
Herrn
Thilo Lichtenberg
Oedesser Straße 14
31234 Edemissen

Ihre Erfindungsmeldung Nr. 2005/0745
"Flexmess II (Manuelle Messaufnahme)"
Unser Zeichen: K 13893 IP

Sehr geehrter Herr Lichtenberg,

wir freuen uns Ihnen mitteilen zu können, daß wir zu Ihrer o. g. Erfindung eine
Schutzrechtsanmeldung eingereicht haben. Ein Exemplar der Anmeldeunterlagen
finden Sie diesem Schreiben beigefügt.

Sofern uns noch kein konkreter Hinweis auf die Benutzung des Gegenstandes der
Schutzrechtsanmeldung im Volkswagen-Konzern vorliegt, bitten wir Sie um
Benachrichtigung, sobald Ihre Erfindung in der Serie realisiert wird. Für diesen Fall
bitten wir Sie zudem um die Bereitstellung von Unterlagen (Bauteilnummern,
Bauteilzeichnungen, Schaltplänen oder sonstiges), mit denen wir die Benutzung
überprüfen können.

Für die zum Schutzrecht angemeldete Erfindung zahlen wir Ihnen als Ausgleich für
den Abkauf Ihrer Rechte nach §§ 14, 16 ArbnEG den vereinbarten Betrag in Höhe von

der Ihnen alsbald unter Berücksichtigung der gesetzlichen Abzüge auf Ihr Konto
überwiesen wird. Sollte sich Ihre Bankverbindung geändert haben, bitten wir um
eine entsprechende Mitteilung.

Bitte senden Sie ggf. die Bankverbindung an die Abt. 1574 (Entgeltberechnung).
Für eine sachgerechte Bearbeitung bitten wir Sie um Erledigung innerhalb von
sechs Wochen.

Mit freundlichen Grüßen
i.A.

Schiefer

Anlage

C: FRE-2
Flexible Measurement System for Modern Automobile Production

T. Lichtenberg¹, H. Holdack-Janssen¹, T. van Niekerk²

¹University of Applied Sciences Braunschweig/Wolfenbüttel, Institute of Vehicle Construction Wolfsburg, Germany
²Nelson Mandela Metropolitan University, Department of Mechanical Engineering, Port Elizabeth, South Africa

Abstract
To stay competitive and to be able to sell high-class products in the modern automobile production it is absolutely necessary to check the quality peak of a manufactured vehicle. The normal measurement strategy to check the quality standard of a produced car via complex measurement systems in the actual series production is an immensely time and money consuming process. Furthermore the measurement systems are fixed on a certain place and a flexible measurement of a produced vehicle is very difficult to realize. Therefore, in this project a measurement system regarding all current guidelines was developed, with which it is possible to measure a completely assembled vehicle wherever and whenever you want. For the first time it gives the possibility to measure the vehicle from the first prototype in the production up to the finished car at the customer.

Keywords
Flexible measurement, digital photogrammetry, quality control

1 INTRODUCTION
The automotive industry today is placing an ever increasing demand on dimensional tolerances, with the quality requirements of the customer constantly rising, and vehicles now consisting of more and more parts and components.

Furthermore, development times have become shorter and the costs involved in development are rising from year to year.

In order to guarantee a safe series production, the correct locations of all attachments have to be examined and defective equipment in the car body has to be eliminated, right from the beginning stages.

Nowadays this is done via complex measurements of the respective vehicle parts with all measured elements being compared to the recorded data (example, CAD drawings) of the construction. Errors can be detected in direction, position and size.

Thus, improvements of production methods can be accomplished, and errors can be eradicated, more easily.

Additionally a measurement of the produced vehicle in the after-sales service is necessary when there are any problems or errors in the product directly at the customer.

The biggest problem to reach and to check the quality standard is caused by the current guidelines, which means that to define a measurement, reference points (RPS) have to be established. These RPS-Points are the basic premise for every kind of measurement, because with these coordinates the object is aligned in the 3-D space. Furthermore these points are the groundwork for the coordinate system. With these RPS-coordinates the object-orientated coordinate system is mounted over the whole object, and every point gets a known position in relationship to the constructed CAD.

These basal points of an assembled automobile are situated in the front and rear chassis rails of the vehicle, thus are invisible to every kind of measurement.

Figure 1 - RPS Situation VW Golf A5
Therefore it isn’t possible to measure a completely assembled vehicle in a flexible way when it stands on the ground. With no mobile present-day measurement system it is possible to localize the hidden points in the chassis rails when the vehicle stands in a realistic condition on the wheels.
2 TODAY'S SITUATION

2.1 Strategy
The normal way in the production to check the quality standard of a completely assembled vehicle is to use stationary coordinate measuring instruments. The whole system consists of three tactile sensors. (cp. Figure 2)

The strategy to localise the buried RPS-Points in the chassis rails is, to drive the vehicle over a cavity. In this cavity is one of the tactile sensors with which it is possible to maintain the necessary coordinates of the RPS-Points. The measurement procedure is that you must detect the coordinates of the RPS-Points with the sensor from under the vehicle at first. The result is than the positions of the RPS-Points in the machine-orientated coordinate system. After that you can align the whole car in the three-dimensional space, and you can mount the object orientated coordinate system. In this coordinate system every point in and outside the vehicle has an exact precise position. So after that you can measure every point of interest with the two tactile sensors outside the cavity and compare the coordinates with the CAD.

Figure 2 - co-ordinate measurement system

With this system you are able to benchmark the whole vehicle with an inspection of the quality and checking the right position of every part. But this strategy gives some disadvantages. The whole measurement process is a very time-consuming process. For a Golf A5 the complete procedure takes up to 1,5 days. Furthermore the measurement is a stationary process that means the vehicle has an exact precise position. So after that you can measure every point of interest with the two tactile sensors outside the cavity and compare the coordinates with the CAD.

2.2 Fixed on a tool
Another way in the industry to measure all parts of a constructed vehicle as an assembly is to fix the car on a tool. In Figure 3 the basic principle is shown. To avoid the third tactile sensor and the cavity for the co-ordinate measurement system, the whole vehicle is surveyed on a tool.

Figure 3 - Golf A5 fixed on a tool

So the chassis rails and therefore the RPS-coordinates are in a defined position (comparable with CAD) and the coordinates are known for the measurement and the alignment.

2.3 Problems
The today’s situation is an approved method to check the car in the production process. But as said before there are some disadvantages. To fix the vehicle on the tool the car must be disassembled and the vehicle is not in a realistic condition. When the vehicle is measured on a tool it is not in that condition which the customer sees.

Generally it is very complicated to do a continuous measurement in the whole process from the first prototype up to the finished product at the customer. But in the modern automobile production it is absolutely necessary to have a benchmark of the whole vehicle with regard to the current guidelines wherever and whenever you want.

3 BASIC IDEA

3.1 Concept
To realize a flexible measurement wherever and whenever you want, the idea and the basic concept is the mechanical dislocation of the relevant invisible points for the measurement. An established system pertaining to other observable points outside the vehicle is used. These points have a known relation to the invisible RPS-Point in the chassis rails. With this relation it is possible to locate the required coordinates of the main reference points. This system which is built in cooperation with the Volkswagen Company Wolfsburg, Germany is referred to as FlexMess.

3.2 Measurement system
For this flexible measurement project the TRITOP System from the company GOM mbH Braunschwig / Germany is used. TRITOP is an industrial optical measurement system which is used for highly non-contact measurement of 3D-coordinates and discrete object points, adapter and features. TRITOP is a mobile system based on the photogrammetry.
Relevant object points are identified with markers, adapters or markings and the object, in this case a completely assembled vehicle, is recorded by a high-resolution photogrammetric camera from different directions.

Based upon these digital images, the TRITOP-Software automatically calculates the 3D coordinates of the adhesive markers and adapters. In addition object features can be defined. TRITOP is used for objects up to and over 20m. The system achieves measuring accuracies of 0.02mm per 1m object size. The TRITOP Software can handle several thousands measuring points and allows the use of different recording devices.

3.3 Hardware
To be able to locate the buried reference points on an assembled vehicle, it is necessary to have an established system pertaining to other observable points outside the vehicle.

In this project the basic concept of the mechanical dislocation of the relevant points for the measurement will be used.

With this relation it is possible to locate the required coordinate of the main reference points (RPS).

To maintain the necessary coordinates by using the points on the carbon tubes a special add-on to the TRITOP software was developed and programmed. With this macro it is possible to maintain the RPS coordinates in an automatic way when only the points outside the car are visible to the system.

4 TEST STAGE
4.1 Measurement procedure
A complete measurement with the TRITOP System and the FlexMess hardware functions as follows.

Because of the fact that the FlexMess is dismountable – means that you can screw off the carbon tubes from the chuck for the transport – the hardware must be calibrated before starting the measurement and mounting the FlexMess under the vehicle. This is done with a special calibration plate. On this plate you can put the 4 components of the FlexMess when they are built together. Then you must take some photos with the TRITOP camera.

For this calibration another macro was programmed in the software, which is able to locate the actual position from the points on the tubes in relation to the point in the chucks which is in the measurement at the car the required RPS coordinate. So after this calibration the ratio between all the points on the hardware is determined. After that action you can mount the 4 components directly in the RPS holes in the chassis rails under the car. After preparing the points of interest on the vehicle with markers or taepelines the real measurement could start. The whole vehicle, especially the parts where the FlexMess is visible is recorded freestyle by the digital camera.
When there are enough photos, they can be sent directly to the computer where the TRITOP software is installed. Now the special add-on must be used.

Figure 8 - screenshot TRITOP system with FlexMess in the analysis software

While indicating the visible points from the FlexMess in the photos which are shown in the program, the software calculates automatically the invisible RPS-coordinates in the 3-D space. After that procedure you have the necessary coordinates to align the vehicle and to mount the object orientated coordinate system all over the vehicle. Now every point of interest could be compared to the CAD and a statement of the quality standard could be given and malfunction sources could be localized.

4.2 Data interpretation

To be able to judge, to compare and to make use of the results of the measurements that will be done with the FlexMess a test stage at the Volkswagen Company was done.

Figure 9 - Test stage at Volkswagen with both systems

That happened in several measurements with both systems (co-ordinate measurement instrument vs. FlexMess with TRITOP). First, every vehicle was measured three times with the old system – after that the same car was measured with the newly developed system also three times. With the results of these measurements from several cars the basis for the calculation of the specificity was created.

In these measurements it was shown, that it is generally possible to measure a completely assembled vehicle in a flexible way when it stands on the ground. In Figure 10 five of these measurements are diagrammed. Here is shown the average deviation from the FlexMess with respect to the co-ordinate measurement instrument (cmm).

Figure 10 - interpretation of 5 measurements

In several other measurements it was shown, that the FlexMess in combination with the TRITOP System gives a maximum deviation to the conventional measurement strategy from 0.3mm. So it is possible to measure a completely assembled vehicle wherever and whenever you want in an acceptable accuracy.

5 ADVANTAGES

To be able to measure the finished car both in the whole production process and directly at the customer gives a lot of advantages:

- Immensely time saving process with a simple operation
- Flexible with little required space
- Measurement from the complete vehicle state from the customer view in a realistic condition
- Continuous measurement from the start of production (body shop) up to the customer
- No cost-intensive measurement tools for the complete vehicle necessary
- No baseplates for the measurement instruments necessary
- Possibility of application in the after sales service
- Applicable for every platform in the Volkswagen company

6 SUMMARY

This document presents the possibility of a flexible vehicle measurement in the modern automobile production in observance to current guidelines from the Volkswagen Company. The intention is to enable a complete measurement wherever and whenever you want.
7 ACKNOWLEDGMENTS
We acknowledge the support of the staff of the Volkswagen Company in Wolfsburg / Germany, Department Anlauf- und Prozessoptimierung, and in particular the Institute of vehicle construction in Wolfsburg / Germany for their help in the whole measurement project.

8 REFERENCES


9 BIOGRAPHY
Thilo Lichtenberg studied at the Fachhochschule Wolfsburg in Germany (University of Applied Sciences) with the special subject, construction of vehicles. He carried out a practical semester at Skoda Auto a.s., Mlada Boleslav, Czech Republic at the exhaust development department. Within the diploma thesis “Construction of a measurement tool for the product optimization” at the Volkswagen Company he attained the qualification of diplom Engineer (Dipl.-Ing.[FH]). Since April 2005 he is the head of the project “CarMetric - Measurement in the Volkswagen Car Production” at the Institute of Vehicle Construction in Wolfsburg.

Prof. Dr.-Ing. Hinrich Holdack-Janssen obtained his Doctor Degree in Technical Sciences from the University of Hannover / Germany. In 1994 he was appointed Professor in vehicle climatisation at the University of applied Sciences in Wolfsburg, Germany.
Appendix F single values from the certification

### MESSUNG-IM-AUSBgebautem-Zustand-STIFT0

**Zentrierung** | X [mm] | Y [mm] | d [mm] | Ebenenprojektionen | PXPZ1 [°] | PYPZ1 [°] | PXPZ2 [°] | PYPZ2 [°] | PXPZ3 [°] | PYPZ3 [°]
--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
1) | -0,0135 | 0,0336 | 0,0362 | 1) | 89,81028 | 89,82500 | 90,21889 | 89,92667 | 90,02444 | 90,09611
2) | -0,0127 | 0,0352 | 0,0374 | 2) | 89,81611 | 89,82222 | 90,21500 | 89,92972 | 90,02306 | 90,09167
3) | -0,0119 | 0,0387 | 0,0405 | 3) | 89,80389 | 89,82694 | 90,22111 | 89,92222 | 90,02694 | 90,10028
4) | -0,0138 | 0,0385 | 0,0409 | 4) | 89,79750 | 89,82917 | 90,22583 | 89,91833 | 90,02861 | 90,10472
5) | -0,0133 | 0,0370 | 0,0393 | 5) | 89,80417 | 89,82750 | 90,22583 | 89,92783 | 90,02694 | 90,09944

**Abweichung** | X [mm] | Y [mm] | d [mm] | Ebenenprojektionen | PXPZ1 [°] | PYPZ1 [°] | PXPZ2 [°] | PYPZ2 [°] | PXPZ3 [°] | PYPZ3 [°]
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2) | 0,0008 | 0,0016 | 0,0018 | 2) | 0,00583 | -0,00278 | -0,00389 | 0,00306 | -0,00139 | -0,00444
3) | 0,0016 | 0,0051 | 0,0053 | 3) | -0,00639 | 0,00194 | 0,00222 | -0,00444 | 0,00250 | 0,00417
4) | -0,0003 | 0,0049 | 0,0049 | 4) | -0,01278 | 0,00417 | 0,00694 | -0,00833 | 0,00417 | 0,00861
5) | 0,0002 | 0,0034 | 0,0034 | 5) | -0,00611 | 0,00250 | 0,00361 | -0,00389 | 0,00250 | 0,00333

**Mittel** | 0,0006 | 0,0038 | 0,0039 | Mittel | -0,00486 | 0,00146 | 0,0222 | -0,00340 | 0,00194 | 0,00292
**StdAbw** | 0,008 | 0,0016 | 0,0016 | StdAbw | 0,00777 | 0,00298 | 0,00453 | 0,00474 | 0,00236 | 0,00543
**Spanne** | 0,0019 | 0,0051 | 0,0053 | Spanne | 0,01661 | 0,00694 | 0,01083 | 0,01139 | 0,00556 | 0,01306

### MESSUNG-IM-AUSBgebautem-ZUSTAND-STIFT5

**Zentrierung** | X [mm] | Y [mm] | d [mm] | Ebenenprojektionen | PXPZ1 [°] | PYPZ1 [°] | PXPZ2 [°] | PYPZ2 [°] | PXPZ3 [°] | PYPZ3 [°]
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3) | -0,0033 | -0,0311 | 0,0313 | 3) | 89,77056 | 89,83333 | 90,23389 | 89,90139 | 90,05056 | 90,11306
4) | -0,0019 | -0,0264 | 0,0265 | 4) | 89,76417 | 89,83583 | 90,24167 | 89,89639 | 90,05194 | 90,11861
5) | -0,0067 | -0,0277 | 0,0285 | 5) | 89,76306 | 89,83194 | 90,23750 | 89,89222 | 90,05333 | 90,12139

**Abweichung** | X [mm] | Y [mm] | d [mm] | Ebenenprojektionen | PXPZ1 [°] | PYPZ1 [°] | PXPZ2 [°] | PYPZ2 [°] | PXPZ3 [°] | PYPZ3 [°]
--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
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### MESSUNG-IM-AUSGEBAUTEM-ZUSTAND-STIFT10

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**Mittel**

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| StdAbw | 0.0026  | 0.0096 | 0.0062 |
| Spanne | 0.0071  | 0.0212 | 0.0176 |

**MESSUNG-IM-AUSGEBAUTEN-ZUSTAND-STIFT20**

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Standardabweichung | 0,0006 | 0,0036 | 0,0001 | 0,0018 |
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