

## RECOMMENDATIONS FOR AN ACCEPTANCE AND VERIFICATION TEST OF OPTICAL 3-D MEASUREMENT SYSTEMS

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### ABSTRACT

The paper reports on the development of a new guideline for acceptance and verification of optical 3-D measuring system, e.g. photogrammetric systems or fringe-projection systems. The work has started in 1996, initiated by the working group "Close-range Photogrammetry" of the German Society for Photogrammetry and Remote Sensing (DGPF) and by the working group "Co-ordinate measuring machines" of the German Society for measurement and automatic control (VDI/VDE-GMA). A new VDI working group has been established joining almost all important users and manufacturers of optical 3-D systems. The new guideline VDI 2634 proposes procedures for the acceptance of point-wise photogrammetric systems (part 1), and area-based surface measurement systems (part 2). For both groups of systems the "error of length measurement" has been selected as the most significant criterion for an over all performance assessment. Surface measurement systems shall also be checked according to "error of flatness measurement" and "probing error". Suitable calibrated reference objects are proposed as well.

### 1 INTRODUCTION

#### 1.1 State of the art

Optical 3-D measuring systems are increasingly used in industrial applications. Their major benefits are given by non-contact probing of the object and in their mobility, i.e. objects do not have to be transported to the measuring systems but, can be measured directly in the field or even during production process.

For a longer period industrial applications were limited to the use of manual and automated theodolite measuring systems (Staiger 1992), and large-format analogue photogrammetric systems (Fraser & Brown 1986, Dold 1997). These techniques were mainly used for the measurement of large objects (aircraft industry, production tools etc.) due to the lack of alternative measuring methods. Relative accuracies of those systems varied between 1:100.000 and 1:250.000. However, the verification of these results is not trivial because neither suitable reference objects for large measuring volumes (>10m) nor more accurate alternative measuring methods are available.

Since around 1995 the development of high-resolution digital cameras has lead to an increased use of digital photogrammetric systems in industry (Atkinson 1996, Luhmann 2000). They enable the fast and on-line data flow from image acquisition to the final result in the workshop. One can mainly distinguish between off-line systems (object targeting, sequential image acquisition, subsequent data processing) and on-line systems (tactile probing, simultaneous multi-image acquisition, integrated real-time point determination). Due to limitations of image format and pixel resolution of digital cameras (approx. 3000 x 2000 to 7000 x 4000 pixel) high accuracies can only be achieved by use of suitable targets that can be measured automatically to sub-pixel accuracy.

In addition to classical point-wise triangulation systems, area-based measuring systems have been established that allow the three-dimensional surface reconstruction by projection and imaging of suitable patterns. Pure photogrammetric methods (e.g. Schewe 1987, Wrobel 1987) have not yet been generally accepted while fringe projection methods are widely used for objects of less than 1m dimension. However, larger objects or more complex surfaces can only be

measured if separately acquired object patches are matched to a global surface model. The required spatial orientation of these patches can either be performed by mechanical drives (robot, CMM), or indirectly by photogrammetric resection using a certain number of tie or control points.

There are, as yet, no standardized methods for acceptance and verification of these novel optical 3-D measuring systems as they are available for conventional 3-D coordinate measuring machines (CMM). The existing guidelines VDI 2617 and ISO 10360 have been developed for use of cartesian CMMs and do not consider the special requirements of triangulation systems. In contrast to stationary cartesian CMMs many optical systems are characterized by a high degree of mobility, free configuration of measuring sensors (e.g. camera stations) and a very variable measuring accuracy (e.g. depending on scale and system setup). In addition off-the-shelf reference objects such as ball plates, step gauges (Figure 1) can only be used for tactile photogrammetric systems which are working similar to CMMs (Schwenke et al. 1998).

On the other hand, there is a growing need for cost-advantageous, simple and fast methods to assess the overall measuring accuracy, especially in the field of modern production metrology where the test procedures are no longer the responsibility of specialised metrologists but are increasingly integrated into the manufacturing process. Therefore a working group was set up in order to develop a guideline for acceptance and verification of optical 3-D measuring systems.

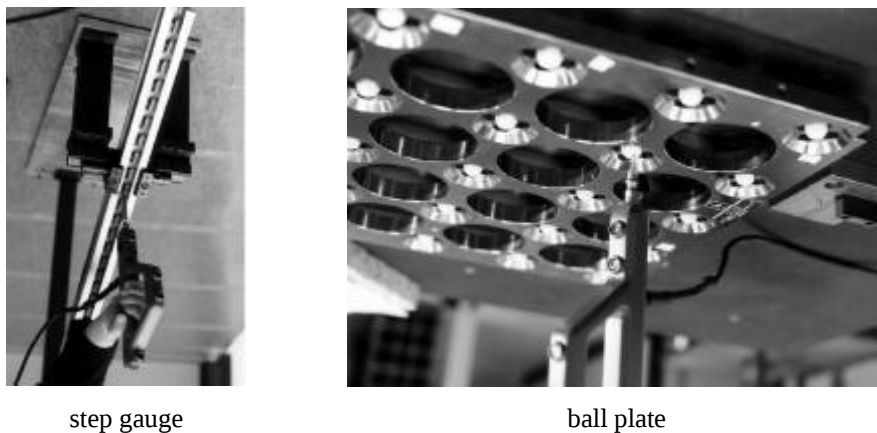


Figure 1: reference objects for CMM verification

## 1.2 Working Group “Optical 3-D Measurement Systems”

In 1996 the working group “Close-range Photogrammetry” of the German Society for Photogrammetry and Remote Sensing (DGPF) and the working group “Co-ordinate measuring machines” of the German Society for Measurement and Automatic Control (VDI/VDE-GMA) have initiated a joint working group that shall develop a standard guideline for acceptance and verification of optical 3-D measuring systems. This working group (VDI FA 3.32, chaired by the authors) has gathered more than 30 experts of well-known system manufacturers, universities and users who are dealing with this topic (<http://www.vdi.de./gma/fa-3-32.htm>). Since 1999 this working group is, due to its technical importance, a major group in the VDI/VDE-GMA organisation. In the end of 1999 two parts of the new guideline VDI 2634 have been finished that propose acceptance and verification procedures for point-wise and area-based optical measuring systems.

## 2 OPTICAL 3-D MEASURING SYSTEMS

Nowadays imaging, optical 3-D measuring systems are used in a large number of applications in production industries such as automotive industry, shipbuilding or large machine building industry, microwave antenna and building industry, aircraft and spacecraft manufacture. The systems work on the principle of triangulation. According to their probing principle industrial optical 3-D measuring systems can be distinguished in two major groups:

- Systems for point measurement
- Systems for surface measurement

The functional principle will be discussed in the following chapters.

## 2.1 Systems for Point Measurement

### 2.1.1 Off-line Measuring Systems

Using one single camera the object is recorded sequentially with an unlimited number of images. After image acquisition measurement of image points (tie and control points, coded targets) and subsequent image orientation (bundle adjustment) are performed. If the object is completely represented by these image points then all required object co-ordinates are given right after bundle adjustment. Any additional object points have to be determined in a subsequent process using pre-orientated images (e.g. spatial intersection). The object may not change due to movements or deformations. Usually it is assumed that the camera has a constant interior orientation during the whole process of image acquisition (it is known that many still-video cameras change lightly their interior orientation in short intervals).



Figure 2: Off-line image acquisition (Imetric)

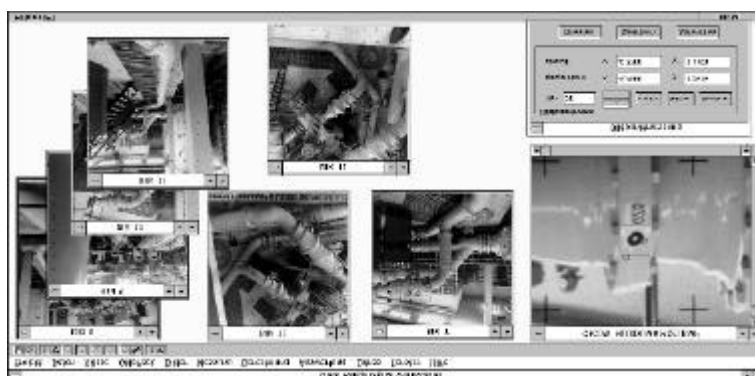


Figure 3: Off-line image processing (Rollei CDW)

### 2.1.2 On-line Measuring Systems

Most tactile photogrammetric on-line systems are using a passive measuring probe that consists of a probing tip and a number of calibrated targets. Usually the measuring probe is driven manually onto the object surface. Using a minimum of two synchronized cameras the 3-D co-ordinates of the targets can be measured leading to the spatial position of the probing tip. During measurement the spatial relation between measuring system (e.g. the two cameras) and the object must be stable or, has to be determined periodically by additional measurements of independent control points. Figure 4 shows some examples of on-line systems.

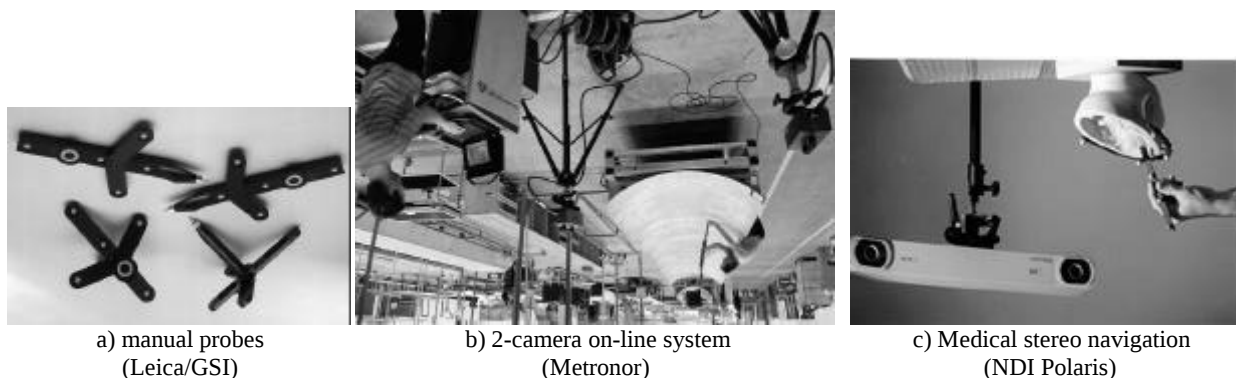


Figure 4: On-line measuring systems

In most cases two cameras are used. As it is known from standard stereo photogrammetry the accuracy of object co-ordinates is mainly influenced by image measuring accuracy, camera configuration (distance-to-base ratio) and image scale. In addition the non-systematic error of tactile probing is existing.

Figure 5 shows an active tactile photogrammetric on-line system that integrated three digital cameras inside of the measuring probe. These cameras are observing one or more signaled point fields (panels). By automatic measurement and identification of these control points the spatial position and orientation of the measuring probe is determined (Sinnreich & Bösemann 1999).



Figure 5: On-line measuring system with active probe orientation (AICON Procam<sup>3</sup>)

A number of additional on-line systems exist for special applications where a well-defined measuring task can be solved by a fixed setup of a number of cameras. For instance, the measurement of brake pipes, the control of production tools or robot calibration can be mentioned.

## 2.2 Systems for Surface Measurement

### 2.2.1 Photogrammetric Measuring Systems

Photogrammetric systems for the reconstruction of sculptured surfaces are normally based on two or three images of the surface, which must consist of a structure that enables the following image matching procedure. As a standard case two cameras are used in stereoscopic mode, e.g. for the measurement of car bodies (Figure 6). In principle the number of images is not restricted if multi-image matching is used (example in Figure 7). If the surface is not textured, an artificial structure has to be projected. The spatial orientation between projected pattern and object surface must be stable over the period of image acquisition. The measuring volume is not limited by the method.

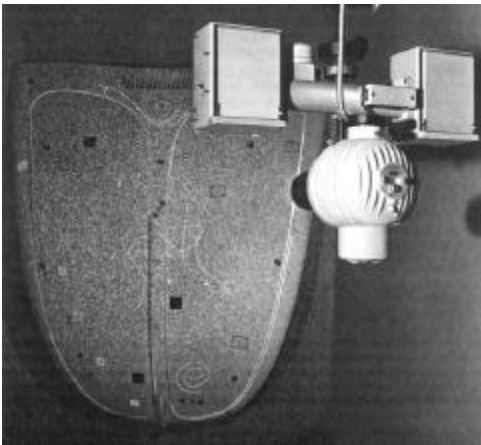


Figure 6: Photogrammetric surface measurement system Zeiss Indusurf (stereo camera and pattern projector)

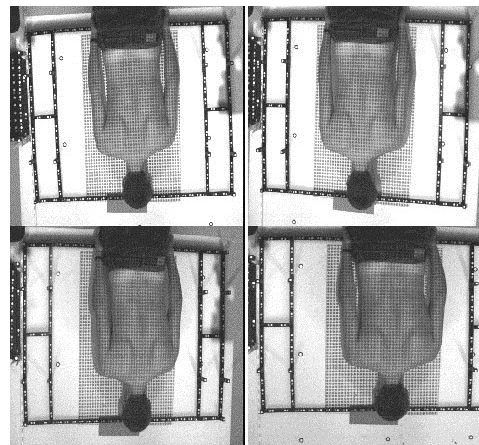


Figure 7: Multi-image configuration for back surface reconstruction (Gäbel 1993)

### 2.2.2 Fringe Projection Systems

Measuring systems based on fringe projection are using at least one projection unit and one CCD camera. In sequential mode different fringe pattern are projected onto the object surface, and the related picture is acquired by one or more cameras. Then each object point is calculated as an intersection of the image ray and the corresponding projection ray of an oriented fringe projector. While the method of coded light approach leads to unique 3-D co-ordinates of each point, the classical fringe projection yields phase differences that are only unique up to  $\pi$ . Phase differences have to be transformed into absolute height values (Figure 8). Therefore state-of-the-art surface measuring systems often enable both fringe projection methods. A complete measurement can be performed within a few seconds. The measurement volume is normally limited to less than 1m.

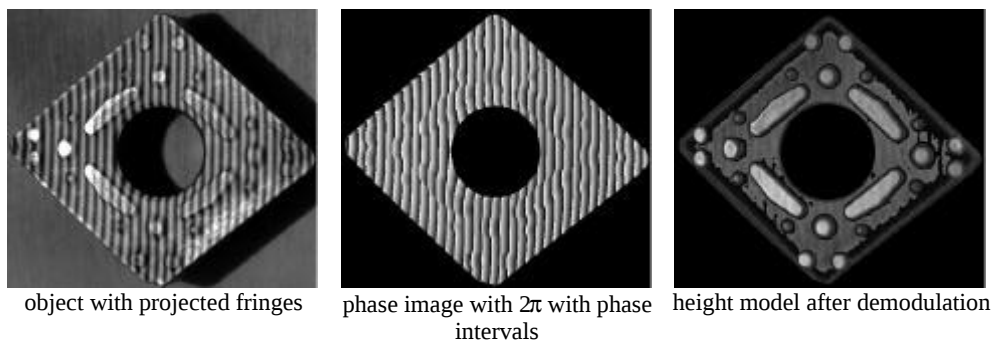


Figure 8: Fringe projection with phase-shifting (Breuckmann 1993)

### 2.2.3 Hybride Measuring Systems

Hybride surface measuring systems consist of a fringe projection system whose spatial orientation is determined by photogrammetric methods as mentioned in chapter 2.1. This methods enables the measurement of large complex surfaces. Control points are required in order to calculate photogrammetric orientation as well as transformation of single point clouds into a common workpiece co-ordinate system (Winter & Reich 1997). Especially the last step of point cloud matching may yield to discrepancies if the orientation of individual image scenes is uncertain or if point clouds are consist of inhomogeneous point distributions.

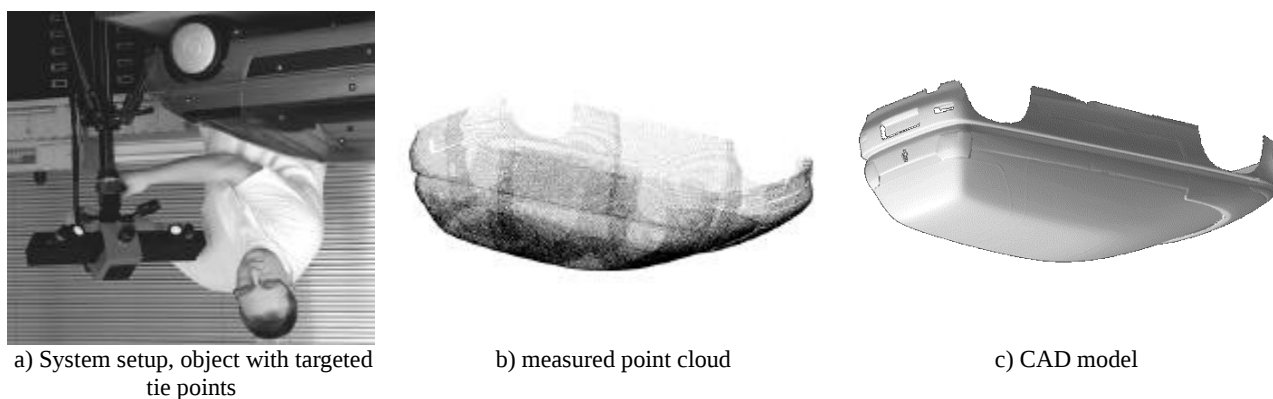


Figure 9: Hybride surface measurement system (GOM ATOS)

## 3 REQUIREMENTS FOR PERFORMANCE VERIFICATION

An ideal test procedure for checking the over-all geometrical performance of measuring systems has to met a number of requirements. The test

- has to be sensitive to all system-specific error components
- should produce results, that are easy to interpret
- is supposed to be cheap, easy, and fast to handle
- should be in conformity with existing standards and guidelines as fas as possible
- must provide traceability (link to the definition of the unit “metre”)
- must provide a mechanism by which a global go/no-go decision on the performance of the system can be made

Due to practical experiences (Schwenke et al.) and world-wide tendencies we can state that these requirements can best fulfilled with the aid of calibrated reference objects. This seem to be the only way to a comprehensive verification of sensors, hard- and software and algorithms as well, without the need to have detailed knowledge about specific functionality or error budget of the system (black box procedure).

It is important to distinguish between methods for calibration and uncertainty assessment of measuring systems and those procedures used for acceptance and verification. The methods for calibration and uncertainty assessment have to combine additionally task-specific error sources such as environmental conditions, measuring task, measuring strategy and object characteristics. This lead to the problem that comparisons about the accuracy of different systems are difficult to achieve. Therefore, for acceptance and verification tests, the measuring task, measuring strategy and characteristics of reference objects are specified as described in the following.

## 4 ACCEPTANCE TEST AND VERIFICATION TEST

The acceptance test is used for the comparison of different measuring systems and for checking the system’s accuracy specified by the manufacturer. The verification test enables the user to check periodically the principle performance of his system during the production process on his own responsibility. Acceptance and verification tests are based on standardized measuring tasks in order to test specific accuracy parameters.

## 4.1 Principle

The proposed acceptance test is based on calibrated reference objects that are measured like ordinary workpieces. Informations about the current status and performance of a measuring system is derived from the differences between measured and calibrated values of reference objects.

As optical 3-D measuring systems use different methods of probing (see chapter 2), different quality parameters are defined to check the systems:

- for systems with point-wise probing
  - a) the maximum error of length measurement
- for systems with area-based probing
  - a) the maximum probing error
  - b) the maximum error of length measurement
  - c) the maximum error of flatness measurement

The error of length measurement was selected as quality parameter because all error components have an effect on length measurement at least proportionately. Further reasons are: (a) That error is introduced as quality parameter on international level (ISO 10360), so the result of the proposed test is compatible to other approved test procedures. (b) Length measurement is a simple but nevertheless important measuring task, and deviations of length measurements are easy to interpret. Thus the error of length measurement is very suitable for comparative studies.

Probing error and error of flatness measurement are proposed with respect to specific behavior of area-based surface measurement systems and their practical use.

### 4.1.1 Reference objects

Different reference objects are proposed: one-dimensional scale-bars with several circular targets are used for point-wise probing systems; spheres and ball bars (example in Figure 10) are used for the assessment of the length measurement error and the probing error of area-based systems; cuboid objects with plane surfaces are used for the assessment of the error of flatness measurement. Shape and length of reference objects must be calibrated within 1/5 of the permissible error limit that has to be verified.

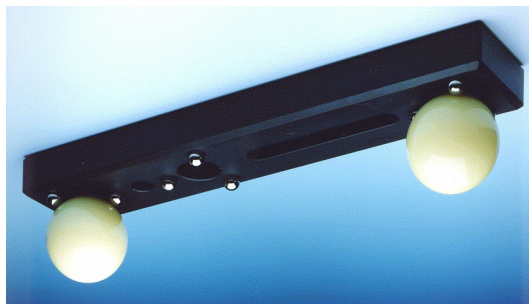


Figure 10: Ball bar with exchangeable spheres

### 4.1.2 Procedure

Before starting an acceptance test it must be ensured that the measuring system is running according to the technical specifications of the system manufacturer, e.g. environmental conditions, warm-up time, specific sensor configurations). Otherwise comparisons between systems and accuracy assessment can not be guaranteed.

#### Systeme with point-wise probing

The maximum permissible error of length measurement is tested along a minimum of seven different measuring lines, distributed in the measuring volume according to Figure 11. In each line five different lengths should be measured whereby at least one distance should have a length of 2/3 of the spatial diagonal of the measuring volume, which is proposed to have a dimension of 2 m x 2 m x 1,5 m.

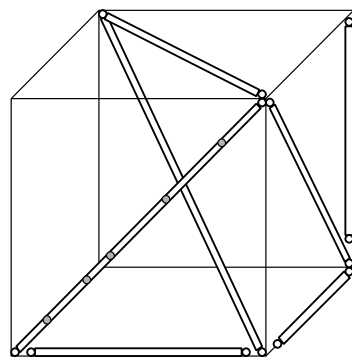


Figure 11: Arrangement of measuring lines in the measurement volume

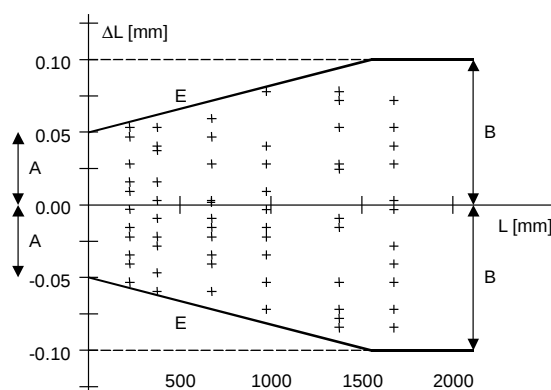


Figure 12: Diagram of deviations of length measurement

### Systems with area-based probing

Probing error, error of length measurement and error of flatness measurement are tested separately. It is proposed to use

- a) diffuse reflecting spheres to assess the probing error,
- b) ball bars (Figure 10) to assess the error of length measurement,
- c) cuboids with diffuse reflecting plane surfaces to assess the error of flatness measurement.

It is recommended to measure each reference object in 6 or 7 different positions.

#### 4.1.3 Calculation and interpretation of results

##### Systeme with point-wise probing

For each measured distance the difference between measured value and calibrated value is calculated and displayed as a length deviation diagram (Figure 12). The system is accepted if no difference exceeds the specified permissible error  $E$  according to

$$E = A + K \cdot l \leq B$$

where

- A, B: system specific constants  
 l: measured distance  
 K: a length-dependent gain factor (may be zero)

##### Systems with area-based probing

A part of a calibrated sphere is measured in order to calculate the probing error. For each sphere an adjusted least-squares sphere is calculated where a maximum of 3‰ of all measured points (observations) may be eliminated (e.g. caused by reflections, hot spots, or outliers). The remaining radial residuals are used to calculate the interval of measuring deviations. None of the calculated interval may exceed a specified threshold. A similar procedure is used to check the error of flatness measurement.

The error of length measurement is tested by comparing the calculated and calibrated distance between two spheres on a ball bar. Their Position and coordinates of the centre are determined from measured surface coordinates.

## 4.2 Verification

For periodic verification of his measuring system the user specifies own error limits as quality parameters according to his own practical requirements. Verification is used to ensure long-term stability of the system. Periodic performed tests enable statistical analysis of measuring performance of the system.

Similar to the acceptance test the system has to be checked under specified conditions. The same reference objects are used, while the number of test measurements can be reduced. Thresholds for the maximum permissible errors may also be modified. Responsibility for performing the verification tests is strictly addressed to the user (customer).

## 5 CONCLUSIONS

It has been shown that optical 3-D measuring systems are widely used in industry. They follow different measuring and probing principles. All systems have in common that accuracy can vary due to changing system setups or applications. It is therefore not satisfying to assess their accuracy using the existing procedures from mechanical CMM technology.

Over three years a joint working of experts has discussed and set up a new guideline for acceptance and verification of optical 3-D measuring systems. In conformity to existing guidelines the error of length measurement is proposed as quality parameter to assess the geometric performance all systems, point-wise probing systems and area-based systems as well. For area-based systems the performance is characterized additionally by the probing error and the error of flatness measurement. Calibrated reference are used to check, whether the systems under test meet the maximum permissible error specified by the manufacturer.

During the next future it has to be evaluated how this guideline is accepted in industry. The authors like to thank the VDI working group FA 3.32 and its members for their discussions and contributions during the last years.

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