Development of a feature adapted measurement evaluation strategy

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Abstract

This article describes a methodical approach for developing a feature adapted measurement evaluation strategy using the example of a multi-scale multi-sensor fringe projection system. In a first step calibrated standard features were selected and measured in the next step by different fringe projection sensors with varying measuring range and resolution. For selecting which sensor is most appropriate for which feature the standard deviation as well as the deviation between calibrated values and measured values were considered. Finally the results were summarized in a decision matrix, which helps to select a feature adapted measurement strategy.

1 Introduction

In times of increasing raw material and energy costs, saving resources provides not only economical and sustainable advantages but also monetary benefits. Especially by improving production technologies a reduction of raw material consumption is possible. On the one hand the aim is to use as less material and energy as possible. On the other hand products themselves should be as light and simultaneously as stable as possible. In many cases these demands could only be met partially by current production technologies. Indeed these are able to deliver lightweight structures and products, but only at high cost [1]. Therefore the transregional collaborative research centre (Transregio) 73 is developing a new economical as well as sustainable manufacturing technology by combining advantages of sheet and bulk forming. The process class sheet-bulk metal forming enables the production of highly integrated workpieces with features of varying size, form and function in only a few process steps. To ensure the savings of material and energy a production related inspection of workpieces and tools is necessary. The challenging geometries and surface structures together with short inspection cycle times can be met best by a multi-sensor fringe projection system. Thereby fringe projection sensors with different measuring ranges and resolutions are used to provide an appropriate sensor for each feature. Subsequent to the several measurements all datasets are fused to one entire dataset [2].

The data fusion of is a crucial step for calculation of measurement values. Often there are overlapping areas of several datasets. To calculate features sizes there are two widely used strategies: Laying all datasets over each other and calculating the sizes by using all available measurement information. Or separating the datasets and using the more accurate dataset where possible. Which evaluation strategy is best to get a reliable measurement value, has not been investigated for multi-scale multi-sensor datasets of sheet bulk metal formed features yet. Thus the two shown strategies are used for evaluating different standard geometries in order to detect the differences in the resulting measurement value. This way feature adapted measurement evaluation strategies can be derived for sheet-bulk metal formed workpieces.

This article is divided into three different key sections. The first section describes the technology of the sheet-bulk metal forming and the requirements for measuring systems arising thereby. In order to meet these requirements a prototype of a new multi-scale multi-sensor fringe projection system is explained as well as different concepts of data fusion, which are often used. In the second section an approach for the development of a feature adapted measurement strategy is introduced and relevant parameters and standards are outlined. The third key sections measurements and their results are presented, which lead to a decision matrix helping to set up multi-scale measurements.

2 Development of a multi-scale multi-sensor fringe projection system

2.1 Challenges of the sheet-bulk metal forming

Increasing demands for energy and material saving leads to a rising importance of lightweight design, especially in the automotive industry. Downsizing of engines without a loss of performance leads to higher loads and requires materials of higher strength. Using state-of-the-art processes for manufacturing components of the power train, e. g. synchronizer rings, results in long process chains and high costs [3]. In consequence, research on new manufacturing methods, which meet those challenges, is necessary. An innovative approach is the application of bulk forming processes on sheet metals. The first definitions of so-called sheet-bulk metal forming are given by [4] and [5]. A comprehensive description of sheet-bulk metal forming was made by [2]. The definition of the sheet-bulk metal forming contains five distinctive characteristics that must be met for the assignment to the process class:

- The semi-finished product is a sheet or a plate with a thickness from 1 mm to 5 mm
- Locally and temporally changing 2- and 3-dimensional stress and strain states
- Local change of the sheet thickness
- Interaction of area of high and low deformation and load
- The processes enable a combination with sheet metal forming processes [2]

Bulk forming of sheet metals results in characteristic three-dimensional stress and strain states in the sheet metal. This is untypical for conventional sheet forming processes, but responsible for the flow of materials in sheet thickness direction. In addition to an increase of the sheet thickness, the definition also includes an intended thinning of the sheet. To manufacture highly stressed feature like gear teeth, a local increase of the sheet thickness is of interest, whereas local thinning, which goes along with work hardening, is used to meet the idea of lightweight construction. Forming of complex geometries results one the on hand in large contact areas between the workpiece and tool, and on the other hand in strong strain hardening due to high deformation. Both aspects on their own and especially their combination result in high forming forces. Because of the temporally and locally varying contact and strain states in various areas of the component, the design of the forming tools is of major importance. Regarding the workpiece, the combination of sheet and bulk metal forming operations results in areas of high and low strains, which simultaneously occur during the process within the component [2]. This interaction affects the material flow and in consequence the component quality. Additional influences on the material flow are the tribological conditions. In areas, which are associated with the sheet metal forming, there are comparatively low contact normal stresses and at the same time long sliding paths. Bulk formed areas are characterized by high contact normal stresses and strong surface enlargement. In consequence different areas of the component show unequal surface properties. Very smooth and bright surfaces can exist beside dull surfaces of higher roughness. For the quality assurance of sheet-bulk metal formed components, this creates new challenges on measurement techniques. On the one hand tactile techniques are not suitable to measure a laminar component with small functional elements holistically. On the other hand, optical measurement devices can hardly handle those locally high reflective surfaces [6].

2.2 Prototypically multi-scale multi-sensor fringe projection system

A characteristically advantage of sheet-bulk metal forming processes is the possibility of combining features of different scale and size in one workpiece. In order to ensure a holistic inspection of filigree small features as well as of large features and the complete workpiece itself a feature adapted measuring system is necessary. The challenges of the inspection of complex workpieces can be explained by considering the "golden rule of measuring metrology", which was developed by Georg Berndt in 1968 and is kind of a recommendation for selecting appropriate measuring systems [7]. Therefor the measurement systems' uncertainties have to be known and these should be less than a fifth, better less than a tenth, of the tolerance width. If this minimum requirement could be met, it is assured that the measurement results are accurate enough.

Next to varying requirements on the measurement uncertainty due to the differing features' sizes and forms also the environmental conditions as well as the short inspection time have be met by the measuring system. Based on all these requirements a multi-sensor multi-scale inspection concept resting upon fringe projection technology was worked out and realized in a prototypically measuring system. The main parts of the prototype system are three different types of commercially available fringe projection sensors. Each type has a different measuring range as well as a different resolution. To get an overview of the workpiece and also to measure large features at once, a fringe projection sensor with a measuring range of the size of the workpiece is installed. In the realized setup the overview sensor is exchangeable. For the experiments of this work the fringe projection sensor GOM ATOS Compact Scan 2M is used as overview sensor. But the accuracy of the overview sensor is not high enough to measure also filigree elements. Therefore two other types of fringe projection sensors can be arranged as detail sensors around the workpiece. For the experiments of this work two different fringe projection sensor of GFM MicroCAD pico are used. Each sensor captures only one feature, but in a resolution, which is adapted to the feature's size [8], [9]. In order to guarantee a robust setup, which can be used in a production-related environment the system itself is installed on dumpers. The technical specifications of the different sensor types are itemized in figure 1.

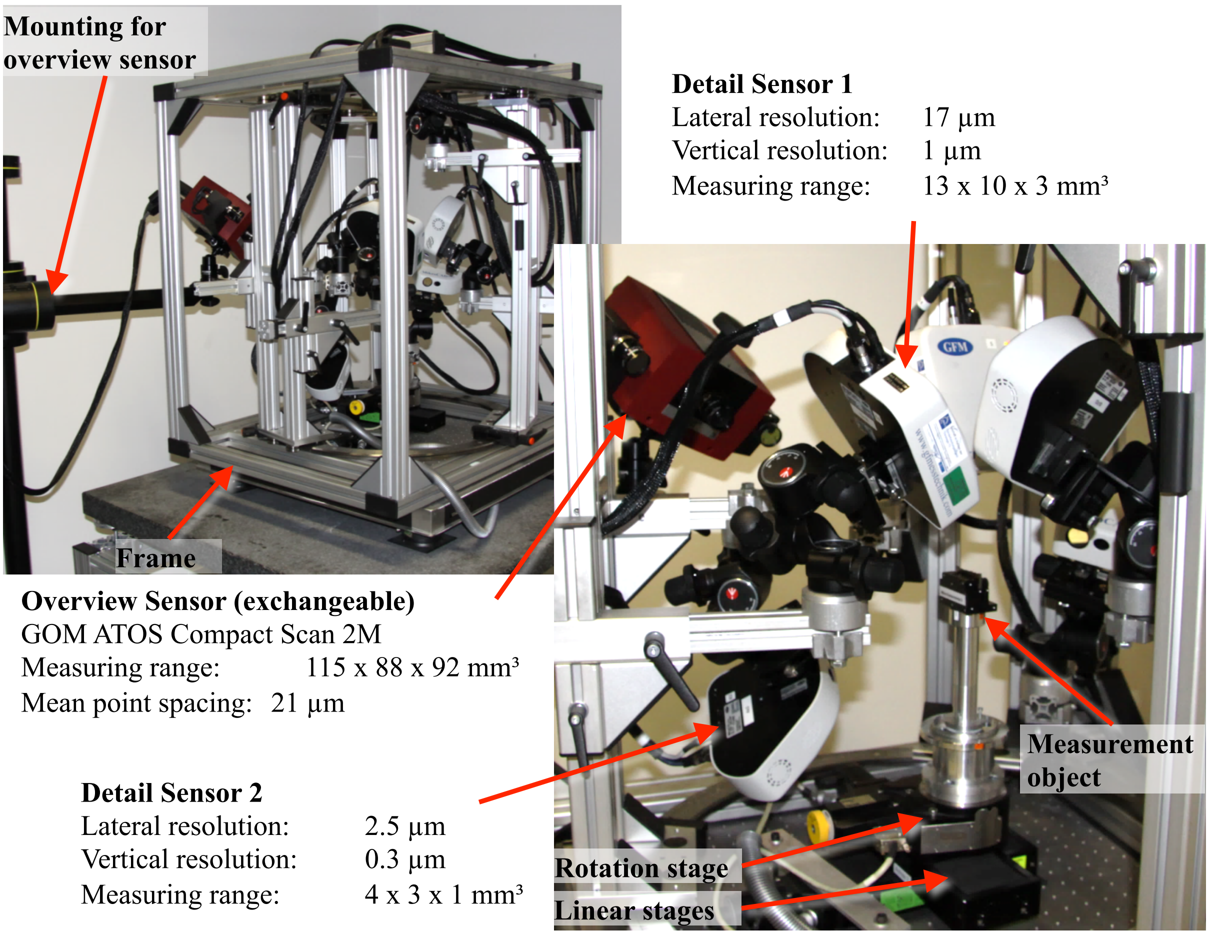


Figure 1: Setup and specification of the multi-scale multi-sensor fringe projection system

2.3 Concepts of data fusion and evaluation of multi-scale measurement data

After gathering measurement data from each sensor the datasets are fused together in order to calculate measurement values. Aim of multi-scale measurements is to detail a dataset were necessary and get therefore a more accurate general dataset. Due to the varying resolutions of the different fringe projection sensors the level of detail divers between the datasets. Hence the used concept of data fusion and evaluation is a crucial step. In figure 2 two widely used concepts are illustrated. In the left part of figure 2 all available measurement data are laid over each other. High accurate as well as less accurate datasets are used for the calculation of measurement values. As a consequence the calculated value is influence by the dispersion of each sensor. The idea why using this concept is the assumption, that the more accurate dataset, which contains a higher number of data points with a smaller dispersion at the same time compensates the dispersion of the few data points of the less accurate dataset. Simultaneously the dispersion of the less accurate dataset is not left out for the calculation. In the lower left part of figure 2 the different number of data points in multi-scale datasets can be seen when overlapping all measurement data. The concept of overlapping measurement data is abbreviated in the following figures by the word “Add”.

Another way to combine datasets of different resolution is to use only the most precise data when there are overlapping areas. Therefor the datasets of the most accurate sensor is selected as a reference and this area is cut out of each other dataset. Then the measured value of a feature is calculated only by using the most precise data points, which are available. In the right part of figure 2 this concept is shown whereas in the lower part a multi-scale general dataset is shown with using the cut out method. When using this concept of data fusion only the dispersion of the most accurate sensor influences the calculation of measurement values. All other available measurement information is left out. The concept of cutting out measurement data is abbreviated in the following figures by the word “Cut”.

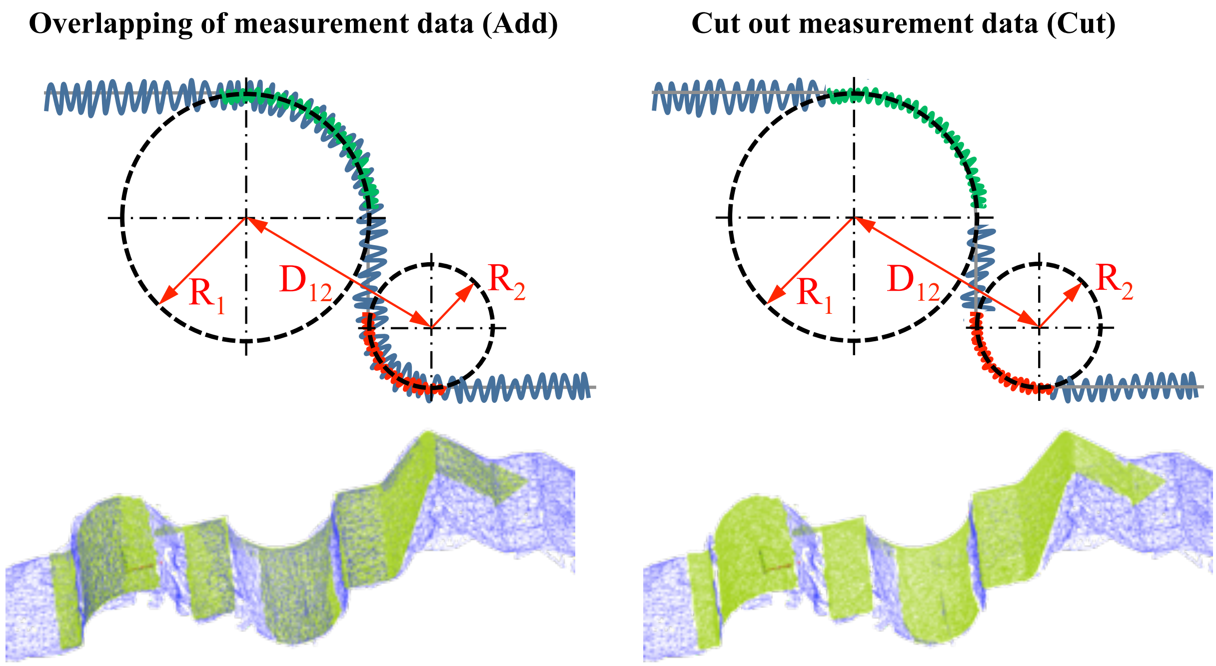


Figure 2: Concepts of data fusion

3 Approach for a feature adapted measurement strategy

3.1 General approach

The methodical approach for developing a feature adapted measurement strategy contains four main steps. The approach is using the example of a holistically inspection of sheet-bulk metal formed workpieces by a multi-scale multi-sensor fringe projection system.

In the first step typical features of sheet-bulk metal formed parts as well as frequently manufacturing defects were detected. Then calibrated standards were selected, which are similar to the typical features and to the manufacturing defects. Hereby very accurate reference values are available for comparison with measured values by the fringe projection sensors. Moreover the measurement strategy is developed on features, which are similar to the original measuring task.

In the second step the performance of the overview sensor is evaluated by measuring the selected standards. The results help to detect areas of interest for further detailing by multi-scale measurements. In addition the measurements with a fringe projection sensor, which measuring rage is large enough for detecting the whole workpiece, like the overview sensor does, are often a standard approach in industrial quality assurance.

Multi-scale measurements are done in the third step based on the results of the overview sensor's measurements. The more accurate fringe projection sensors detail the dataset of the overview sensor where it seems to be necessary. Out of the results of these measurements feature based rules can be derived, where multi-scale measurements are useful and which settings for the data fusion should be used. A verification of the rules completes the approach in the fourth step.

3.2 Selecting calibrated standards

One of the main characteristics of the sheet-bulk metal forming is a three-dimensional material flow. If this is not working proper, it can lead to characteristic defects. Figure 3 shows some of the most frequently manufacturing defects.

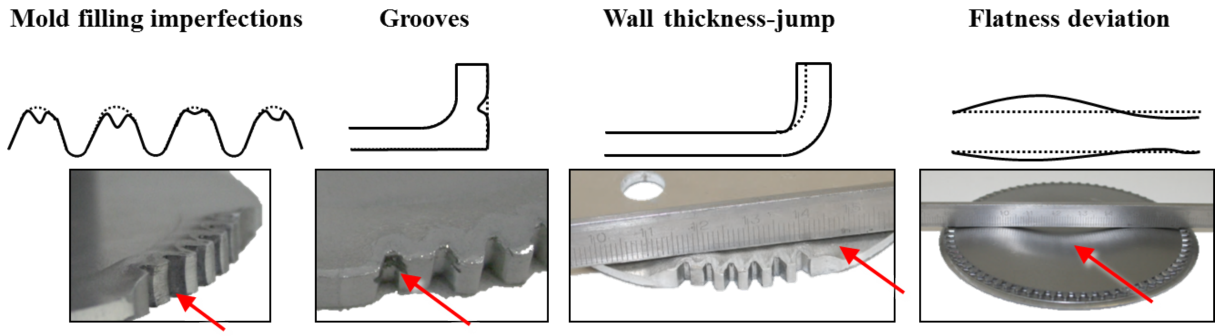


Figure 3: Selection of manufacturing defects

Essential for a correct contour molding is a correct mold filling of the mold cavity. The material flow has to be set up in a way, that material is dispersed ideally in the mold cavity and filled this completely [10]. Complex workpieces with features of different size and form require an adapted material flow according to the particular volumes of the features [11]. In contrast, also significant surface deviations can appear. As a consequence of too much available material, there could be variability of the sheet thickness as well as of the material hardening which can differ locally. Both cases lead to a deviation of the flatness due to inserted stresses [1].

After detecting frequently manufacturing defects calibrated standards that are similar to the defects have to be found. The micro-contour standard from the PTB [12] seems to be appropriate for this. It has very filigree surface structures similar for example to tooth systems and also the features' sizes of the standard are almost equal to the typical sizes of sheet-bulk metal formed features. Especially radii and step heights can be found very often as features on different sheet-bulk metal formed workpieces. Therefore these kinds of features of the PTB micro-contour standard are of particular interest and considered for the further experiments. Figure 4 shows the selected calibrated features. Next to step heights and radii of different sizes also distances between features are considered. Thus also features larger than the measuring ranges of the detail sensors can be analysed.

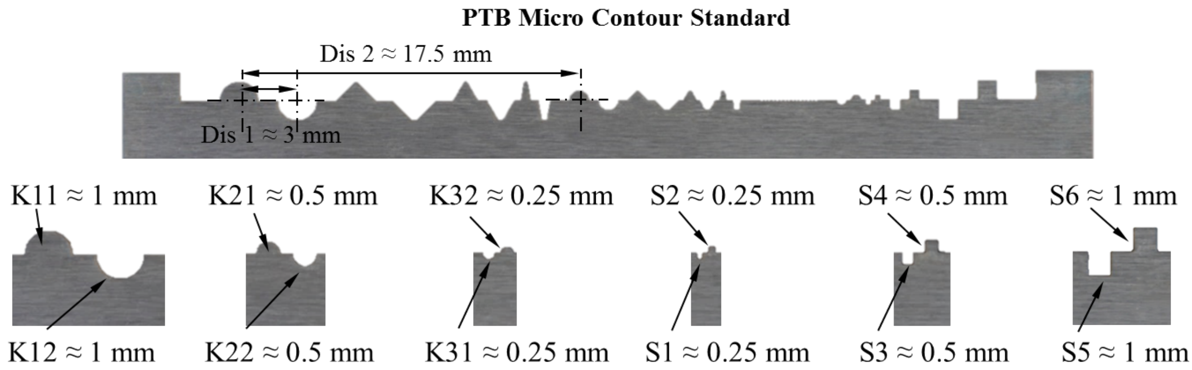


Figure 4: Selected features of the PTB micro-contour standard for the experiments

In Figure 5 two relevant parameters are shown, which are varied in the experiments. The measurement angel is for this article defined as the angle between the perpendicular to the measurement table and the orientation of the fringe projection sensor. The cut out distance is used when merging datasets together without creating overlapped data. Therefor one dataset is cut out of the other dataset. The resulting gap between both datasets is called cut out distance.

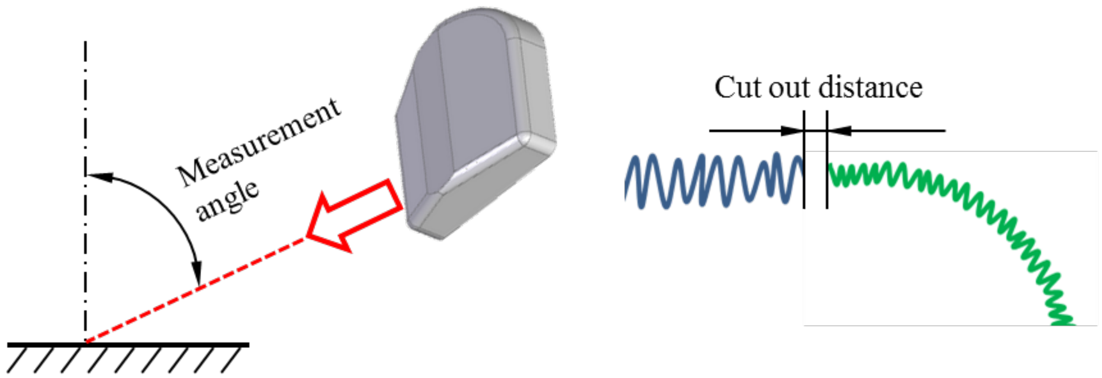


Figure 5: Relevant parameters

4 Results

4.1 Standard measurement with a conventional fringe projection system

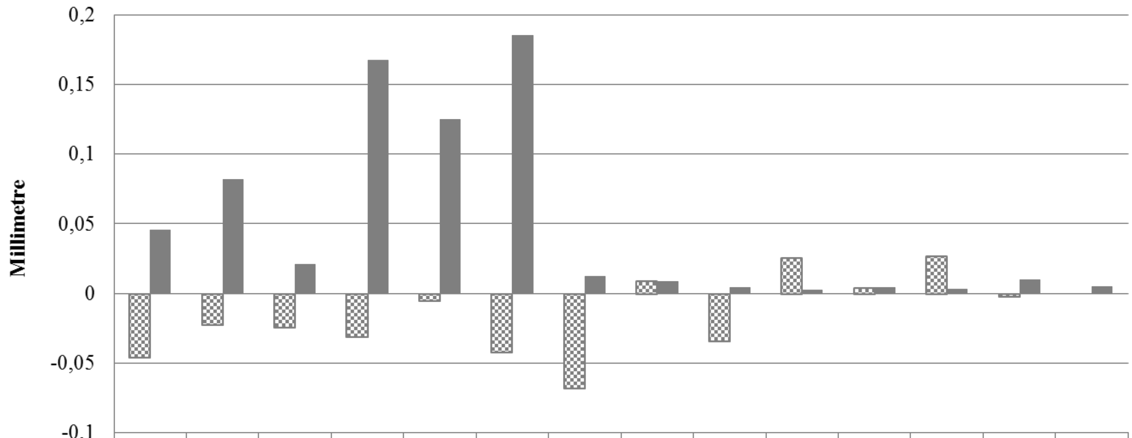
To get a reference in order for detecting differences due to multi-scale measurements standard measurement with the overview sensor are done as example for a conventional fringe projection. The settings for the measurement can be seen in Table 1 whereas in Figure 6 the results are shown. Considered are the mean deviations of the measured value for a feature with the conventional fringe projection system and the calibrated value as well as the standard deviation of the results for each feature. For both parameters also specific results are given below the diagram.

The standard deviation of the radii increases with decreasing features' sizes. Due to the constant resolution of the overview sensor, the resolution is less appropriate the smaller the size of the feature is. Therefore the smaller the features' size the more increases the dispersion of the measured values and as a consequence thereof the standard deviation of the measured values. In contrast, the mean deviations between measured values and calibrated values do not depend on features' sizes. Although measured values disturb stronger the smaller the radius is, mean deviation is nearly constant.

Table 1: Settings for the measurements with the overview sensor

Parameters	Settings
Measurement angles	0°, 30°, 45°, 60°
Rotation angle	30° (except at 0°)
Number of measurements	37
Concepts of data fusion	-
Fringe projection system	Overview Sensor
Data file format	STL
Evaluation software	PolyWorks IMInspect
Evaluation method	Best-Fit

In comparison to the results for the radii deviation and standard deviation for step heights as well as for distances are significant smaller. Step heights are not as complex as radii. This fact leads to a better detection also by a fringe projection system with a comparatively low resolution. For the calculation of both distances the centre of the radii are considered. The appearing dispersion in the radii measurements also influences the results for the distances. But due to a similar dispersion for both radii the calculated mean distances between two of them is nearly the same. This again leads to a small standard deviation in comparison to the radii.



	K11	K12	K21	K22	K31	K32	S1	S2	S3	S4	S5	S6	Dis1	Dis2
Deviation in mm	-0,046	-0,022	-0,024	-0,031	-0,005	-0,042	-0,068	0,009	-0,034	0,026	0,004	0,027	-0,0020	0,000
Stddev in mm	0,046	0,082	0,021	0,167	0,125	0,185	0,012	0,008	0,004	0,002	0,004	0,003	0,010	0,005

All values in millimetres

Figure 6: Results for the measurements with the overview sensor

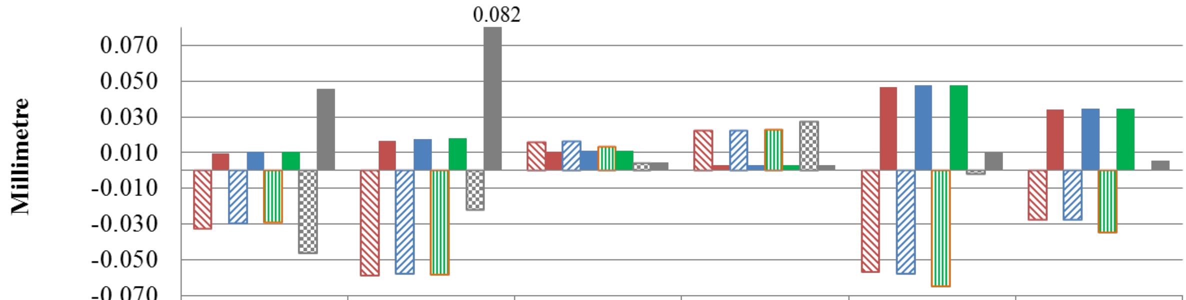
4.2 Multi-scale mutli-sensor measurements

The measurements of a conventional fringe projection system, represented by the overview sensor, are the reference for detecting differences due to multi-scale multi-sensor measurements. All relevant parameters for these measurements are shown in Table 2. Compared against conventional fringe projection measurements the measurement angle of multi-scale multi senor measurements cannot be set clearly. When measuring with more than one fringe projection sensor the measuring ranges of both sensors have to be positioned around the feature, which should be measured. In order to avoid collisions of the sensors, it is not possible to set for both sensors the same measurement angle. Each sensor of the multi-scale multi-senor fringe projection system measures features only once. In addition to the overview sensor there are datasets of three different measuring sensors for each feature. These datasets are fused into one dataset bay using all three concepts of data fusion for each dataset.

Table 2: Settings for the multi-scale measurements

Parameters	Settings
Measurement angles	0° - 45°
Rotation angle	-
Number of measurements	1 per sensor and feature
Concepts of data fusion	Overlapping („Add“) Cut out distance 0.2 mm („Cut 02“) Cut out distance 0.5 mm („Cut 05“)
Fringe projection system	Overview sensor Detail sensor 1 Detail sensor 2
Data file format	STL
Evaluation software	PolyWorks IMInspect
Evaluation method	Best-Fit

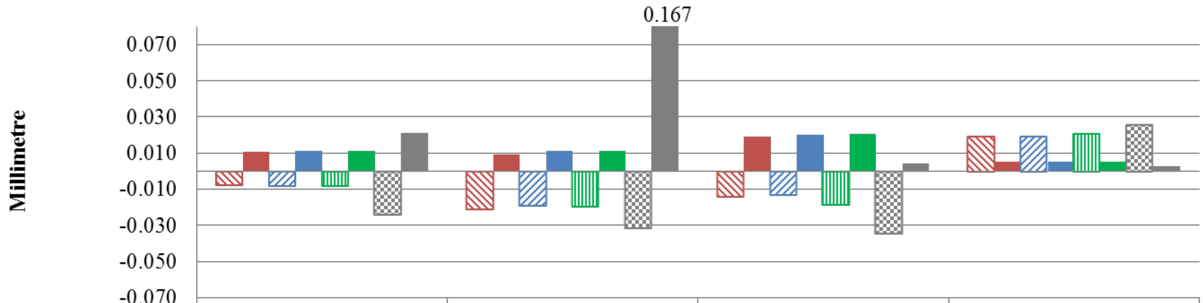
The results of the multi-scale multi-sensor measurement can be seen in Figure 7, Figure 8 and Figure 9. To show the differences to the reference measurement with the overview sensor also these results are shown in the figures.



	K11	K12	S5	S6	Dis1	Dis2
Deviation "Add"	-0.033	-0.059	0.016	0.022	-0.057	-0.028
Stddev "Add"	0.009	0.016	0.010	0.003	0.047	0.034
Deviation "Cut 02"	-0.030	-0.058	0.016	0.022	-0.058	-0.027
Stddev "Cut 02"	0.010	0.017	0.011	0.003	0.048	0.035
Deviation "Cut 05"	-0.029	-0.058	0.013	0.023	-0.065	-0.035
Stddev "Cut 05"	0.010	0.018	0.011	0.003	0.048	0.035
Deviation "FPS"	-0.046	-0.022	0.004	0.027	-0.002	0.000
Stddev "FPS"	0.046	0.082	0.004	0.003	0.010	0.005

All values in millimetres

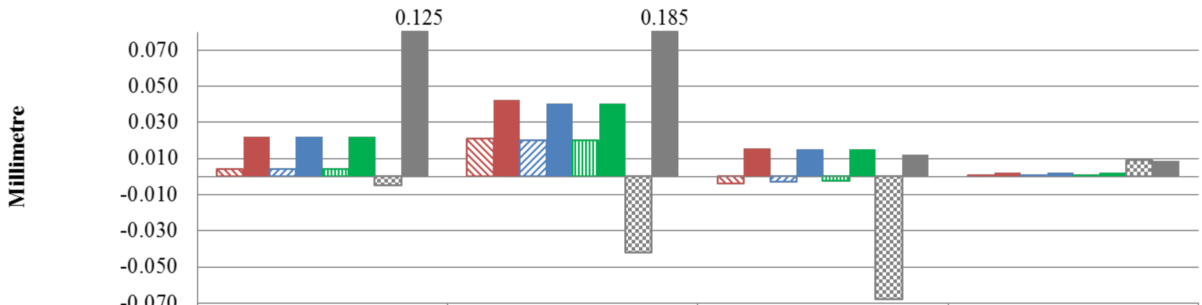
Figure 7: Results of multi-scale measurements for a feature size of 1.00 mm and larger



	K21	K22	S3	S4
Deviation "Add"	-0.007	-0.021	-0.014	0.019
Stddev "Add"	0.011	0.009	0.019	0.005
Deviation "Cut 02"	-0.008	-0.019	-0.013	0.019
Stddev "Cut 02"	0.011	0.011	0.020	0.005
Deviation "Cut 05"	-0.008	-0.019	-0.018	0.021
Stddev "Cut 05"	0.011	0.011	0.021	0.005
Deviation "FPS"	-0.024	-0.031	-0.034	0.026
Stddev "FPS"	0.021	0.167	0.004	0.002

All values in millimetres

Figure 8: Results of multi-scale measurements for a feature size of 5.00 mm



	K31	K32	S1	S2
Deviation "Add"	0.004	0.021	-0.004	0.001
Stddev "Add"	0.022	0.042	0.016	0.002
Deviation "Cut 02"	0.004	0.020	-0.003	0.001
Stddev "Cut 02"	0.022	0.040	0.015	0.002
Deviation "Cut 05"	0.004	0.020	-0.002	0.000
Stddev "Cut 05"	0.022	0.040	0.015	0.002
Deviation "FPS"	-0.005	-0.042	-0.068	0.009
Stddev "FPS"	0.125	0.185	0.012	0.008

All values in millimetres

Figure 9: Results of multi-scale measurements for a feature size of 0.25 mm

4.3 Decision matrix for an appropriate measurement strategy

Out of the results of the measurements with both types of fringe projection systems rules can be developed, which helps choosing an appropriate measurement strategy. For this purpose feature's type, size and orientation are considered and analysed, which type of fringe projection systems leads to better results for the parameters deviation and standard deviation. The resulting rules are summarized in a decision matrix, which can be seen in table 4.

With the support of the decision matrix a feature adapted measurement strategy can be set up. The matrix is suitable for features, which are similar to the radii step heights or distances. Also the feature's size has to be in the range of the considered calibrated standard features.

Table 4: Decision matrix for an appropriate measurement strategy

Feature		Radius		Step height		Distance	
Size	Orientation	Deviation	Std.dev.	Deviation	Std.dev.	Deviation	Std.dev.
0.25 mm	in	Multi-scale	Multi-scale	Multi-scale	Multi-scale / Conventional	-	-
0.25 mm	out	Multi-scale / Conventional	Multi-scale	Multi-scale	Multi-scale	-	-
0.50 mm	in	Multi-scale	Multi-scale	Multi-scale	Conventional	-	-
0.50 mm	out	Multi-scale	Multi-scale	Multi-scale	Multi-scale / Conventional	-	-
1.00 mm	in	Conventional	Multi-scale	Multi-scale	Conventional	-	-
1.00 mm	out	Multi-scale	Multi-scale	Multi-scale / Conventional	Multi-scale / Conventional	-	-
3.00 mm	-	-	-	-	-	Conventional	Conventional
17.50 mm	-	-	-	-	-	Conventional	Conventional

4.4 Verification

To verify the rules presented in the decision matrix a challenging inspection task was selected with a measuring object, which features are nearly the same size as the calibrated standard features. Figure 10 depicts a die plate, which is used for forming of gear-ring by pressing a circular blank of sheet-metal (diameter 20 mm, height 2mm) into the eight punches. Due to the 45°-symmetry of the punches, the forming process is capable to reflect the characteristics of orthotropic material behaviour, which is typical for rolled sheet-metals. Additionally the punches are designed with flat flanks.

Consecutively, using different lubricants for the forming process, the influences of contact and friction behaviour become apparent in the final outcome. Furthermore the small radii of the punches lead to local high plastic deformations as it is for example required for testing adaptive approaches for finite element simulations. Therefore this forming process, developed by the collaborative research centre Transregio 73, serves as a versatile benchmark for simulations and experiments in Sheet-bulk metal forming.

Regarding the demanded size of the punches with radii of 0.2 mm and small distances between each other the manufacturing process of the die plate requires micro-milling tools. In detail, the vertical walls and the bottom area of the die were manufactured using an end-milling cutter with a diameter of 1 mm and a corner radius of 0.2 mm so that the small radii could be realized directly during wall finishing. The upper area of the punches was manufactured by a ball-end milling cutter with a diameter of 1 mm. Furthermore a hardening process was conducted before milling the die plate to achieve a high surface quality and shape accuracy of the punches. Due to their geometry, micro-milling of the die plate is also a real challenge, especially due to the hardness of the high-speed steel ASP 2023 (63 HRC).

For setting up a feature adapted measurement strategy for the inspection of the die plate and it's features the fringe projection sensors were matched to the features according to the recommendation of the decision matrix. In addition the features were also measured by using only the overview sensor. Table 5 shows the detected deviations between desired values and measured actual values. The results show clearly the advantage of multi-scale multi-sensor measurements. Mean and median of all deviations of multi-scale measurements are smaller the parameters for conventional fringe projection measurements. Also the dispersions of the measured values are smaller, symbolized by the smaller standard deviation. Only the numbers of outliers are higher when using multi-scale multi-sensor measurements. The detected outliers are excluded from the calculation of the other parameters. Comparing both methods of data fusion there is not significant difference between the “Add” and the “Cut” method.

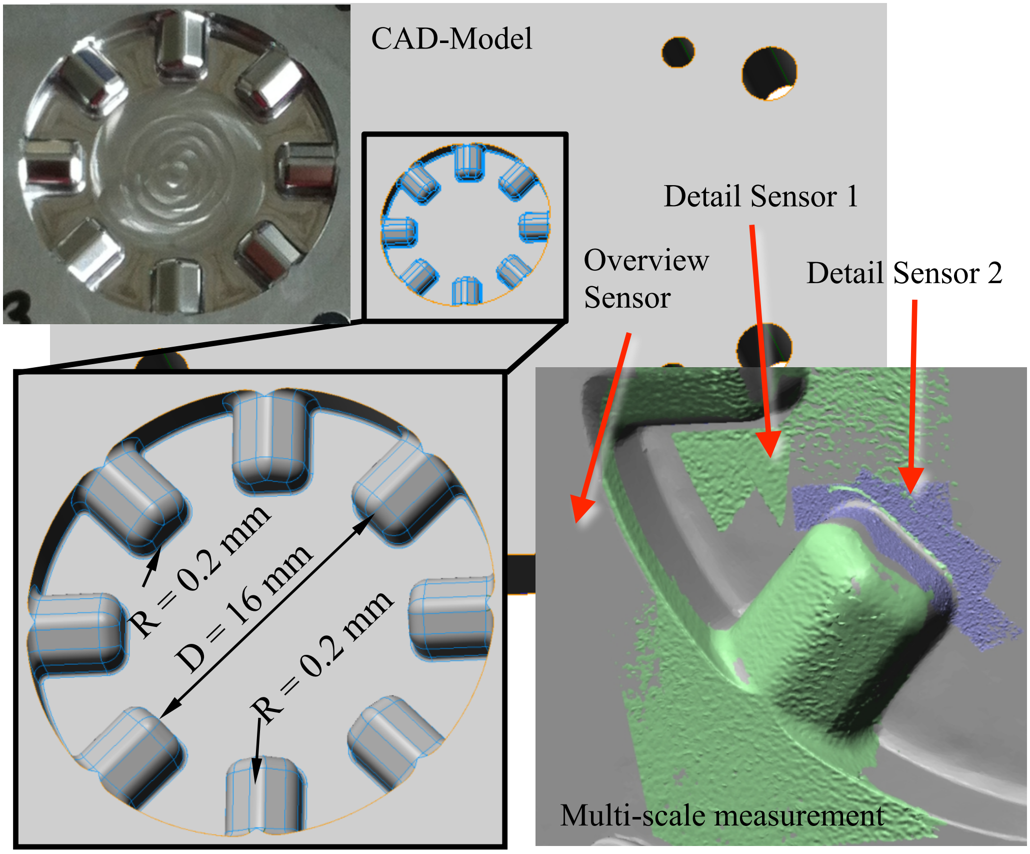


Figure 10: Verification measurements

Table 5: Results for deviations between desired and actual values

	Multi-scale measurement “Add”	Multi-scale measurement “Cut”	Overview sensor
Number of values	50	50	50
Mean	0.005 mm	0.007 mm	0.013 mm
Median	0.003 mm	0.004 mm	0.008 mm
Standard deviation	0.017 mm	0.019 mm	0.030 mm
Range	0.071 mm	0.086 mm	0.132 mm
Number of outliers	8	6	2

5 Conclusion

In the article an approach for the development of a feature adapted measurement strategy was shown using the example of a multi-scale multi-sensor fringe projection system. Therefor calibrated standard feature were selected which are similar to features of sheet-bulk metal formed workpieces the multi-scale multi-sensor fringe projection system was developed for. The selected calibrated standard features were measured by a conventional fringe projection system, like it is standard in today's industrial quality assurance. The results were compared with multi-scale multi-sensor measurements and lead to a decision matrix when which type of fringe projection sensor is more appropriate for which feature of which size and which orientation. Verified were the rules of the decision matrix by using a real measuring task in the field of the sheet-bulk metal forming. Whereas clear differences between conventional and multi-scale multi-sensor fringe projection could be detected, there is no difference between the two introduced concepts of data fusion.

For all experiment only the best-fit evaluation method was considered, which is shown in the left part of Figure 12. A useful extension of the experiments could be the consideration of further evaluation methods like they are exemplary shown in the middle and on the right side of Figure 12. Hereby also the function of features in a technical system can be considered, which requires different evaluation methods.

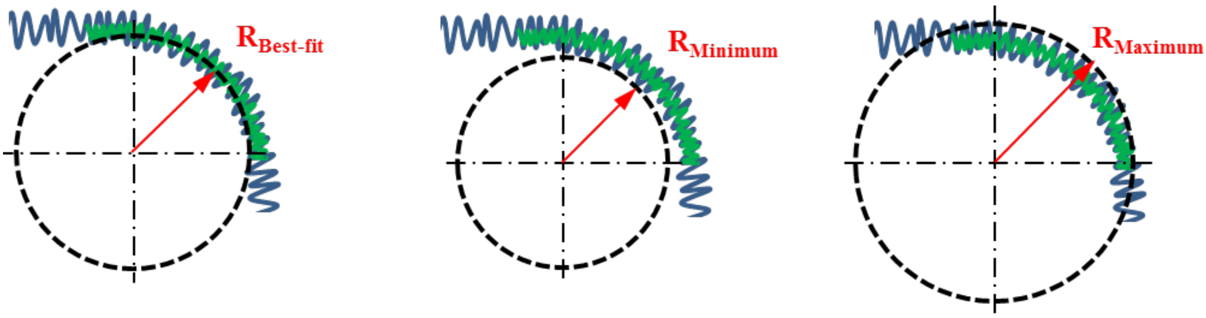


Figure 12: Extension of further evaluation methods

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