ALBERT WECKENMANN, JOHANNES WEICKMANN

University Erlangen-Nuremberg
Chair Quality Management and Manufacturing Metrology
Naegelsbachstr. 25, 91052 Erlangen, Germany
e-mail: weckenmann@qfm.uni-erlangen.de

OPTICAL INSPECTION OF FORMED SHEET METAL PARTS APPLYING FRINGE PROJECTION SYSTEMS AND VIRTUAL FIXATION

Modern forming technology allows the production of highly sophisticated free form sheet metal components, which are subject to a reversible geometrical deformation caused by residual stress, gravity or variations of the material. This distortion is usually removed during assembly and therefore the part's tolerated parameters have to be inspected in fixed state, which simulates assembly conditions. Today this time-consuming work is done on CMMs (Coordinate measuring machines). Using fast optical measuring systems and virtual fixation, this process chain can be dramatically shortened and in-line measurement seems to be possible in future. Virtual fixation means that at first a workpiece is measured in distorted state without fixation and afterwards the shape in assembled state is simulated by FEM analysis. Thus, workpieces can be inspected with significantly reduced effort.

Keywords: virtual distortion compensation; fringe projection; Finite Elements Method (FEM); optical metrology; inspection process

1. INTRODUCTION

Modern sheet metal forming technology allows the production of highly sophisticated free form sheet metal components, allowing great flexibility in design matters and manufacturing processes across a wide range of industries. An example is the automobile industry where engineers are constantly trying to realize more extraordinarily-looking car bodies.

Due to residual strains, the workpiece can deform after a deep drawing process. During assembly the workpiece has to endure forces that can distort its shape according to its structure. In order to set the workpiece in its assembled state, the workpiece has to be fixed or clamped during the measurement process with conventional measuring systems (e.g. tactile coordinate measuring systems). Therefore a fixation device in which the workpiece can be measured must be designed. The inspection process is laborious, time consuming and some actions (e.g. fixation/clamping) cannot be automated, [1]. For this reason 100% testing of all parts in mass production is impossible. Only sampling inspection (statistical control) is practicable with this conventional approach.

Only optical measurement procedures can satisfy the restrictive conditions (time and automation) for an in-line measurement process. Nowadays optical coordinate measuring systems are fast, suitable for automation and robust enough to be used in an industrial environment. Systems that use fringe projection technique allow a fast, parallel and non-contact acquisition of point clouds of the workpiece surface. The fringe pattern is projected on the distorted workpiece and one or more cameras acquire the data. Fringe projection systems are based on the triangulation principle between the camera and projector. From the measured point cloud a triangle mesh of the surface can be generated, which could be used in Finite Element Method (FEM) simulations of the fixation or clamping process. By using this virtual fixation method, the inspection process chain can be significantly shortened, reduced in time (e.g. for the measurement of a car door from 1 day to a few minutes) and automated. The measurement time amounts approximately to 10-15 seconds. All other steps can be performed by a PC-system, meanwhile the workpiece can continue to run through the production process. This method provides a 100%-test of the production with simultaneous increase of control over sheet metal production and a decrease of inspection costs, [2], [3].

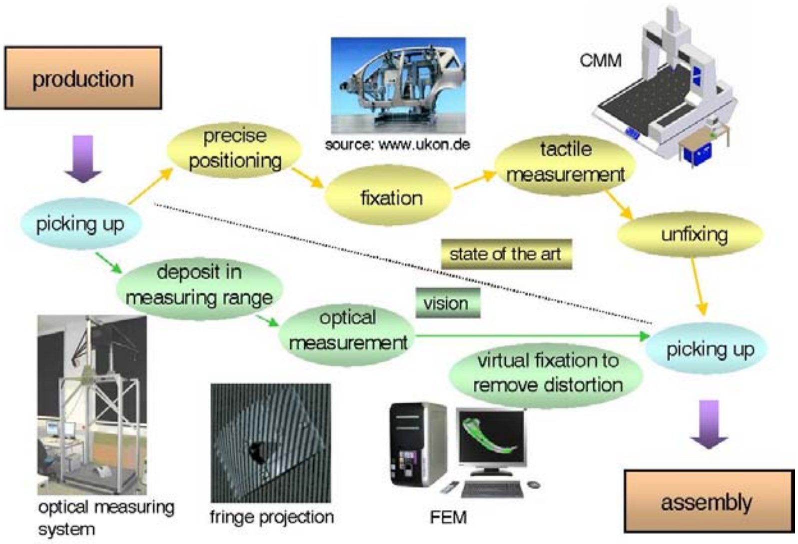

Fig. 1. Measuring chain with a tactile and an optical measurement system.

2. FRINGE PROJECTION MEASURING SYSTEM

Optical surface measuring systems allow fast, parallel and contact-free sampling of the surface of a workpiece. Fringe projection systems turned out to be the most successful method due to their velocity, robustness, flexibility of configuration, exact data acquisition and the suitability for automation. The 3D data acquisition is based on the triangulation principle. A parallel fringe pattern is projected on the measuring field and is recorded by one or more cameras under the calibrated triangulation angle α, Fig. 2. The phase difference between the observed picture and the picture recorded by measuring an calibrated plane (reference plane) is proportional to the position Δz in normal direction to this reference plane, according to the triangulation principle. This means that distance Δz is depicted as displacement Δx on the camera. This method is suitable for the measurement of non reflective surfaces, as reflection of the projected marker leads to outliers and makes accurate measuring results impossible, [5].

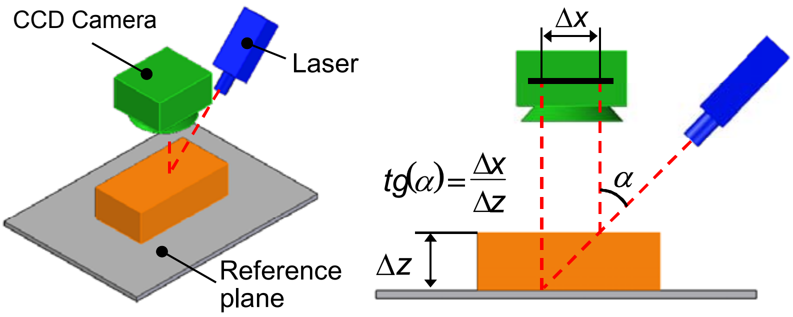

Fig. 2. Triangulation principle with a single CCD camera.

In this research project the fringe projection system MacroSPS from GFM, consisting of two cameras and a DMD projector (Digital mirror device, [6]), is used. It was designed for measuring large sheet metal parts as used in the automotive industry.

<u>Technical specifications:</u>

Measuring field:	400 x 700 x 900 mm
Collected points:	1400 x 1800
Angle of triangulation:	23°
Lateral resolution:	500 µm
Transversal resolution:	200 µm
Deviations according to VDI/VDE 2634	
Distance between sphere:	< 620 µm
Spherical shape:	< 126 µm
Flatness:	< 225 µm
Repeatability:	< 10 µm
Contrast ratio:	500 : 1
Measurement period:	< 3 min

Fig. 3. Two camera fringe projection system.

3. MEASURING PROCESS

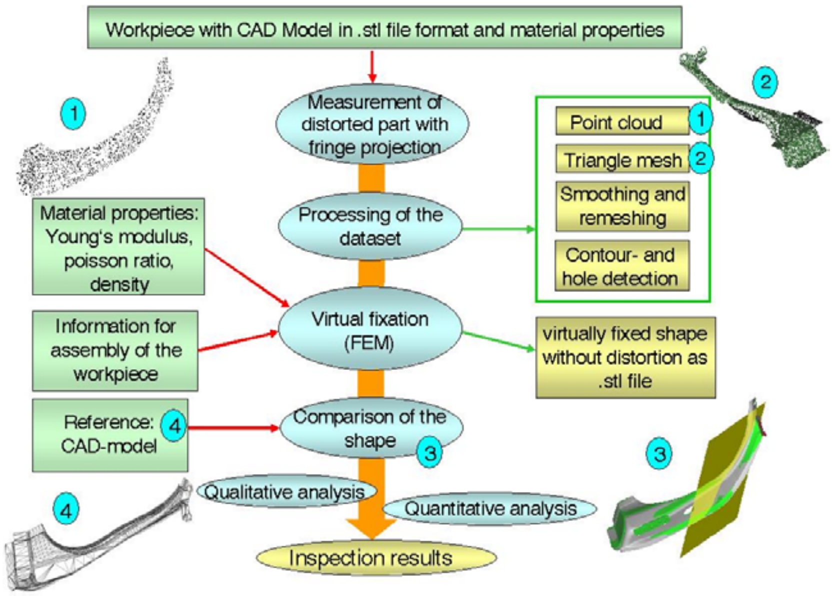

Fig. 4. Process chain: The green boxes depict necessary information and tools.

As shown in Fig. 3, the workpiece is measured in distorted state without a fixation device. Afterwards the data set (including information about holes an edges) is processed (see Fig. 4) and with the information about fixation (e.g. position of holes) and material properties a FE-analysis – representing the virtual fixation – is performed. The last step is a comparison with the CAD-model or the fixed workpiece. The workpiece is indispensable only for the measurement (which lasts 15-30 seconds). The other steps are realised by a PC. There is no need to stop production for testing a workpiece. Thus this method is more suitable for an in-line test than a conventional tactile measuring system. The most important steps are described in the following chapters.

4. DATA PROCESSING

Fringe projection systems deliver some millions of point coordinates (x, y, z) per measurement as a so-called point cloud. To receive the results of the following steps in an appropriate time, the amount of points has to be reduced to 30,000 – 50,000. The points of the surrounding measuring field are deleted and the remaining point cloud is reduced by a curvature based method where most points in flat areas are deleted and points in zones with strong curvature are kept. Thus all geometrical properties are preserved. Because noise of the measured surface would falsify the FE-simulation result, the maximum permissible smoothing is elaborated (under the condition that surface properties are kept). This smoothing is done by filters (e.g. median, Gaussian, [8]).

For creating the surface, a triangle mesh – based on the point cloud – is generated, Fig. 5. There is no three-dimensional order contained in the list, for geometrical operations a comparison of all points is required to find the point's neighbourhood relations. A linear approximation to the surface is a triangle mesh, in which the space between the adjacent points is approximated by triangles, Fig. 5. Methods like Delaunay triangulation allow the automated determination of a unique triangle patch representing the measured surface [4]. The processing time for the realisation of the triangle mesh is approximately one minute.

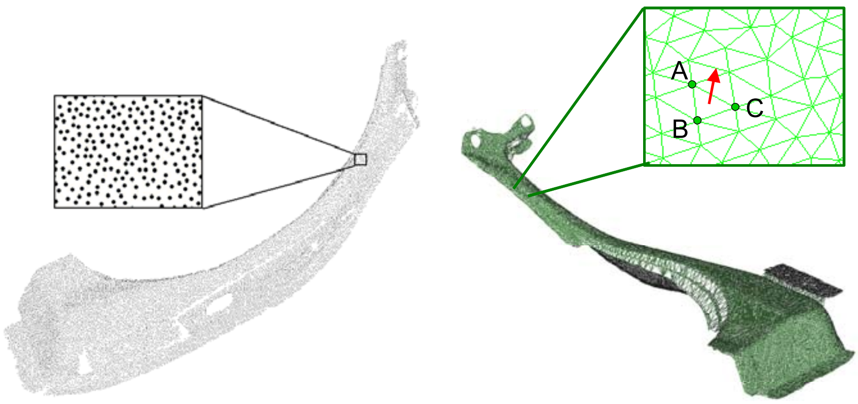

Fig. 5. Triangle mesh (right) created from point cloud (left).

5. VIRTUAL FIXATION

The measured, smoothed and diminished triangle mesh of the distorted workpiece is the base for the FEM model. Each triangle is defined as a shell element with a given thickness. Boundary conditions have to be identified and fixed when modelling the simulation [9]. Below, the boundary conditions for the example depicted in Fig. 6 are given:

- The material properties are determined as follows: Young's modulus E = 210,000 N/mm2, Poisson´s ratio $\nu = 0.4$ and density $\rho = 7.87$ kg/dm^2.
- In the given example the average wall thickness for the whole workpiece is 0.8 mm.
- Crucial boundary conditions are the "Degrees of Freedom" (DoF) at the fixation points including impressed displacements, rotations, forces and moments. These points are taken from CAD-models or technical drawings (e.g. holes) and transferred to the FE-model in a realistic manner. Detection of holes and edges can be automated by the use of algorithms [4] [10]. In the given example the following conditions were assumed: Points A1 … A4 belong to the CAD-model, points B_1 … B_4 belong to the virtual fixed data. Points A_1 and A_2 coincide with the analogue points B_1 and B_2. For the points B_3 and B_4 there is a

displacement in the direction of the violet arrows. At the end of the simulation the points B_3 and B_4 coincide with the respective A_3 and A_4.

In the presented example the workpiece was measured in relaxed, distorted state and in fixed state. By virtual fixation – that means removing the distortion virtually –, the unfixed state was transformed into the fixed state. At the end of the process a new file (e.g. .stl-file) with a new form of the surface is obtained, which considers the boundary conditions. The processing time depends on the model and varies between a few seconds and a few minutes.

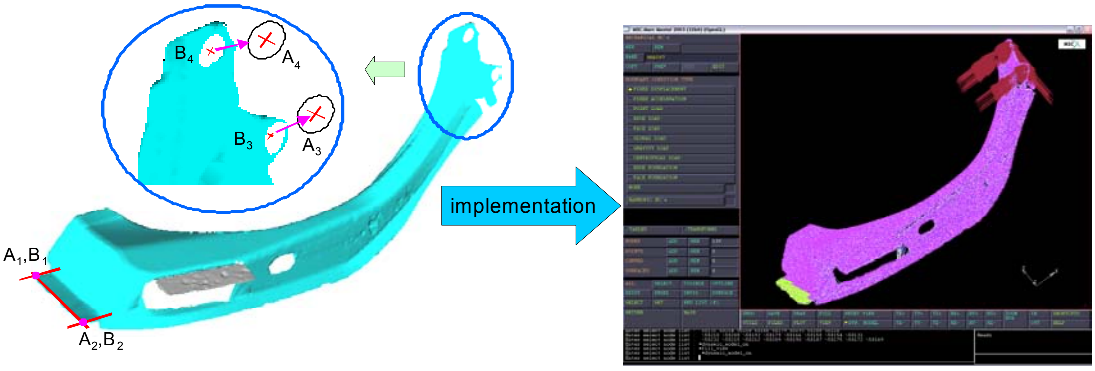

Fig. 6. FEM model with boundary conditions.

6. QUALITATIVE ANALYSIS OF THE RESULTS

The CAD-model and the virtual fixed shape (both are colour coded) are being overlapped. Taking the surface of the CAD-model as reference, it is possible to characterize positive or negative deviations based on the visualized colour in a the specific area of the work piece, which is under consideration, Fig. 7.

The two data sets have two different coordinate systems and therefore different origins and orientation. For this reason a transformation (= translation + rotation) of the workpiece coordinate system is indispensable ("Registration")[3]. The translation can be accomplished in different ways:

- With definite points: the matrix of the transformation is defined with the coordinates of some characteristic points.
- Best fit method: the CAD-model and the virtual compensated shape are overlapped in the best possible way (Gaussian or minimum method).

The processing time for the transformation is approximately 35 seconds.

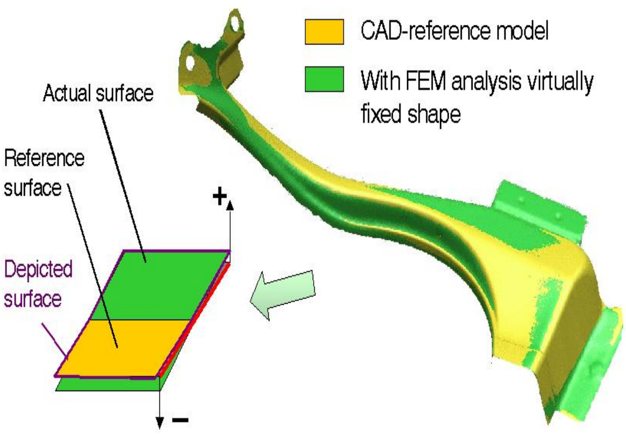

Fig. 7. Principle of the qualitative analysis (FEM-model and CAD-model).

7. QUANTITATIVE ANALYSIS OF THE RESULTS

7.1. Quantitative analysis by section planes

The crucial point of this work is a quantitative comparison of the virtual fixed shape with the CAD-model (= reference). Figure 8 illustrates the method used:

- Overlapping of the CAD-model and the virtually fixed model (consecutively called FEM-profile or FEM-model);
- Section plane areas used for creating comparable contours of the two surfaces;
- The comparison is made at critical points (e.g. at a radius or an edge) where the deviation from a nominal position is calculated. Distances between holes can also be measured: These distances can be compared with the nominal dimension, which is given in a CAD-model or an engineering drawing.

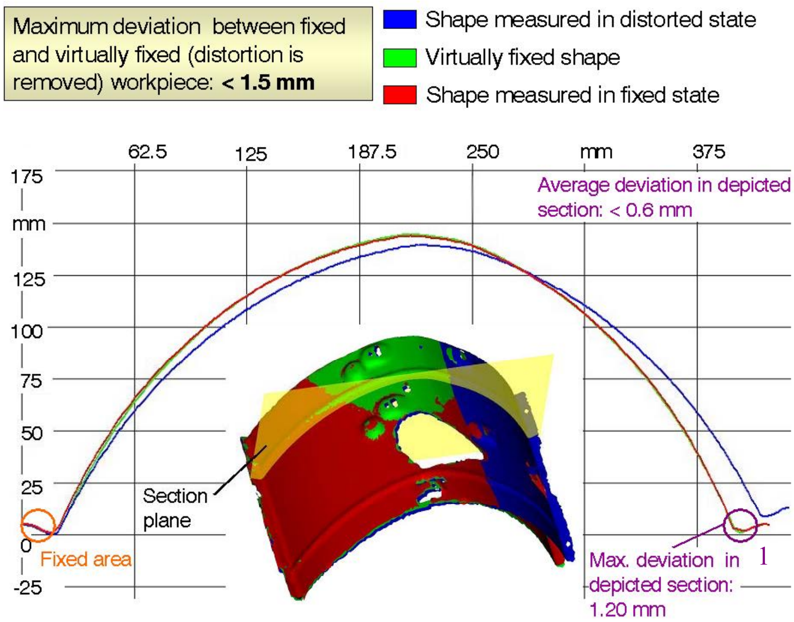

Fig. 8. Quantitative analysis: unfixed (blue), fixed (red) and virtually fixed (green) datasets.

Figure 8 shows as sample object a cylindrical formed metal sheet. The comparison between the virtually fixed and the unfixed shape shows the success of virtual fixation, which is carried out by means of FEM analysis. For this purpose the relative deviation of the critical edge in area 1 to the corresponding reference area of the real shape in fixed state is calculated. Maximum deviation from real shape in fixed state in the considered edge area 1 is reduced from **15.88 mm to 1.20 mm**. The average deviation in the depicted section was reduced by virtual distortion compensation to a value of **< 0.6 mm.**

7.2. Holistic quantitative analysis at a complex structure

If the focus of the comparison lies on the overall shape of a workpiece, a holistic false colour rendering is used. Below, a complex reinforcement structure of a car body is used as an example, Fig. 9. Figures 10 and 11 show the success of virtual fixation, as the average deviation from the reference CAD-model is reduced from **5.4 mm to 1.4 mm**. Please note in Figure 10 that the used reengineering software is unable to depict the whole compared structure, as the deviation before performing virtual fixation is too large in some areas. Thus the software is not able to assign all measured points to equivalent reference points. After performing virtual fixation and distortion compensation (Fig. 11) the software can handle the comparison of the whole shape.

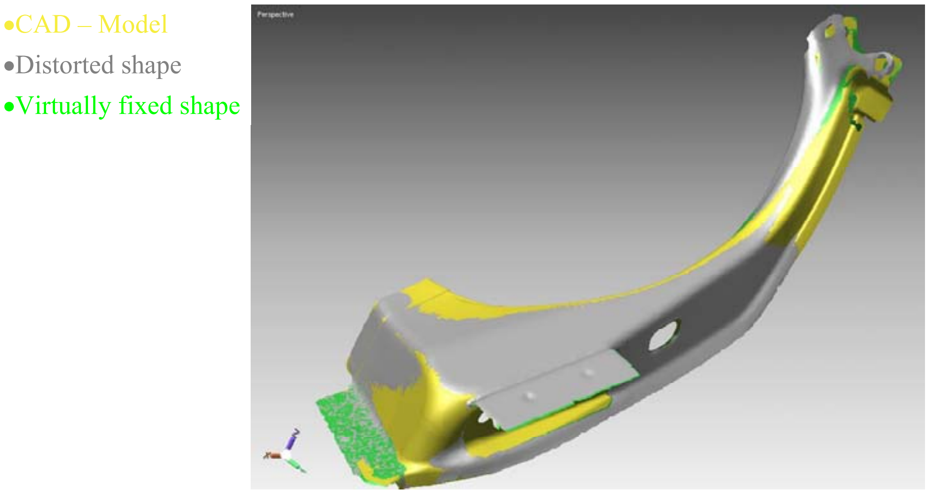

Fig. 9: Registered shapes of complex workpiece.

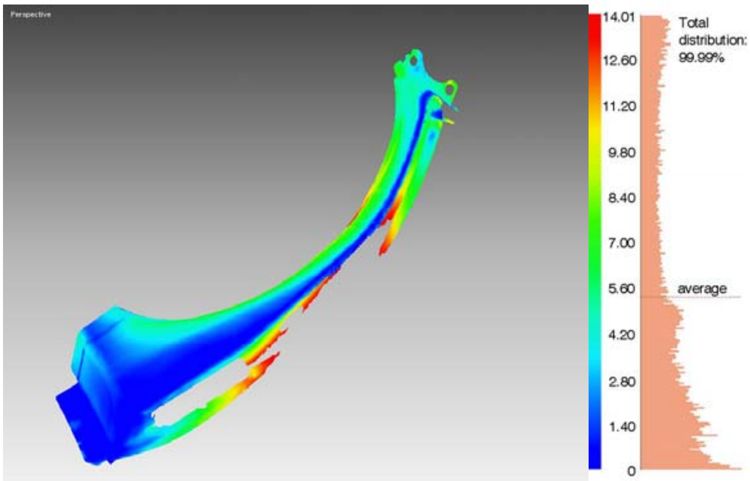

Fig. 10. False colour rendering before virtual fixation.

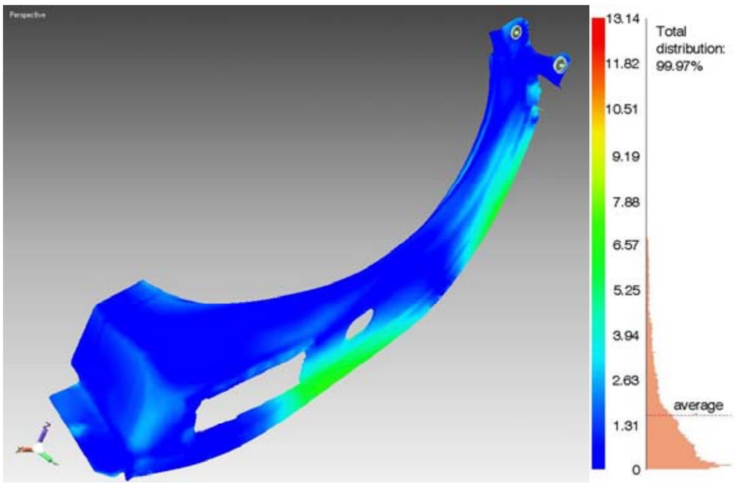

Fig. 11. False colour rendering after virtual fixation.

The X-crosssection in Fig. 12 shows that through virtual fixation the areas between the fixation (or clamping) points converge towards the reference shape. Still the method could be enhanced. Because this virtual fixation and distortion compensation is done by means of FEM-analysis, special focus has to be set on optimizing the boundary conditions. Especially the degrees of freedom at the fixation points and the local wall thickness are subjects where improvement is still possible. For that purpose these parameters will be optimized in the context of further research.

The performance of virtual fixation is evaluated by an indirect comparison between the virtually fixed data and the measured data set of the fixed (= real distorted) workpiece, using the CAD-model as reference. A proprietary developed fixation device is used. The positions of the fixation points are based on the CAD-model. Figure 13 shows the deviation of measured sample points to equivalent points on the CAD-model.

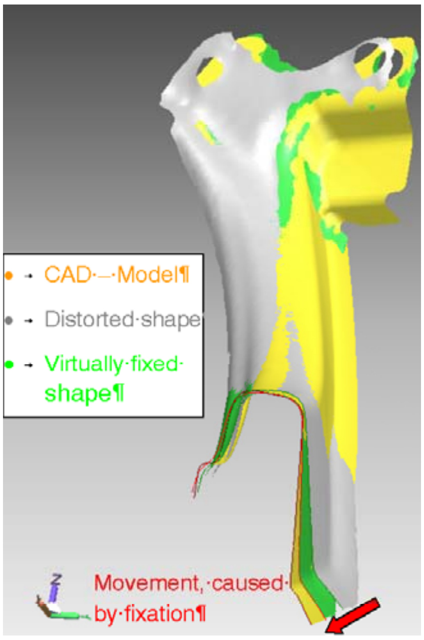

Fig. 12. Section view; please note positions of right wall.

The results validate that the used fixation device and the used workpiece meet the drawing specifications with good approximation and are suitable for verifying the results of the virtual fixation. A fixation device could also be used for tactile and optical control surveys in production runs. The maximum deviation to the CAD-model is 1.2 mm [3], so the aim is to receive equivalent results by using virtual fixation.

Point A	1.1 mm ± 0.7 mm
Point B	0.9 mm ± 0.7 mm
Point C	1.0 mm ± 0.7 mm

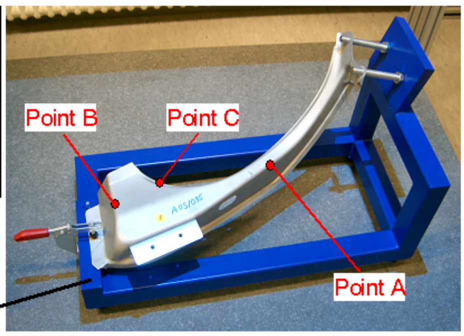

Fig. 13. Fixation device and deviation to CAD-model in sample points.

To sum up: already at this early stage of research the achieved results with the method of virtual fixation are very precise and reflect the real workpiece's shape very well. The maximum deviation of the shape is satisfactorily accurate for most applications.

8. MEASUREMENT UNCERTAINTY

The accuracy of the virtual fixation method is limited by measurement uncertainty, which is the object of further analysis. The measurement uncertainty is the sum of the uncertainty of the fringe projection system, the uncertainty of FEM simulation (e.g. wall thickness assumption), uncertainty in the simulation of the fixation system and the uncertainty of the evaluation of point coordinates between which the distance is calculated as an indicator for deviation. With the current configuration of the MacroSPS, the uncertainty of virtual fixation is calculated to ±0.7 mm [3]. In comparison, the measurement uncertainty of CMMs for the same tasks is added up to ±0.1 - 0.2 mm [7].

Figure 14 shows the Ishikawa diagram for fringe projection systems. As depicted, operators and measurement strategy are the main factors that influence the quality of measurement results. Therefore it is crucial to find the ideal configuration of the measuring system, e.g. the geometrical relation between projector, camera(s) and object. It is also necessary to consider the quality of components, as the resolution of measuring systems depends on the CCD-Matrix in the camera, for example [3]. For the analysis of these effects, the measurement will be simulated by a virtual and flexible measuring system. Thus it will be possible to optimize the measurement situation and to compile the acquired knowledge in an operator assistance system.

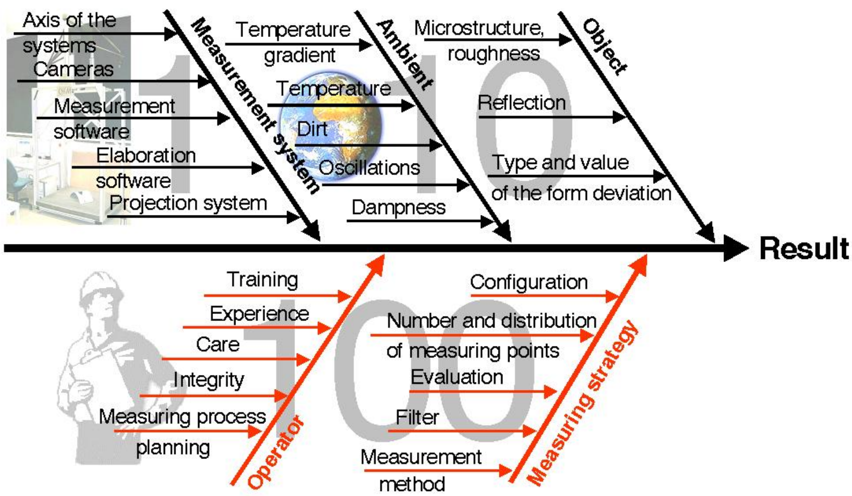

Fig. 14. Ishikawa diagram for fringe projection system.

9. CONCLUSION

Fringe projection systems are suitable for fast and contact free measurement of formed sheet metal parts without fixation or clamping. The measurement result can be used to extract features on the workpiece, like holes or edges. Some of these are relevant for the assembly process and subject to further inspections. Thanks to the information about the deviation of the assembly features from their actual position to their nominal position, virtual distortion compensation – which means virtual fixation – can be used to calculate feature parameters of the distortion compensated shape. Thus the shape in assembled state can be simulated and the inspection process chain can be shortened and automated simultaneously. Procedures for automating the process must be developed.

The comparison between the measurement with the fixed work piece and the virtually fixed data shows that the method could be improved. For example boundary conditions to simulate a real model of the fixation system. Furthermore, the geometric conditions can be improved: for example thickness was an average value for all the workpieces. In further analyses variable wall thickness (as in the real workpiece) will be applied. Another object of research will be a comparison between optical measurement, tactile measurement and virtual fixation. Tactile measurement is state of the art in quality inspection of formed sheet metal parts and thus will be used for verifying results.

The actual limitation of the method is the measurement uncertainty and uncertainty of the accuracy of the FEM simulation. Because of this, further investigations aimed at optimizing the measurement situation and reducing the uncertainties will be performed. The results of these investigations will be introduced to an assistance system for guiding the operator.

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