Precision Engineering 54 (2018) 396–402

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Holistic approximation of combined surface data☆

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ARTICLE INFO

Keywords:
Holistic approximation
Dimensional metrology
Micro-production
Geometric decomposition

ABSTRACT

Modern micro-production processes demand fast and robust inspection techniques up to 100% inspection rates. For instance, a fast acquisition of the objects surface in the needed precision and density can be realized by optical measurement systems. In order to extract the relevant geometric quantities from the surface data of prismatic workpieces, the measured data points need to be assigned to the nominal geometric primitives, e. g. cylinder, plane or sphere. For this purpose, an automatable algorithm is desired, which assigns all measured points to the corresponding geometric elements and minimizes the measurement uncertainty. Such an optimal segmentation routine of combined geometric data can either be performed by rating neighboring measurement points based on their curvature or by a holistic approximation. Whereas the first approach is sensitive to noisy data and not able to distinguish between spheres and cylinders with certain radii, the holistic approximation in combination with further statistical methods promises an automatic detection of outliers.

In order to analyze the achievable measurement uncertainty with the holistic approximation approach for an object geometry composed by three-dimensional base elements (cylinder, torus, plane), the method is applied to determine the geometric features of micro deep-drawing dies. For verification, the measured geometry of the object is simulated including uniformly distributed noise within a range of ± 2.5 µm. As a result, the determined radius of the cylinder (defined to 412 µm) has a standard uncertainty due to random errors below 11 nm and an uncertainty due to systematic errors less than 1.1 nm. Furthermore, real tactile measurement data are evaluated to validate the holistic approximation. In comparison to certified analysis software, which requires a manual segmentation, the results show differences below 0.25 µm for the cylinder diameter. The increased measurement deviations are caused by assumptions of the model-based evaluation, which is essential for the automated data processing. However, the achievable uncertainty qualifies the holistic approximation for a robust and automated evaluation of geometric tolerances in the field of micro-production.

1. Introduction and state of the art

Modern production techniques enable the precise manufacturing of parts and, thus, promote the demand for high quality products. Proving the quality on high levels raises the requirements for both the acquisition and the evaluation of quality features. At the same time, increasing production rates demand fast and robust inspection techniques. Even in mass production, the trend goes towards a 100% inspection rate. The field of micro-production additionally increases the requirements for measurement systems due to the handling and the fragility of micro products. A general challenge are size effects [1], which exemplary occur on a physical-technical level by an increased ratio of surface to volume [2]. Especially the material properties are changing with decreasing dimensions. In micro-forming, for example, under certain boundary conditions the process forces increase with the grain size [3]. This is in contrast to the theory of metal forming in macro dimensions (Hall-Petch-relation) [4]. Therefore, not only the geometric inspection of the produced parts is important, but also the dimensional characterization of micro-forming tools in order to analyze process mechanisms and to optimize friction effects. Furthermore, an automated characterization of geometric features is also important for a closed-loop control of micro-production processes [5].

In terms of dimensional metrology, a fast acquisition of the parts surface in the needed precision and density can only be realized by optical measurement systems. Several measuring approaches exist, but the automatic data evaluation is still challenging. The methods can be roughly divided into 3 fields of application:

1. The evaluation of free-form surfaces, which requires a registration of the measured points to a reference model, e. g. by the Iterative

☆ This paper was recommended by Associate Editor Han Haitjema.

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https://doi.org/10.1016/j.precisioneng.2018.07.009
Received 9 March 2018; Received in revised form 18 July 2018; Accepted 25 July 2018
Available online 30 July 2018

Closest Point (ICP) algorithm [6], and a comparison to the nominal or CAD data. A good survey regarding the metrology of freeform shaped parts is summarized in Ref. [7].
2. The separation of different orders of shape deviations for data acquired by high definition metrology. For example, entropy, contrast and correlation techniques [8] or shearlet-based methods [9] can be used to separate roughness, waviness and form portions of a technical surface.
3. The evaluation of prismatic workpieces, which requires an assignment of the actual measurands to the nominal geometric primitives, e. g. cylinder, plane, sphere and torus.

The application of this work is related to the third field. Therefore, the following paragraphs focus on methods to assign the measured points to geometric objects.

In macro dimensions, the assignment is often performed by using the nominal data and an alignment of the measured points. This is a standard procedure and part of the measurement strategy [10], especially for tactile measuring systems. In most practical applications, this procedure implies neglecting points close to edges of the feature or in the area of intersecting elements. Depending on the number of measured points, which can be rather low for micro-features, and the fraction of the measured feature (Fig. 1), the minimal achievable measurement uncertainty is not attained [10–13].

The example in Table 1 illustrates the increasing uncertainties of the center and the diameter of a circle, respectively, with decreasing acquired points on the full circumference. The second example in Fig. 1 demonstrates the further increasing diameter uncertainty with decreasing central angle of the arc, on which 12 acquired points are distributed.

In addition, Fig. 2 demonstrates the effect of wrongly assigned points: The measuring data of a cross section is simulated for a micro feature (combination of a line, a circle and another line), acquired with 25 points per mm. In this dimensions, a quarter of a circle (radius r = 153.0 µm) is acquired with only 6 points. With a simulated uncertainty (uniformly distributed noise in normal direction within a range of 0.9 µm) the approximation of all 6 acquired circle points delivers a radius of 152.8 µm whereas a circle approximation of the 6 circle points together with a neighboring point on each of the lines calculates a radius of 155.0 µm. As a result, the approximation of the correct points leads to a measurement deviation (to the nominal value) of 0.2 µm, whereas the inclusion of only 2 wrongly assigned points increases the deviation by one decade. Thus, for a fast production of high quality micro products, an automated procedure is necessary, which optimally assigns all measured points to the corresponding geometric elements.

Two approaches exist for a general automated segmentation of combined geometric data:

Table 1
Uncertainties U_x, U_D (confidence level P = 95%) for the center and the diameter, respectively, approximated for different numbers of equidistant points n on a full circle, valid for independent and uniformly distributed deviations, normalized to the standard deviation s = 1 [12].

points n	Center U_x/s	Diameter U_D/s	Points n	Center U_x/s	Diameter U_D/s
4	8.98	12.70	20	0.67	0.95
5	2.72	3.85	50	0.40	0.57
6	1.84	2.60	100	0.28	0.40
10	1.06	1.50	1000	0.09	0.13

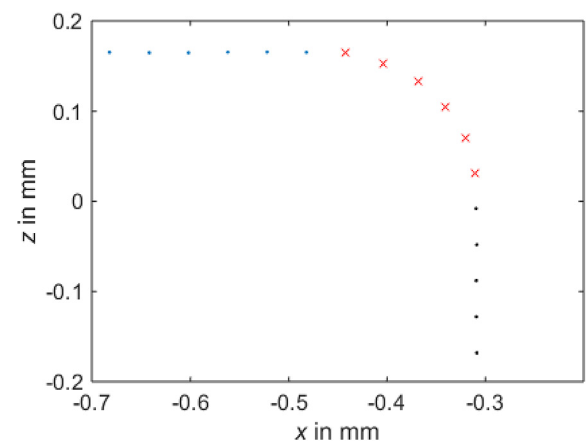

Fig. 2. Simulated measuring data of a profile, combined of a line (dots), a quarter circle (radius: 153 µm, crosses) and another line (dots), acquired with 25 points per mm.

1. Methods for the reverse engineering of unknown surfaces,
2. Model-based approaches for geometric feature extraction.

In the first field, the methods can be divided into edge-based or face-based methods. A good summary is provided in Ref. [14]. One example is rating neighboring measurement points based on their curvature and assigning them to corresponding geometric elements [15]. This method can provide very accurate solutions under certain conditions, but it is sensitive to noisy data and not able to distinguish between spheres and cylinders with certain radii.

In the second field, a model-based holistic approximation can evaluate a composed set of data in a single approximation task [16]. By the definition of separating functions, an optimal assignment of the measurement points to the corresponding geometric elements (segmentation) can be carried out simultaneously. The application for a planar line-circle-line profile is presented in Ref. [17]. A 3D application to evaluate the geometry of micro deep-drawing punches as a

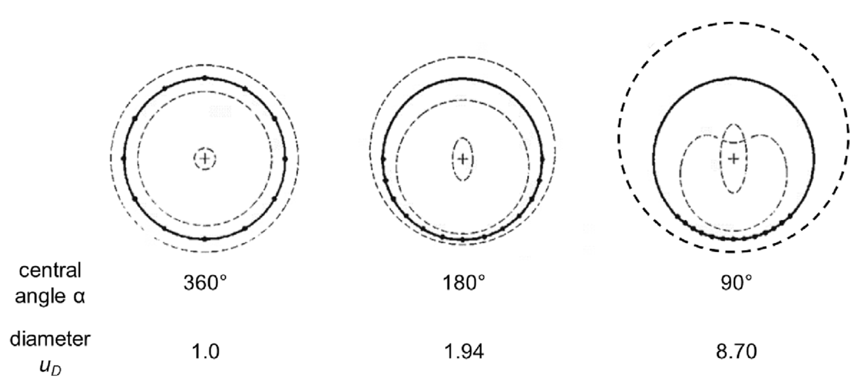

Fig. 1. Uncertainty u_D of the approximated circle diameter depending on the distribution of 12 points on the circumference normalized by the uncertainty for a fully acquired circle (α = 360°) [12].