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Form errors estimation in free-form 2D and 3D geometries

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Abstract

Purpose:
The aim of this work is to present a method for the verification of form tolerances in free-form geometries.

Method:
New free-form error parameters, in accordance with ISO GPS standards are defined. Geometrical errors in 2D e 3D geometries are calculated using a new fitting method consisting in an association operation where nominal profile/surface is resized (with an offset), located and oriented on the non-ideal geometry. Form tolerance is estimated using peak-to-valley deviation after the best fit.

Result:
Automatic algorithms are implemented to analyse 2D free-form profiles of moulds for ophthalmic lenses obtained with grinding and polishing operations and to analyse 3D free-form surfaces of an injection moulded lamp lens for automotive industry.

Discussion & Conclusion:
The comparison between results obtained using this approach and using traditional fitting methods shows differences on the fitting and errors parameters estimation. In particular in the traditional fitting there is a repartition of the size error contribution in the translation and form errors. The differences increase proportionally to the offset value estimated. The calculation of offset parameter allows the separation of size from geometric errors in free-form profiles/surfaces and the "true" form error estimation.

1 Introduction

Profile tolerance specification is extensively used to specify complex free-form and regular geometric features. It is a powerful method because it offers the possibility to simultaneously control size, form and position tolerances [1]. In industry, there exists a great need to inspect parts with complicated and free-form surfaces to ensure high quality for manufactured products [2]. However, actual standards regarding free-form surfaces verification are inadequate, because measurement methods and parameters for errors assessment are not yet defined [3].

The importance of free-form profile/surfaces for functional performances of the products requires the definition of a unified and unambiguous method for the verification of complex features, coherent to most recent ISO standards regarding inspection of the parts.

1.1 GPS standards related to profile tolerancing and inspection

In order to guarantee functionality, safety and reliability of the part, geometric requirements are defined during the design stage. The indication of profile/surface tolerance, its interpretation and the definition of the tolerance zone are stated in ISO 1101 [4]. The specification and the verification are strongly related to each other; but the reference document for the measurement of geometric errors is the old ISO/TR 5460 [5].

A more recent GPS approach for the product verification is given in ISO 17450 [6][7]. When regular geometries are considered, ISO GPS standards can be used to verify straightness [8][9], flatness [10][11], roundness [12][13] and cylindricity [14][15]: an association operation is used to fit ideal feature to non-ideal feature according to a specific criteria. When profile tolerances is used to control complex profile or surfaces no specific standards for the verification of conformity are available [16][17].

1.2 Research background

Many scientific works have described methods for the inspection of free-form profile/surface. These works are focused on the CAD-based inspection method, due to the increasing of reliability of contact and non contact sensor technology, the possibility to acquire many data points on the surfaces and the improving of automatic inspection systems [18]-[20]. The general approach consists in aligning clouds of measured points on the virtual model (usually a CAD model), using a fitting algorithm, to perform the geometric characterization of the part.

A review of the main free-form surface inspection techniques is given in Li and Gu [21]: the inspection problem regards determining rigid rotation and translation components which best align the measured points on the surface. Different algorithms for the localization of measured data on nominal surfaces are presented and a software for automatic comparison of free-form geometries is implemented [20][22][23]. Ristic et al. [24] and Zhu et al. [25] implement a method to locate points on a NURBS surface and [25] introduces an unified algorithm to orientate/position clouds of points on complex parametric surfaces. Other works [26][27] propose a pre-fitting to improve the computing efficiency. A review of algorithm used to accelerate the localization process is given in [28].

Cerardi et al. [29] propose a method for identifying and separating the size error from form, position and orientation error in 2D profile inspection.

In this paper a method for the verification of form tolerances for free-form geometries is proposed and new parameters, in accordance with ISO GPS standards, are defined.

2 New approach to free-form inspection

According to ISO/TS 14638, this work proposes a method for the geometric verification of free-form profiles and surfaces. The method influences chain link 3 and chain link 4 of standards on form of line and form of surface in the general GPS matrix.

2.1 Definition for actual feature – characteristic or parameter

According to ISO/TS 17450 concepts, it is proposed an association operation to fit ideal profile/surface to non-ideal feature using a specific criteria. Reference profile/surface, intended as the associated profile/surface to which the deviations are referred, is calculated from nominal feature, for example a CAD profile/surface, that is resized (with an offset), located and oriented on the non-ideal feature.

In accordance it's consistent defining size and geometric errors as:

- Offset parameter: characteristic which indicate the variation in size of the reference feature from the nominal feature,
- Local profile/surface deviation: minimum distance from a point on the extracted profile/surface to the reference profile/surface.

2.2 Assessment of the deviations of the workpiece – comparison with tolerance limits

According to ISO standards regarding form tolerances the following parameters can be defined:

- Peak-to-valley profile/surface deviation FFPt/FFSt: sum of the largest positive local profile/surface deviation and the largest negative local profile/surface deviation
- Peak-to-reference profile/surface deviation FFPp/FFSp: value of the largest positive local profile/surface deviation from the least squares reference feature
- Reference-to-valley profile/surface deviation FFPv/FFSv: value of the largest negative local profile/surface deviation from the least squares reference feature

2.3 Discussion

The analysis of the ISO standards highlights the lack of a specific standard regarding the verification of free-form profile and surface tolerances. Moreover the study of the state of the art brings out that the use of advanced technologies in verification stage is increasing. The prevalent approach used to have the geometric characterization of a free-form feature compares clouds of measured points with the CAD model of the parts. It consists in an optimization process that minimize the sum of the squared distances between the measured points and the nominal feature, as a function of the rotation and translation parameters.

Differently, in this paper the optimization process is performed as the fitting an offset of the nominal feature to a non ideal feature. The determination of the offset parameter is necessary because in the traditional fitting there is the repartition of the size error contribution in the position, orientation and form error: geometric errors can be overestimated and the rejection of a conformed part can be expected [29]. According to ISO/TS 17450, the separation of size from geometric errors allows more effective machine setting adjustments and the control of process parameters. Furthermore the determination of the offset parameter, and its interpretation as the size error, makes it possible to use a similar approach for the verification of regular as well as free-form features. Unfortunately the computation cost is higher than in the traditional fitting, because the offset parameter is added in the optimization problem.

3 Examples of free-form errors calculation

Some example of free-form profiles and surfaces inspections are reported in the following. The algorithm proposed in [29] has been improved: nominal profiles are defined as NURBS, that are supported in CAD systems and can describe any kind of curves. The algorithm has been extended in 3D and it has been implemented in a CAD environment. The aim of those experiments is to demonstrate the efficacy of the method for the "true" form error calculated.

3.1 Free-form profile inspection

Free-form profiles of moulds for ophthalmic lenses obtained with grinding and polishing operations were studied (Fig. 1). Nominal profile, described by the equation used for aspheric curve

$$z(x) = \frac{1}{p}\left(R - \sqrt{R^2 - p \cdot x^2}\right) \qquad (1)$$

where p is the asphericity coefficient and R is the radius of curvature in the center, is replaced with a NURBS curve (the maximum deviation from the nominal profile is 3.0e-6 mm). Measured points are obtained using the profilometer Zeiss TSK SURFCOM 1800D. In figure 2 the nominal profile and the measured points are shown. To analyse a 2D feature, the algorithm is implemented in MATLAB using functions of MATLAB Optimization Toolbox Library (Fig. 3).

Estimate parameter, as define above, are summarized in table 1. In figure 4 the local deviations estimated for both profiles are reported.

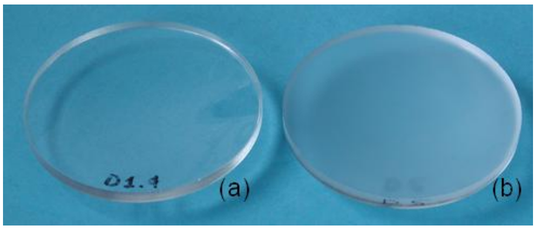


Fig. 1 Measured surfaces:
(a) polished lens; (b) ground lens.

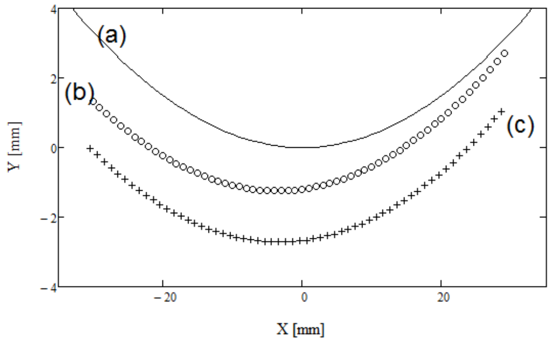


Fig. 2 Nominal profile (a),
p and R are respectively -1.8 and 132.45 mm;
measured points (12000) on ground lens (b)
and polished lens (c)

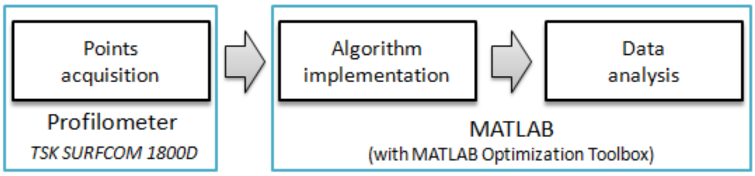


Fig. 3 Inspection process and tools for 3D free-form characterization.

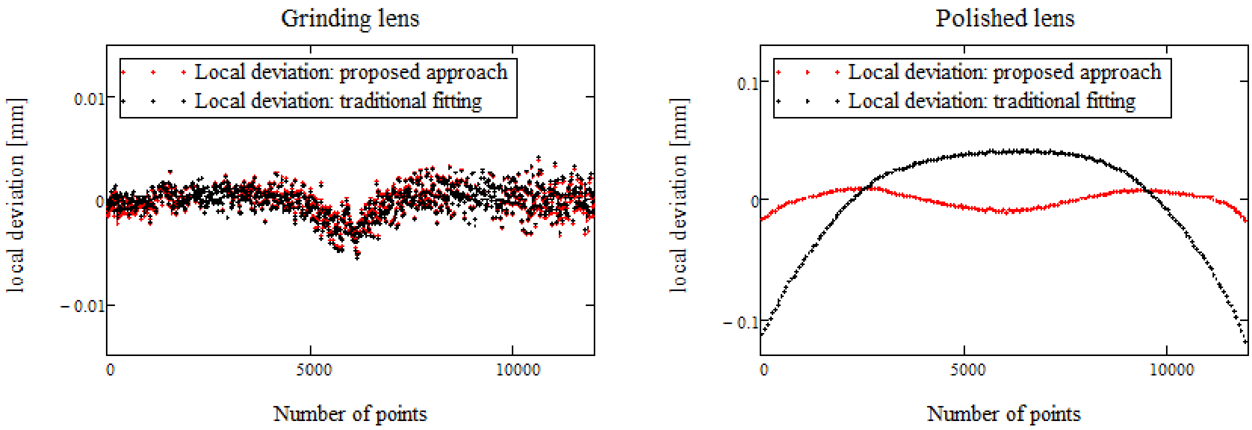
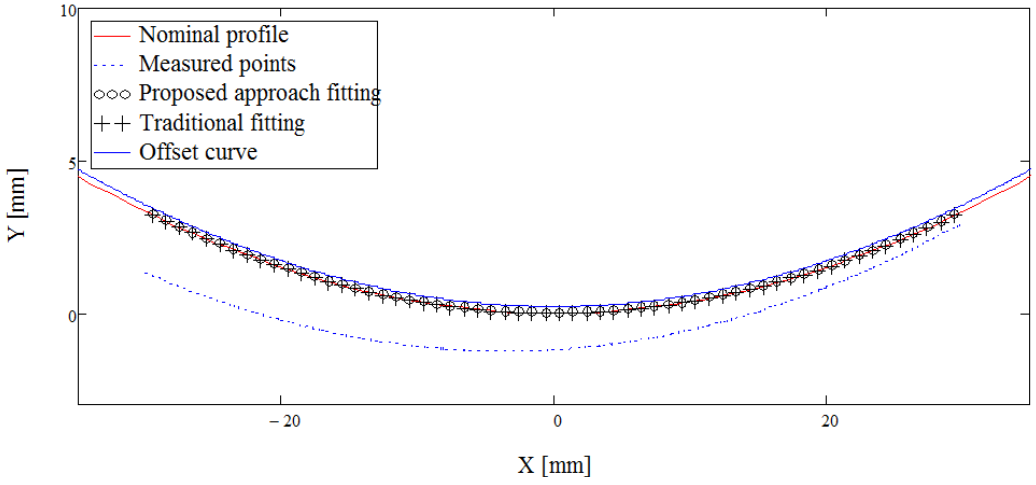


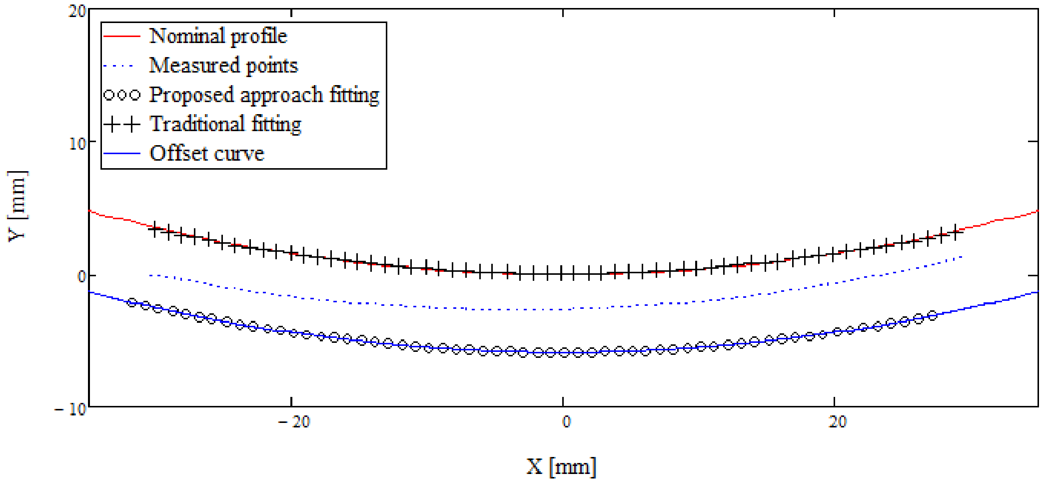
Fig. 4 Local deviation: ground lens on the left; polished lens on the right

		Ground lens		Polished lens	
Parameter		Proposed approach	Traditional fitting LSM	Proposed approach	Traditional fitting LSM
Fitting parameters	Offset [mm]	-0.032916	n.c.	5.888558	n.c.
	Translation [mm]	in x 0.449679 in y 1.228043	in x 0.441914 in y 1.194840	in x -1.394877 in y -3.212377	in x 0.311799 in y 2.718983
	Rotation [rad]	-0.023729	-0.023786	-0.035240	-0.022560
Form tolerances parameters	FFPt [mm]	0.010632	0.010790	0.030455	0.167603
	FFPp [mm]	0.005173	0.005073	0.010913	0.041776
	FFPv [mm]	0.005460	0.005717	0.019543	0.125826

Tab. 1 Parameters obtained for the optical lenses



(a)



(b)

Fig. 5 Best alignments obtained for ground mould lens (a) and polished mould lens (b)

3.2 Free-form surface inspection

Free-form surfaces of an injection moulded lamp lens for automotive industry was analyzed. Points on the surface lens are acquired using a measuring arm (FARO Arm Platinum) equipped with the laser sensor V2. Measurement data are compared with the nominal CAD model. The inspection algorithm for the analysis of the 3D features is implemented in Rhinoceros by the use of Python programming language in order to directly visualize the results of the inspection process (Fig. 6).

The estimation of errors is performed in 3 steps: the first step consists in a pre-localization, using three data points chosen by the user; the second step consists in an automated fine localization, where measured points are aligned as close as possible to the best offset of the CAD model; in the last step, parameters for geometrical characterization are calculated.

Results of the process are summarized in Tab. 2 and shown in Fig. 7. Local deviation distributions are reported in Fig.8.

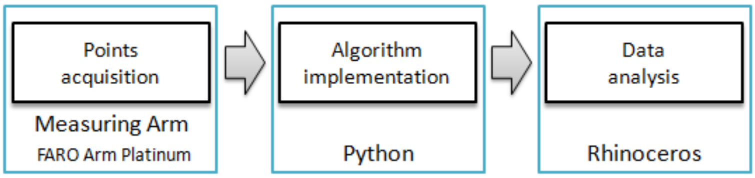


Fig. 6 Inspection process and tools for 3D free-form characterization.

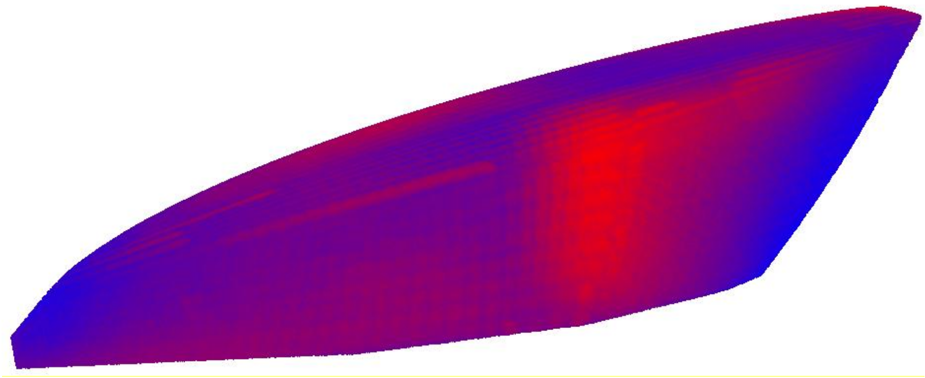


Fig. 7 Colored local deviation calculated on left lamp lens (257000 points)

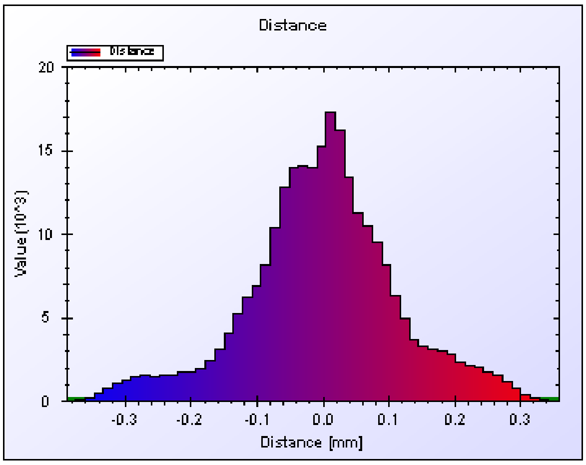


Fig. 8 Local deviation distribution

Injected left lamp lens			
Parameter		Proposed approach	Traditional fitting LSM
Fitting parameters	Offset [mm]	-0.25710	n.c.
	Translation [mm]	in x -0.33407 in y -0.34685 in z -0.79474	n.c.
	Rotation [rad]	in x -0.00475 in y 0.00198 in z 0.00556	n.c.
Form tolerances parameters	FFPt [mm]	0.74637	0.86078
	FFPp [mm]	0.35779	0.45581
	FFPv [mm]	0.38858	0.40497

Tab. 2 Parameters obtained for the lamp lens

4 Discussion

The proposed method was applied to evaluate errors in free-form profiles of moulds for ophthalmic lenses and free-form surfaces of lamp lenses for automotive industry. For 2D profiles at the end of the fitting operation, an offset parameter of -0.032916 mm was calculated for the ground mould lens and of 5.888558 mm for the polished mould lens. The comparison between fitting parameters estimated using this approach and fitting parameter calculated using traditional fitting methods, reported in table 1, emphasizes the repartition of size error contribution in the translation parameter and form errors: the difference increases proportionally to the offset value. In addition when size contribution is not considered the form error (FFPt) is always overestimated as visualized in figure 4. Best alignments are showed in figure 5, which confirms the consistency of the values reported in table 1.

For the 3D surface an offset error of -0.25710 mm was calculated, with the form errors smaller than those calculated using traditional approach.

5 Conclusion

An advanced method for free-form profiles and surfaces verification was presented. The method consists an association operation to fit ideal profile/surface to non-ideal feature as required in ISO GPS standards: unlike most traditional fittings, acquired points are aligned to an offset of the nominal profile/surface. Furthermore in this work are proposed new definitions for the geometric parameters, according with ISO GPS standards regarding form tolerances. Automatic algorithms were implemented to solve 2D and 3D dimensional problems. For 2D profiles the algorithm is implemented in MATLAB; the algorithm for the analysis of the 3D features is implemented in Rhinoceros by the use of Python programming language

Some examples of free-form verification of optical lenses and lamp lenses are proposed in this paper. Results confirm that this advanced fitting approach implies the estimation of lower but more realistic form error.

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