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A novel approach for 3D part inspection using laser-plane sensors

N. Audfray[a], C. Mehdi-Souzani[a,b,]* and C. Lartigue[a,c]

[a]LURPA, ENS Cachan – Univ. Paris Sud, 61 av. du président Wilson, 94235 Cachan cedex, France
[b]IUT St-Denis, Univ. Paris 13, place du 8 mai 1945, 93206 St-Denis cedex, France
[c]IUT Cachan, Univ. Paris Sud, 9 av. de la div. Leclerc, 94235 Cachan cedex, France

Abstract

The paper deals with the relevance of using laser-plane sensors in 3D part inspection. First, based on the evaluation of the measuring system capacities, a digitizing strategy permits to obtain a set of points with a sufficient quality as regards geometrical specifications. Despite the optimized strategy, the digitizing noise associated to the sensor alters data quality, and may affect the estimation of the surface defects (form deviation for instance is strongly affected by digitizing noise). An original filtering method is proposed to remove digitizing noise before the evaluation of the specifications.

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Keywords: 3D Digitizing; Measurement; geometrical Specification; Data treatment; Contactless sensor.

1. Introduction

3D part inspection is a full part of life cycle products [1]. For on-line or off-line (in metrological lab) inspections, CMMs equipped with a touch probe are widely used in industry as they provide high accuracy, repeatability and reliability when measuring part surfaces [2, 3]. However, measurement speed (about a maximum of 60 points per minute) and the accessibility limitation of CMMs represent a serious disadvantage that may involve industrial declining competitiveness. In this context, non-contact measurement systems, as laser-plane sensor based-systems seem to have the potential to address CMM weaknesses. A laser-plane sensor is based on triangulation and consists of a laser projector and a CCD-camera. As the laser source projects a line onto the part to be digitized, the intersection laser-line/part is seen in the CCD camera as shown in Fig. 1b. From the measured pixels, the 3D coordinates of the corresponding measured points are obtained thanks to a calibration stage. Nowadays, the fast technical evolution of laser-plane sensors allows having a high density of data (over 30 000 points per second) in very a short time [4]. Moreover, considering their versatility of use, laser-plane sensor based-systems become very interesting for 3D part inspection [3, 5, 6].

Within this context, studies have recently emerged in the literature about laser-plane 3D inspection. Martinez *et al.* propose to follow some advises in the digitizing strategy to obtain a convergence of acquired data with touch probe sensors (headed on the CMM) taken as reference [1]. Pottmann *et al.* propose to make the inspection by localizing the 3D point cloud (generated by the laser-plane) relatively to the CAD model based on a modified ICP algorithm [7]. The transposition of CMM inspection process to laser-plane sensor inspection is not a successful strategy, as the quality of the resulting measurement strongly depends on the digitizing process [6, 8, 9, 10]. In this direction, Mahmud *et al.* propose to define a digitizing strategy (set of sensor configuration) in function of an uncertainty to respect calculated according to the tolerance interval [11]. Furthermore, it is not possible to affect directly each digitized point to a single surface part. A step of data treatment turns out to be essential, in particular for data segmentation [4, 12, 13, 14]. Therefore, 3D part inspection using non-contact sensors includes two main activities complementary

* Corresponding author. Tel: +33 1 47 40 29 85; fax: +33 1 47 40 22 20.
email: souzani@lurpa.ens-cachan.fr

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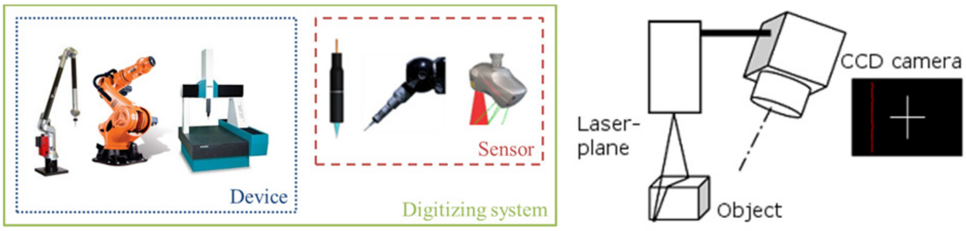

Fig. 1. Digitizing system (a.) and description of a laser-plane sensor (b.)

activities: digitizing path planning according to quality criteria and data treatment and analysis.

In this paper, a specific attention is done to data treatment and analysis in relation with the ISO specification verification. After a short introduction of usual treatment steps as data cleaning and fusion, a segmentation method based on an extension of the Maximally Stable Extremal Regions method (MSER) to meshes is shortly detailed. According to the tolerance interval, data filtering is introduced based on phase correct filters. This filtering operation leads to remove the digitizing noise from the digitized data. The assessment of the filtering approach is proposed thanks to the measurement of a reference feature. Finally, the approach is illustrated using a study case that consists of geometrical specification verification.

2. Digitized data treatment and analysis

Let us consider the inspection of the part defined in Fig. 2 using a laser-plane based system, which consists of a CMM mounted with a laser-plane sensor, oriented via a PH10 head (Fig. 3). The part is acquired thanks to 4 orientations of the sensor, leading to the point cloud presented in Fig. 4. As expected, data are marred with digitizing noise. Although attention has been done to use one sensor orientation per surface, points that do not belong to the desired surface are acquired at the same time, which leads to a set of points of different areas of the part that are not dissociable (Fig. 4). Thus, the point cloud is not usable for part inspection as a specification to be verified is linked with a single surface. A specific treatment is then necessary to make the data exploitable for specification assessment. Two key steps must be performed: data segmentation, and data filtering. The first one leads to the partition of the data into a set of point clouds, each one corresponding to an elementary surface. The second activity allows removing the digitizing noise from the data. In the next, both activities are detailed before the implementation of part inspection. Only the case of the flatness of the plane (S1) and the parallelism of the plane (S5) are investigated in the

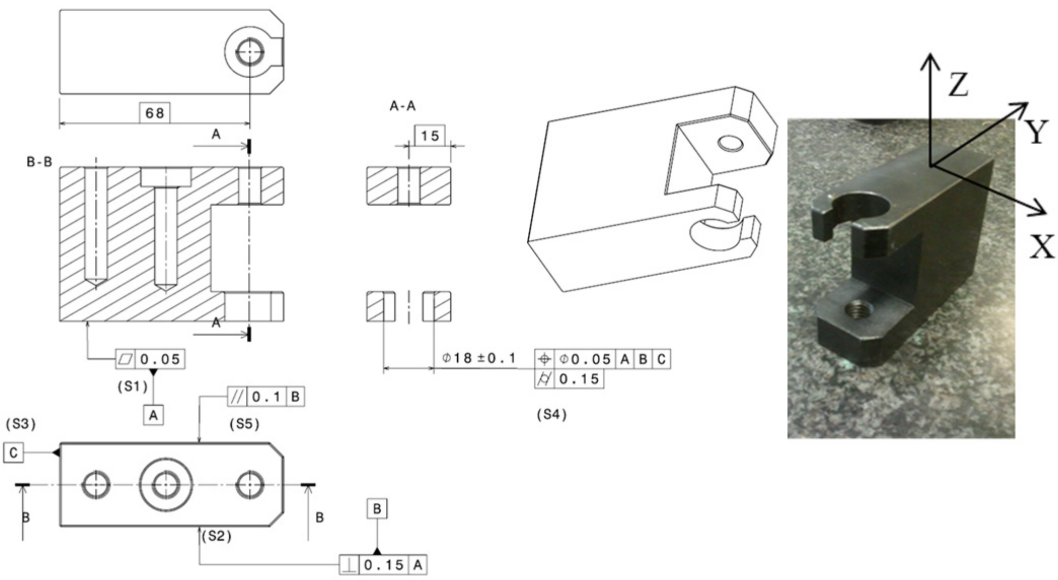

Fig. 2. Part to be controlled

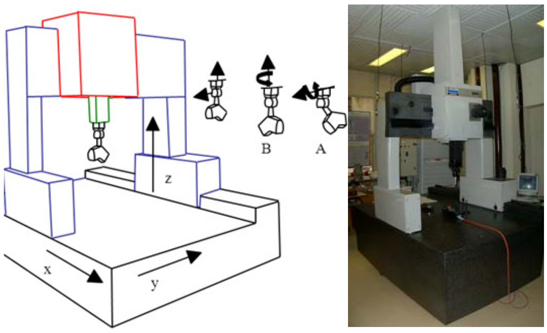

Fig. 3. Laser-plane sensor mounted on CMM

paper.

2.1. Data Segmentation

The segmentation algorithm used first requires the meshing of the point cloud [14]. In a second step the analysis of the surface mesh is performed using a numerical and topological tool: the tree of level sets. For any scalar function defined on the surface mesh, a fast algorithm is used to build topological tree level sets of this function. From this tree it is then possible to extract significant level sets by an extension of the Maximally Stable Extremal Regions method (MSER) to meshes [4]. The intrinsic function used is the mean curvature of the surface. The selection by the MSER of those level lines, allows segmenting the mesh surface into low curvature regions separated by high ridges curvature that probably will define the boundaries. It is then reasonable to make a simple regression model on regions with homogeneous curvature to achieve the segmentation (Fig. 4). Each sub-set of points so identified is associated to its ideal reference surface.

2.2. Data filtering.

The need in data filtering is illustrated through the verification of the form defect specification of plane A. As flatness is concerned, according to the GPS standard ISO 1101 and ISO 12781-1 [15, 16] the extracted surface may be included within the volume defined by two parallel planes the distance of which is given by the tolerance interval. To check the specification, an ideal plane is associated to the acquired points with respect to the Tchebychev criterion (to ensure the minimization of the form deviation). If e_i represents the distance of a point M_i to the associated plane, d_f the flatness is calculated thanks to Eq. *(1)*.

$$d_f = \max_i e_i - \min_i e_i \qquad (1)$$

The specification is verified if $d_f < it$. For the study case, $it = 0.05$ mm. If data are directly used, the form deviation calculated is $d_f = 0.0495$ mm which is very close to the limit. Actually, as shown in Fig. 5, results are strongly affected by digitizing noise. To better understand the issue, the plane is also measured using a touch probe. The evaluation of the form defect using contact-measured points gives $d_f = 0.0261$ mm, which is probably close to the expected result. Therefore, acquired data using the laser-plane sensor cannot be used to evaluate properly form defects without filtering.

The importance of the digitizing noise is investigated by measuring a reference planar surface. The surface is acquired with the laser-plane sensor normal to the surface at the distance of 120 mm to minimize the digitizing noise. The plane is aligned to the y-direction of the CMM and the digitizing is carried out by scanning the surface in this direction (the laser-plane is parallel to the xz-plane). It is interesting to highlight that the noise depends on the direction. Fig. 5a shows the point cloud along the digitizing direction; the noise appears to be Gaussian, whereas in the orthogonal direction, the noise

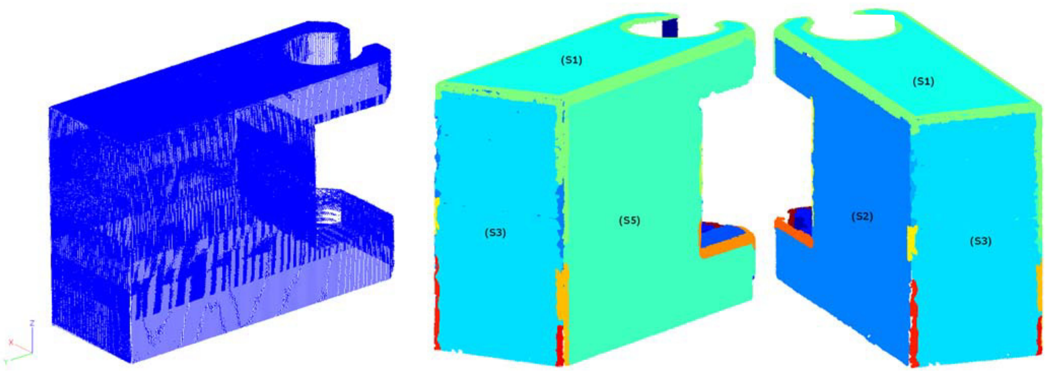

Fig. 4. Digitized part. (a) Digitized point cloud (b-c) Part segmentation

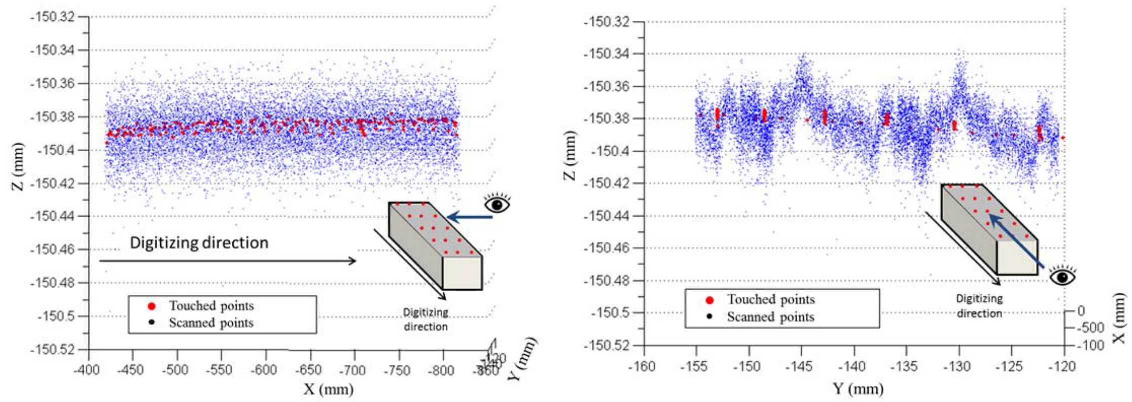

Fig. 5. Scanned point cloud and touch trigger probe point cloud. (a) Digitizing direction (b) Orthogonal to digitizing direction

is different (Fig. 5b). As the noise in the digitizing direction is supposed to be Gaussian, it may be treated as a very short wavelength profile, whereas the noise in the laser-plane field of view may be considered as a short wavelength profile as for the form defect. Thus a wavelength filter may be useful to separate form defect from noise.

2.2.1. Phase correct filters

Among filtering methods proposed in the literature, the use of an analog filtering method to that used in micro-geometry measurements (also called phase correct filters) seems relevant [17]. The interest of such a filter is that it is possible to separate undulation from roughness.

Considering one profile extracted from the measured surface, each point of the 2D profile is moved regarding its neighborhood. If *M* is the point to be moved the following weighting function is applied to the other points of the profile (Eq. *(2)*).

$$s(x) = \frac{1}{\alpha\lambda_{co}} e^{-\pi\left(\frac{x}{\alpha\lambda_{co}}\right)^2} \qquad (2)$$

Where x is the distance between the neighbor and the considered point *M*, and λ_{co} is the cut-off wavelength of the profile filter and with α defined in Eq. *(3)*.

$$\alpha = \sqrt{\frac{\ln 2}{\pi}} \qquad (3)$$

The phase correct profile filter is extended to 3D cases to answer the filtering of digitized data. Considering that the normal to the plane is close to the z-axis, the following weighting function (Eq. *(4)*) has been proposed:

$$s(x,y) = \frac{1}{\alpha\lambda_{co_{eq}}} e^{-\pi\left(\frac{x^2+y^2}{\left(\alpha\lambda_{co_{eq}}\right)^2}\right)} \qquad (4)$$

where x and y represent the distances of a weighted point to the considered point in the **x** and **y** directions. As needs are different in both directions, an equivalent cut-off wavelength is created to take into account the different requirements for cut-off wavelengths and the two distances x and y (Eq. *(5)*).

$$\lambda_{co_{eq}} = \frac{x^2\lambda_{co_x} + y^2\lambda_{co_y}}{x^2 + y^2} \qquad (5)$$

Let z'_M be the z coordinate of an initial point $M(x_M, y_M, z_M)$ after motion, z'_M is given by Eq. *(6)*.

$$z'_M = \frac{\sum_{i=1}^{N} s(x_i, y_i)\cdot z_i}{\sum_{i=1}^{N} s(x_i, y_i)} \qquad (6)$$

A pondered mean is applied to every point and the motion of each point depends on its neighborhood with decreasing influence with respect to the distance to the considered point. In other words, the further a point is from the point to move, the less its weight.

2.2.2. Application to ideal features

To assess the proposed filter, it is applied to the point cloud corresponding to the planar reference surface (Fig. 5) using several cut-off wavelengths. For each case, a plane is associated to the point cloud according to the Tchebyshev criterion, and flatness is calculated using Eq. *(1)*. In Fig. 6 results are reported as well as the value of the flatness obtained when the touch probe is used (d_f =

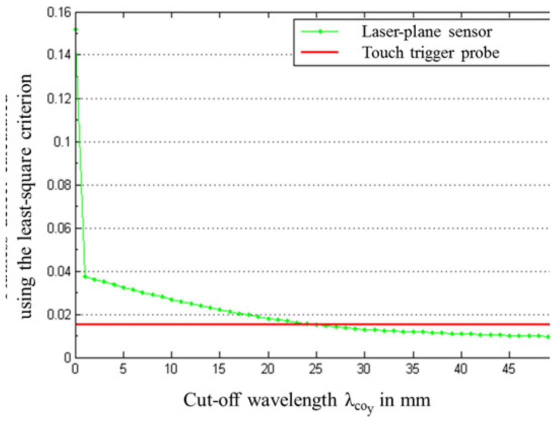

Fig. 6. Flatness results using several cut-off wavelengths

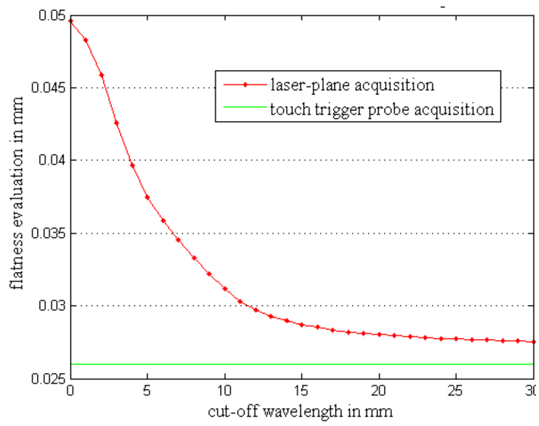

Fig. 8. Flatness results of plane A using several cut-off wavelengths

18 µm). The first main result is that the noise is filtered with a short cut-off wavelength; the value is divided by four with $\lambda_{co} = 1$ mm in both directions.

Therefore, the cut-off wavelength can be set equal to 1mm in the digitizing direction (Fig. 5a). Additional tests are carried out to find the influence of the cut-off wavelength in the other direction. The conclusion that comes as evidence is that the flatness value decreases when the cut-off wavelength increases. Note that, when the cut-off wavelength is greater than 25 mm (Fig. 6), the value of the flatness obtained with the digitized data filtered is slightly less than the reference value (~6 µm). This is probably due to the high point density of the digitized data which leads to a better representation of the surface and thus a better evaluation of the defects, once data are correctly filtered.

Although the acquisition with a laser-plane sensor is noisy, it provides a more complete representation of the surface. Filtering is necessary to determine the form deviation associated to the surface. To remain close to the reference value, the cut-off wavelength must be chosen at 1mm in the digitizing direction, and within the range of [20, 30] (mm) for the other direction.

2.3. Application to the flatness evaluation

Let us go back to the case of the flatness. The flatness assessment is verified if every measured point is included in the volume delimited by two parallel planes distant of 0.05 mm. As the plane (S1) has been digitized in the y-direction, according to the previous section, the cut-off wavelength is set equal to 1mm in this direction. The other one must be chosen between [20, 30] (mm) as previously exposed.

However, to assess the method, all values of the cut-off are tested. Furthermore; the plane is also measured using a touch probe in order to find the best-adapted cut-off as regards the reference form defect (obtained with touch probe). For the first values of the cut-off

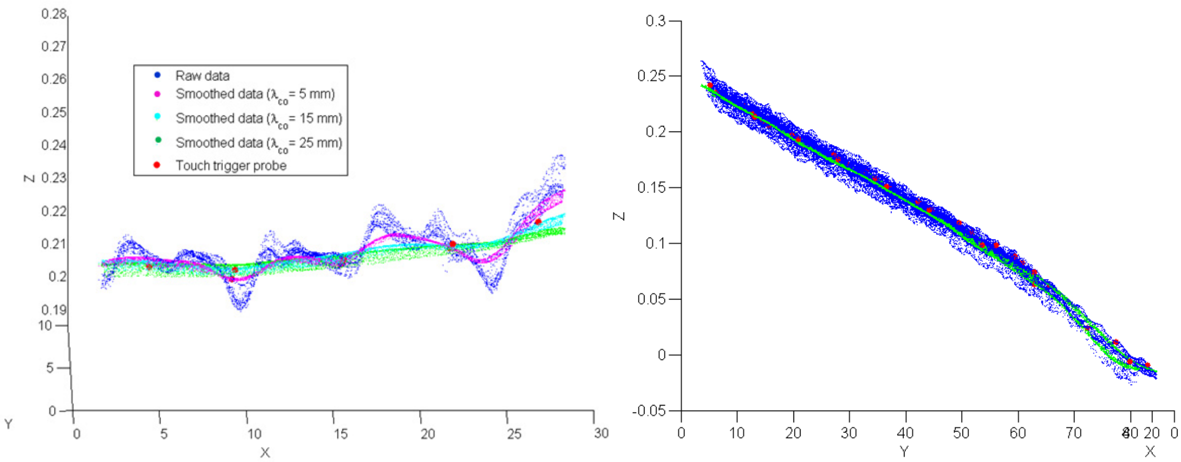

Fig. 7. Raw and smoothed data (a) Digitizing direction (b) Orthogonal to digitizing direction with only λ_{cox}=25mm

wavelength, results are not as significant as those obtained with the marble artefact for the noise filtering. This may be due to marble properties that increase digitizing noise (very short wavelength). Therefore, the effect of the–cut-off wavelength of 1mm is softened. In this case, whatever the cut-off, the flatness evaluated from digitized filtered data remains higher than that obtained with the contact probe. For the latter, data density is poor relatively to that obtained using laser-plane sensor as said before. The good coverage of the surface probably leads to an estimation of the form defect for non-reference surfaces greater than the one obtained with touch probe. The difference is nevertheless very small (less than 3 µm). The choice of a cut-off within the range of [20, 30] (mm) seems relevant. To summarize, filtering is necessary to approach correct values of the form defect when data are obtained with laser-plane sensors. The choice of cut-off wavelengths can be made after the measurement of a reference surface, and in comparison with measurements carried out using a touch probe. Some data are superposed in Fig. 7 to show the influence of smoothing on the point cloud form.

2.4. Parallelism tolerance verification

For the parallelism specification, every point of the surface has to be included within the volume defined by two parallel planes the orientation of which is given by the specified datum (Fig. 2) and distant by 0.1 mm. The datum corresponds to the tangent plane associated to the point cloud (of the surface S2) that minimizes the maximum of the distances. In this case, digitized data corresponding to both planes (the datum and the tolerance plane) must be filtered to ensure a correct estimation of the defect. Therefore, the influence of the datum filtering on the value of the parallelism is investigated. For this purpose, various cut-off wavelengths are tested for the datum, and for each one, the cut-off wavelength of the tolerance plane point cloud was tuned between 0 and 30 mm. As for form deviation, the parallelism defect is also evaluated using the touch trigger probe: d_p = 0.065 mm (Fig. 9). Results are displayed in Fig. 9. As expected, the datum plane needs to be smoothed. Actually, the parallelism defect evaluated without filter is between 13 and 16 µm greater than the reference one (obtained using the touch probe) for the recommended cut-off wavelength of the tolerance surface. Thus, noise introduces an orientation deviation of the associated surface. As shown in Fig. 9, choosing the cut-off wavelength within the range [20, 30] (mm) for both the datum and the toleranced planes leads to evaluate the parallelism deviation close to the reference value: the difference is less than 6 µm.

Thus the same recommendations as for the form deviation evaluation may be considered for the cut-off selection for the smoothing of both the datum and the tolerance surfaces.

3. Conclusion

The main benefits of laser-plane based digitizing systems as timesaving or easiness of implementation make their implementation more and more usual for applications such as 3D inspection. However, the quality of the measurement is less than that obtained when using the touch probe. The paper showed that a specific attention has to be paid to data treatment before

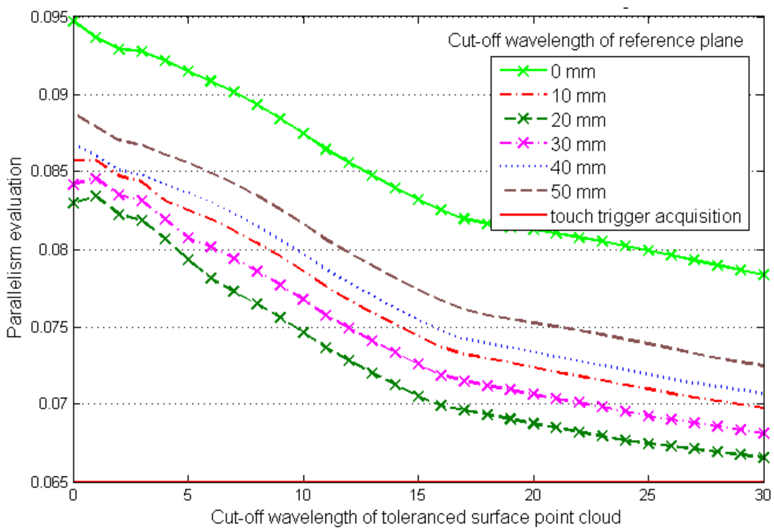

Fig. 9. Parallelism deviation evaluation using several cut-off wavelengths, for both datum and toleranced planes.

application. The needing for data filtering has been clearly demonstrated through the evaluation of form and orientation defects. As it is expected that the noise can be considered as a short wavelength profile and the form deviation as a long wavelength profile, an original filtering method based on the phase correct filters used in micro-geometry has been introduced and assessed. This filter based on different profiles wavelength separation allows filtering noisy data so that classical algorithms of form and orientation deviations may be used with respects to recommendations defined in standards. The efficiency of the smoothing operation is strongly dependent on the cut-off wavelength of the filter. Thus recommendations have been proposed to select the cut-off for both datum and tolerance surfaces. An extension to other surfaces and other types of defects must be conducted. Future works on data smoothing may provide solution to select the appropriate cut-off wavelength as regards the part (materials, color, surface, etc.) and the sensor used. In fact, this selection is strongly linked with the digitizing conditions and may vary for each case.

References

[1] Martínez S, Cuesta E, Barreiro J and Álvarez B. Analysis of laser scanning and strategies for dimensional and geometrical control, *The International Journal of Advanced Manufacturing Technology* 2010; **46** (5-8): 621–9.

[2] Prieto F, Redarce T, Lepage R and Boulanger P. An automated inspection system, *The International Journal of Advanced Manufacturing Technology* 2002; **19**: 917–25.

[3] Li Y and Gu P. Free-form surface inspection techniques state of the art review, *Computer-Aided Design* 2004; **36** (13): 1395 – 417.

[4] Mehdi-Souzani C, Digne J, Audfray N, Lartigue C and Morel JM. Feature extraction from high-density point clouds: toward automation of an intelligent 3d contact less digitizing strategy, *Computer-Aided Design & Applications* 2010; **7** (6): 863–74.

[5] Audfray N, Mehdi-Souzani C and Lartigue C. Assistance to automatic digitizing system selection for part inspection, *ASME 2012 11th Biennial Conference on Engineering Systems Design And Analysis*, 2012, to be published.

[6] Son S, Park H and Lee KH. Automated laser scanning system for reverse engineering and inspection, *International Journal of Machine Tools and Manufacture* 2002; **42** (8): 889–97.

[7] Pottmann H, Wallner J and Leopoldseder S. Kinematical methods for the classification, reconstruction, and inspection of surfaces, *Proceedings SMAI*, Pompadour, France, 2001.

[8] Contri A. *Qualité géométrique de la mesure de surfaces complexes par moyens optiques*, Ph.D. thesis, École Normale Supérieure de Cachan (2002).

[9] Mehdi-Souzani C. *Numérisation 3d intelligente d'objets de formes inconnues basée sur des critères de qualité*, Ph.D. thesis, École Normale Supérieure de Cachan (2006).

[10] Mehdi-Souzani C, Thiébaut F and Lartigue C. Scan planning strategy for a general digitized surface, *Journal of Computing and Information Science in Engineering* 2006; **6** (4) 331–40.

[11] Mahmud M, Joannic D, Roy M, Isheil A and Fontaine JF, 3d part inspection path planning of a laser scanner with control on the uncertainty, *Computer-Aided Design* 2011; **43** (4): 345–355.

[12] Zhao H. *Multisensor integration and discrete geometry processing for coordinate metrology*, Ph.D. thesis, École Normale Supérieure de Cachan (2010).

[13] Osty G. *Extraction de particularités sur données discrètes issues de numérisation 3d. Partitionnement de grands nuages de points*, Ph.D. thesis, École Normale Supérieure de Cachan (2002).

[14] Digne J, Morel JM, Audfray N and Mehdi-Souzani C, The level set tree on meshes, *Fifth International Symposium on 3D Data Processing, Visualization and Transmission*, Paris, France, 2010.

[15] ISO 1101, *Geometrical Product Specifications (GPS) — Geometrical tolerancing — Tolerances of form, orientation, location and run-out* (2006).

[16] ISO 12781-1, *Geometrical Product Specifications (GPS) — Flatness — Part 1: Vocabulary and parameters of flatness* (2011).

[17] ISO 11562, *Geometrical Product Specifications (GPS) – Surface texture: Profile method – Metrological characteristics of phase correct filters* (1998).