Wear analysis through surface relocation

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Abstract. The present paper reports a new method for relocating three-dimensional surface topographies accurately, based on comparison between different displacement vectors and allowing compensation of lateral and rotational misalignments. Relocation is the main step for allowing exploitation of traceable quantification of surface modification, due to wear, etching or friction. The performance of the relocation routine was tested on a reference sample, featuring an array of peaks with a constant lattice of 2.12 µm.

1. Introduction
Characterization of surfaces and of surface evolution is a fundamental topic in precision engineering: scanning probe microscopy, as well as optical techniques can reproduce three dimensional topographies with very high accuracy [1]. On the other hand, inadequate stages cannot provide enough accuracy, and larger areas must be scanned in order to compensate errors occurring during positioning process.

Relocation post-processing operations are particularly valuable and necessary when comparison of corresponding areas is needed: this is the case of micro-engineered surfaces, replica analysis and fine surface evolution control. Finding exactly the same area is fundamental in order to properly characterize modifications and variation occurring with time between correlated surfaces.

Some work has already been proposed for relocation purposes, involving simple instrument relocation [2, 3], integration of reference grids [4], or use of simplex approach, based on reflection, expansion and contraction operations [5]. The present paper reports a new method for relocating three-dimensional surface topographies accurately, based on comparison between different displacement vectors and allowing compensation of lateral and rotational dislocations. Relocation eventually allows traceable quantification of wear volumes. Tests are reported on virtual images and actual surfaces, undergone to surface modification and subsequent estimation of worn volumes with the proposed technique.

2. Wear analysis
The developed method for analysis of surface evolution can be described according to the algorithm reported in figure 1. Firstly, topography measurements performed on the surface before and after modification (due for instance to wear, chemical etching or abrasive friction) are compared through the multiple cross-correlation relocation method, in order to recognise and compensate relative
translational and rotational misalignment. Once the corresponding surface portions are recognised, the difference is calculated operating a point by point subtraction: at this stage, if necessary, a resampling can be performed in order to provide coherent data sets. At the last step the total difference is measured by means of root mean square parameter (Sq parameter in roughness analysis) or by analysing the residual volume.

Figure 1. Algorithm and graphical representation for the estimation of surface variations.

3. Relocation

The developed relocation method is minded for couples of topographies, reproducing at least some portion of surface in common. Thanks to its simple architecture, results are achieved in a few seconds, even when heavy data file topographies are to be processed. The sequence of operations performed by the implemented relocation algorithm is described in the following; for simplicity, the topographies will be hereon referred to as initial and modified surface.

1) Four areas are selected in the initial surface and four are correspondingly localized in the modified surface. Those are resembled by squares in figure 2.

2) Horizontal and vertical single pixel shifts are given to comparison areas in the modified surface: after each shift, a cross correlation function is calculated [6]:

\[ cc = \frac{\sum_{x,y} [(x_r - \bar{z}_r) \cdot (x_c - \bar{z}_c)]_{(x,y)}}{\sqrt{\sum_{x,y} (x_r - \bar{z}_r)^2_{(x,y)} \cdot \sum_{x,y} (x_c - \bar{z}_c)^2_{(x,y)}}} \]  

where \( z_r \) and \( z_c \) represent the local surface height at the horizontal coordinate \( x, y \) in each of the four areas, respectively for the initial and for the modified surface; \( \bar{z}_r \) and \( \bar{z}_c \) are the mean values estimated in each of the four areas respectively in the initial and in the modified surface.

Best matching positions (blue squares in figure 2) are found by maximizing (1).

3) After best matching position has been found for each comparison area, displacement vectors are evaluated. In figure 2, vectors \( \vec{v}_1, \vec{v}_2, \vec{v}_3 \) and \( \vec{v}_4 \) are symbolized by black arrows.

4) Vectors are eventually processed and operated in order to find average translational (red dotted arrows in figure 2) and rotational misalignment (green arrows in figure 2).
Figure 2. Vectors are processed and divided into translational ($\vec{v}_t$, dotted arrows) and rotational components ($\vec{v}_r$, green arrows); red and blue squares represent the detected corresponding areas.

The automatic routine was implemented into commercially available software for surface topographies analysis [7]. Investigations were performed by applying the developed software tool to surface topographies couples, reproducing a finely controlled rototranslational motion. Tests were performed on a silicon reference standard featuring an array of peaks (inverted tips) collated at the corners of a square grid, with a lattice of 2.12 µm (see figure 3a). This was eventually compared with the automatic routine output. In the figure below, main results regarding evaluated translation and rotation vectors are presented (figure 3b and 3c).

Figure 3. a) Reference sample used for testing. b) Absolute deviation between actual and evaluated rotation and (c) translation.

4. Reference area
Once the relative misalignment between the initial and the modified surface topography is compensated, surfaces portions present in both topographies are isolated while the rest is cut out. Thereafter, surface topographies are resampled, in order to have coherent data sets, with the same resolution and the same points relative positioning.

In order to verify where surface modification took place, corresponding areas have to be analysed again. The best strategy for recognising surface modification is to locally analyse cross correlation between corresponding surface portions. Positions where cross-correlation reduction exceeds measurement repeatability are recognised as "modified positions" (red shadowed areas in figure 1). Conversely, where surface topography modification is less than measurement repeatability (including noise and resolution) are recognized as "unmodified positions" (light blue shadowed areas in figure 1).

Unmodified positions are then used to define a reference plane for compensation of installation slope and surface flattening. On the other hand, once segmented modified positions are used in order to compute surface modifications.

Definition of unmodified positions is fundamental in order to define vertical relative positioning of corresponding surface portions. Such vertical alignment is indeed responsible for definition of the zero position, needed for measurement of volume or analysis of root mean square deviations. In figure 4
volume (represented by the blue region) is highlighted in the case of two different vertical positions for the reference zero line (dotted line): it is evident how such variation exponentially modifies volume definition.

![Figure 4](image)

**Figure 4.** Absolute deviation between actual and evaluated rotation (a) and translation (b).

From our experience a reliable definition of vertical relative position can be found when at least 25% of unmodified surface regions can be detected and used for comparison. To this end a key role is played by the accuracy of the measuring system. Indeed the lower is the repeatability of the measuring system, the lower will be the ability in operating a precise segmentation, from modified and unmodified surface portions.

5. Discussion and conclusions
The present paper reports a new method for relocating three-dimensional surface topographies accurately, based on comparison between different displacement vectors and allowing compensation of lateral and rotational misalignments. The automatic routine results are here summarized:

1) The developed method is based on an approximated algorithm: comparison areas are horizontally and vertically shifted in order to find local motions. In case of big rotations, rotational shifts should have to be taken in account: therefore the method is much incorrect as well as bigger rotations have occurred (figure 3b). This can be considered quite a minor problem, since stages can normally ensure an angle control with accuracy abundantly smaller than 5°.

2) Routine output is influenced by surface topographies resolutions: in fact higher deviations were detected whenever lower resolution topographies were analyzed (figure 3b and 3c). This problem can be overcome by considering a resolution software increase: in this way sub pixel accuracy can be achieved.

3) The developed method is not considering and evaluating deformations: for this reason these can lead to staggered results.

The developed method can be applied to all instruments for surface topography characterization: scanning probe, scanning electron, optical based microscopes, etc.

Main interests related with the new analysis tool are connected with exploitation of traceable quantification of surface modification, due to wear, etching or friction.

References

[1] Lonardo P M, Lucca D A and De Chiffre L 2001 Emerging trends in surface metrology *Ann. CIRP* 51(2) 701-723
[2] Pawlus P, Galda L, Dzierwa A, Koszela A 2009 Abrasive wear resistance of textured steel rings *Wear* 267 1873-1882
[3] Cabinettes F, Claret-Tournier J, Mohlin J, Nilsson P H, Rosén B G and Xiao L 2009 The evolution of surface topography of injection cams *Wear* 266 570-573
[4] Zhang H, Brown L, Blunt L and Barrans S 2009 Evaluation of fretting wear on the femoral stem surface *Int. Conf. on Bioengineering & Biomaterials*
[5] Condeo J, Christensen L H and Rosen B G 2001 Software relocation of 3D surface topography measurements *Int. J. Machine Tools and Manufacture* 41 2095-2101
[6] Vorburger T V, Song J F, Chu W, Ma L, Bui S H, Zheng A and Renegar T B 2010 Applications of cross-correlation functions *Wear* (In press, Corrected Proof) doi:10.1016/j.wear.2010.03.030)
[7] Scanning Probe Image Processor (SPIP™), developed by Image Metrology A/S, www.imagemet.com.