Title:
Curvature-based Coarse Registration for Dimensional Metrology

Authors:
Rindra Rantoson, rindra.sanders@lne.fr, LNE-CNAM, FRANCE
Charyar Mehdi-Sourzani, souzani@lurpa.ens-cachan.fr, LURPA, ENS Cachan, FRANCE
Nabil Anwer, anwer@lurpa.ens-cachan.fr, LURPA, ENS Cachan, FRANCE
Hichem Nouira, hichem.nouira@lne.fr, LNE-CNAM France

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Introduction:
In high-precision dimensional metrology, several and multiple measurements by means of various optical and tactile probes are required to measure the whole outer shape of freeform workpieces while controlling reliability and accuracy of the results. Data obtained from one or several measuring machines equipped with one or several probing systems are characterized by different representations, different measurement uncertainties, different/limited overlapping sections and different spatial organization of points. These data are then aligned and fused into a common coordinate system using a registration technique by computing the corresponding optimal rigid transformation parameters to obtain only one set of data covering the entire measured freeform workpiece.

Registration process which almost involves both coarse and fine registration is done per two data sets (scene data and model data) endowed with common overlapping sections. The coarse registration aligns roughly the two data sets with a lower resolution from a global view. The outcome alignment is thereafter optimized (eq.1) through the fine registration for a higher resolution. Standardized iterative methods have been established for fine registration, in quality inspection and in reverse engineering, such as Iterative Closest Points (ICP) and its variants [1].

$$(\boldsymbol{R},\boldsymbol{T}) = \ min_{\boldsymbol{R},\boldsymbol{T}} \sum_{i=1}^{\Omega} \left\| \boldsymbol{R}\boldsymbol{p}_i + \boldsymbol{T} \ - \boldsymbol{q}_i \ \right\|^2 \qquad (1)$$

Where

$(\boldsymbol{R},\boldsymbol{T})$ are the transformation parameters involving the rotation $\boldsymbol{R}$ and the translation $\boldsymbol{T}$.

$(\boldsymbol{p}_i, \boldsymbol{q}_i)$ are the paired points.

$\boldsymbol{\Omega}$ is the number of correspondences $(\boldsymbol{p}_i, \boldsymbol{q}_i)$.

For coarse registration, no conventional method has been adopted yet despite a significant number of techniques which have been developed in the literature to supply an automatic rough matching between data sets [2]. Although the coarse registration aims at aligning roughly two clouds of points together, the result of this first operation is important since the accuracy of the fine registration depends on it.

Main Idea:

In dimensional metrology, coarse registration is widely carried out using interactive approach or/and marker-based approach. Thus, in this paper, we suggest two automatic coarse registration methods for dimensional metrology: an improved Hough transform method and a variant of Ransac method, which both are based on the exploitation of curvature features. For that purpose, shape operator matrix (eq.2 and Fig.1) is computed for each vertex using the modified Cohen-Steiner [3][4] curvature estimation method elaborated in [5].

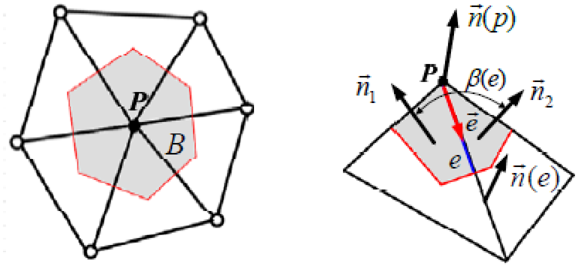
$$\bar{\bar{H}} = \frac{1}{A}\sum_{e\in E}\lambda_e.\ \beta(e).\mathrm{length}(e\cap B).\ (\vec{\bar{e}}\times\vec{\bar{e}}) \qquad (2)$$

where

$$\lambda_e = \frac{\cos^{-1}(\overline{n(p)}.\overline{n(e)})}{\sum_{e\in E}\cos^{-1}(\overline{n(p)}.\overline{n(e)})},\ \vec{n}(e) = \frac{\vec{n}_1+\vec{n}_2}{\|\vec{n}_1+\vec{n}_2\|},\ \vec{n}(p) = \frac{\sum_{i=1}^{K}\omega_i.\vec{n}_i}{\|\sum_{i=1}^{N}\omega_i.\vec{n}_i\|} \qquad (3)$$

With

B, the local region generated on a one-ring neighborhood of the vertex p.
A is the area of B.



(a) (b)

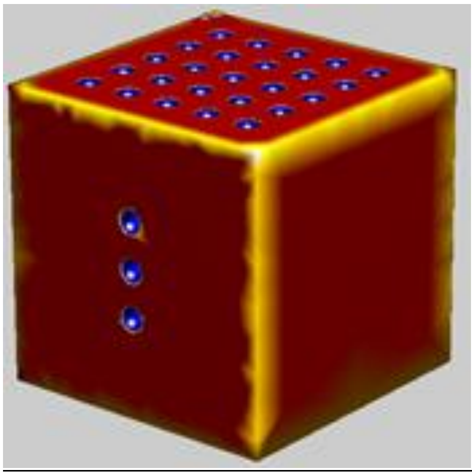
Fig. 1: (a) Local region B associated to a vertex P; (b) Illustration of the angle $\beta(e)$.

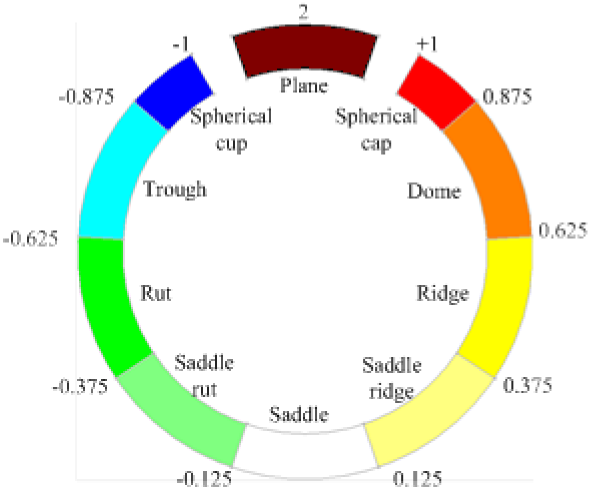
Minimum, maximum principal curvatures and a local frame defined by the normal curvature and the principal curvature directions are derived from the shape operator matrix via eigenvalue decomposition. Shape descriptors including shape index formulated in eq.4 and represented in Fig.2 (a) and (b) and curvedness are afterwards deduced and vertices are classified accordingly. The novel proposed approaches exploit this classification to prune research space which considerably reduces computational time and storage memory.

$$s = -\frac{2}{\pi}\tan^{-1}\left(\frac{\kappa_1+\kappa_2}{\kappa_1-\kappa_2}\right) \qquad (4)$$

Where

κ_1 and κ_2 are the principal curvatures with $\kappa_1 \geq \kappa_2$.





(a) (b)

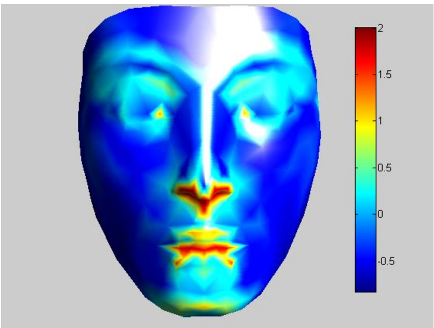
Fig. 2: (a) Illustration of the shape index defining the surface type; (b) Surface type illustration.

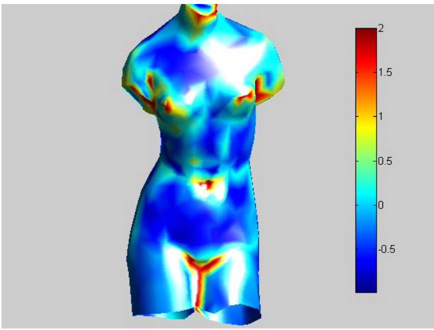
For Hough transform [6], during the exhaustive transformations search, instead of computing the set of transformation parameters from each local frame of the scene data paired with each one of the model data, the set of transformation parameters are only calculated for vertices of the same shape index class.

For Ransac [7], a combination of geometric distance constraints with curvature features constraints is proposed to improve the registration accuracy while reducing correspondences searching time. Thus, the outcome candidates from the geometric distance constraints application will be filtered with respect to shape index and curvedness. Only paired vertices of the same shape descriptors are finally retained for the transformation parameters calculation.

For fine registration, basic ICP is implemented with the use of Singular Value Decomposition (SVD) to solve the minimization problem formulated in eq.1.

The developed algorithms have been tested and validated on a simulated dataset representing a freeform part and generated using CATIA software. The generated cloud of points on which different levels of noise and systematic errors are added, is thereafter subdivided into several data regions.

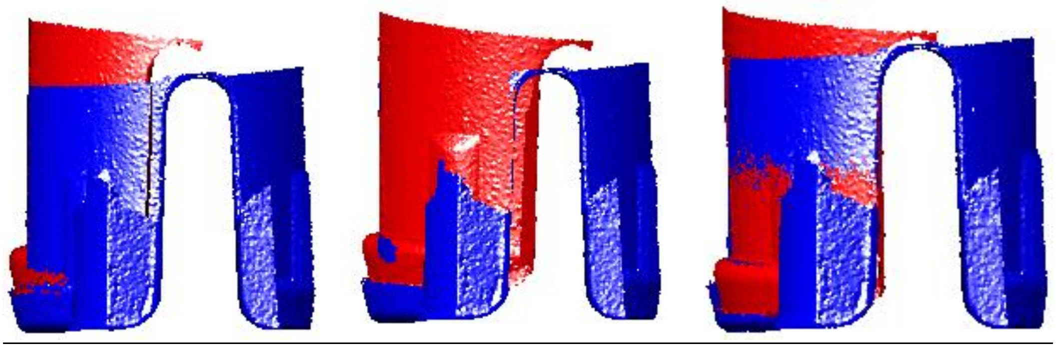




(a) (b)

Fig. 3: Example of Curvature distribution (a) Nefertiti curvature; (b) Venus curvature.

The both developed Hough and Ransac methods are applied and the residuals are compared. A second comparison is done on real data obtained when measuring new developed standard artefacts made of plastic and metal. Different surface features of the artefact are performed via optical and tactile probing systems equipping a CMM machine. The measurement of the artefact is also performed by Zeiss Computed Tomography X system for internal and external shapes with an accuracy at the micrometer level. Again, both the developed Hough and Ransan method are applied and the results are compared. Illustrations of Hough and Ransac results are provided in Fig.4.



(a) (b) (c)

Fig. 4: (a) Hough results; (b) and (c) two illustrations of Ransac results with *k*-random sampling = 20.

Conclusions:

An innovative automated registration method is introduced without the requirement of an operator interaction or the need to use an additive marker on the measured data. Actually is the curvature of the surfaces which is used as local intrinsic geometric marker. Hough and Ransac approaches are integrated to the proposed method in order to increase the registration quality and to decrease the computation time. Thanks to a comparative study case, we can say that computation with Ransac is fast and the resulted registration quality is *k* random sampling times depending while Hough provides a constant result and the computation (speed and quality) mainly depends on the calculated curvature quality. Thus, the meshing is highly important for the curvature features extraction, which implies that data sets should be correctly meshed in a similar manner for both data.

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