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Review

# Nonrigid geometric metrology using generalized numerical inspection fixtures

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ABSTRACT

Freeform surfaces have become an integral part of the automobile and aerospace industries. The parts with a very thin wall in proportion to their size are referred to as nonrigid (or flexible) parts. Generally, for the geometric inspection of such flexible parts, *special inspection fixtures*, in combination with coordinate measuring systems (CMM), are used because these parts may have different shapes in a *free state* from the design model due to dimensional and geometric variations, gravity loads and residual strains. A general procedure to eliminate the use of inspection fixtures will be developed. Presented methodology is based on the fact that the interpoint geodesic distance between any two points of a shape remains unchangeable during isometric deformation. This study elaborates on the theory and general methods for the metrology of nonrigid parts. We will merge existing technologies in metric and computational geometry, statistics, and finite element method to develop a general approach to the geometrical inspection of nonrigid parts.



**Contents**



## 1. Introduction

It is clear that quality product control is essential to company survival in a competitive market. With *computer-aided inspection* (CAI), raw data from a 3D scanner or CMM can be compared to the original CAD design to generate impressive inspection reports. Generally, for the geometric inspection of nonrigid parts, *inspection fixtures*, in combination with coordinate measuring systems (CMM), are used. The aim of this study is to develop new methodology to eliminate the use of inspection fixtures. Three-dimensional optical digitizing systems are suitable for the measurement of large-sized flexible parts for they allow non-contact measurement and are able to deliver, in a relatively short time, large clouds of points that are representative of object surfaces. The part is setup on a portable 3D optical digitizing system which is installed in

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**Nomenclature**

| | |
|---|---|
| $y'_i$ | image of $x_i \mid x_i \in X$ in $Y$ |
| $\sigma$ | stress |
| $(X, d_X)$ | metric space where $d$ is a metric on $X$ |
| $a_{ij}$ | $ij$th element of matrix $A$ |
| $d_{GH}$ | distance Gromov–Hausdorff |
| $d_H$ | distance Hausdorff |
| dis $f$ | distortion of the map $f$ |
| $D_X$ | symmetric matrix of pairwise geodesic distances (for $n$ points, it requires $(n(n-1))/2$ calculations) |
| $d_X(a, b)$ | distance between a pair of points |
| $\mathbb{R}^m$ | $m$-dimensional Euclidean space |
| $R$ | geometric deviation |
| $t_i$ | triangle index |
| $t$ | workpiece thickness |
| X | surface |
| $Y_M$ | space $Y$ sampled by $M$ points |

a production line regardless of datum shown in the engineering drawings. Due to weight, and of course supports, part deformations occur. An identification method must be defined in order to extract geometrical profile deviations due to manufacturing defects while simulating the *use state* to compensate for a spring-back effect and gravity.

In many cases, it is possible to associate specific products, materials, and manufacturing processes with particular types of seeable surface defects. For instance, injection-moulded components may tend to present undesired sink. Similarly, cutting, grinding, and polishing operations may produce characteristic surface markings, including an altered texture and excessive burrs due to tool wear or the inclusion of foreign abrasive materials. It is important to appreciate that in each case, in addition to possible surface discoloration, these defects tend to induce a deviation in the component's surface shape away from a nominal form. The nature of this deviation, or the type of expected defect, is often somewhat predictable. If in addition, a causal mechanism can be identified, then a quantitative analysis of such defects may be used as a basis for automatic process control. These surface defects can be recognized with machine vision technologies. They can also be classified with pattern recognition methods. This study does not address these methods.

The remainder of this paper presents the theory and methods for geometric inspection in nonrigid parts. Section 2 provides a comprehensive literature review of the necessary fields. Section 3 gives theoretical foundations in metric and discrete geometry as well as fast marching method and multidimensional scaling. In Section 4 we introduce the methodology to measure the geometric deviation of nonrigid bodies. Section 5 gives verification and validation of these methods using four case studies. Section 6 presents conclusions.

## 2. Prior works

### 2.1. Geometric inspection of solid and flexible parts

Non-contact 3D digitizing systems exposed a new horizon in industrial inspection of both rigid and nonrigid parts because they deliver much more data than mechanical probes, in a shorter time. A state of the art review of the most important measuring techniques is presented in [1] along with their capacity for freeform measuring tasks. Throughout these presented methods [2–5], the manufactured part is assumed to have a similar shape to the CAD model, allowing for comparison. All presented methods, and most recently Ravishankar et al. [6], have used rigid registration as similarity measures.

Weckenmann and Gabbia [7] proposed a measuring method using virtual distortion compensation. They used the measurement results to extract object features like holes or edges. Some of these were relevant to the assembly process; others were subject to further inspection. From the information about the transformation of assembly features from their actual to their nominal position, virtual distortion compensation was used to calculate feature parameters of the distortion compensated shape. Their method was not completely automated because the suggested method needed some human challenges to identify the correlation between some special points like holes and assembly joint positions. These led the controller to find the boundary conditions of the FEM problematic. Besides, transforming the point cloud to a computer-aided analyzable model is a very time consuming process. These drawbacks then largely improved in [8]. To this end they deformed CAD-model and mapped it towards range data. By this way, they decreased the time of inspection. A FEM-mesh created from a CAD-model, also provided more precise results than a triangle mesh from measurement results. However, proposed method still needed human intervention in order to find the correspondence between CAD-model and range data.

The concept of the *Small Displacement Torsor* (SDT) was developed by Bourdet and Clément [9] to solve the general problem of a geometrical surface model fit to a set of points using rigid body movements. Lartigue et al. [10] took advantage of the possibilities offered by voxel representation and SDT method for the dimensional metrology of flexible parts. This time, they considered the effect of gravity and the spatial location of a scanned part. This method is fundamentally based on finding the correspondence between the cloud of all measured points and CAD meshed data. In fact, the SDT is more suitable for small deformations.

Abenhaim et al. [11] developed an *Iterative Displacement Inspection* (IDI) which smoothly deformed the CAD mesh data until it matched the range data. Their method was based on optimal step nonrigid ICP algorithms [12]. The point cloud needs to be dense enough because the method's similarity measure is based on the nearest distance calculation. The method depends on finding some flexibility parameters which could vary according to thickness. The mentioned drawbacks cause previously mentioned methods to limit their applicability in industrial applications.

### 2.2. Rigid and nonrigid surface registration

Besl and McKay [13] developed an iterative method for the rigid registration of 3D shapes. The ICP algorithm is one of the common techniques for the refinement of partial 3D surfaces (or models) and many variant techniques have been investigated [14,15]. Shi et al. [16] pointed out that ICP-based algorithms may not fit inspection applications because the transformation matrix for registration is estimated in a way that total shape error is minimized. This cannot be applied to industrial quality control. Myronenko et al. [17] introduced a probabilistic method for rigid, affine and nonrigid point set registration, called the Coherent Point Drift algorithm. They considered the alignment of two point sets as the probability density estimation, where one point set represents the Gaussian Mixture Model centroid, and the other represents the data point. They iteratively fitted the GMM centroids by maximizing the likelihood and found the posterior probabilities of centroids, which provide the correspondence probability. The method based on forcing the GMM centroids to move coherently as a group preserved the topological structure of the point sets.

The *Fast Marching Method* was introduced by Sethian [18–20] as a computationally efficient solution to *Eikonal equations* on flat domains. The fast marching method was extended to tri-