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Robust localization to align measured points on the manufactured surface with design surface for freeform surface inspection☆

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HIGHLIGHTS

- A method is developed for predicting variances of localized measurement points.
- Robust rough localization is conducted by matching various geometric properties.
- Robust fine localization is conducted by selecting the optimal coordinate system.

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ABSTRACT

Inspection of a manufactured freeform surface can be conducted by sampling measurement points on the manufactured surface and comparing the measurement points with the ideal design geometry and its tolerance. Since the measurement coordinate system and design coordinate system are usually different, these measured points should be first aligned with the design surface through localization. In this research, robust localization methods are developed for both rough localization and fine localization processes. For rough localization, some target measurement points are selected and their corresponding points on the design surface are obtained based on similarities in curvatures and distances of these points. Compared with curvatures that are often used in localization, the distances are less sensitive to the errors introduced in manufacturing and measurement processes. In fine localization, uncertainties in the measurement and localization processes are considered to predict the uncertainties of the localized measurement points. The optimal design coordinate system is also selected such that the uncertainties of the localized measurement points can be minimized. Two case studies are provided to demonstrate the effectiveness of the developed methods for freeform surface inspection.

1. Introduction

Freeform surfaces, such as turbine blades, car bodies and boat hulls, have been widely used in different industries including automotive, aerospace, marine, and biomedical engineering. Advanced manufacturing technologies, such as 5-axis CNC machining, are used to manufacture parts with freeform surfaces. Since performance of a part with freeform surfaces is significantly influenced by its correct geometry, inspection is often carried out to compare the geometry of the manufactured freeform surface with the ideal design surface and its tolerance requirement defined in a CAD system.

Inspection of a freeform surface is usually conducted by sampling measurement points on the manufactured surface and comparing these measurement points with the design surface. Since the measurement coordinate system is often different from the design coordinate system, the localization process has to be carried out to transform the measured points from the measurement coordinate system to the design coordinate system. Localization is usually conducted in two steps: rough localization and fine localization [1]. Measurement points on a manufactured freeform surface can be acquired by using either contact measurement devices such as coordinate measuring machines (CMMs) or non-contact measurement devices such as three-dimensional (3-D) laser scanners [1]. The number of measured points and the distributions of these measured points influence the accuracy of the localization result [2]. In addition, the accuracy of the measurement device also influences the quality of localization [3].

In the rough localization process, a rough coordinate transformation matrix is obtained to approximately align the measurement points with the design surface. When the measurement coordinate system is quite different from the design coordinate system, the measured points cannot be directly projected onto the

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design surface to find their corresponding points. In rough localization, the intrinsic geometric properties that are independent of coordinate system, such as curvatures, are often used for identifying the corresponding points. In this research area, Yamany and Farag [4] introduced a method to match surface signatures that distinctly represent the surface curvature information observed from certain points. Ko et al. [5] developed a method to select three measured points and match them to their corresponding points on the design surface based on similarities of Gaussian and mean curvatures. Li and Gu [6] extracted and matched geometrical features on the measured and design surfaces based on similarities of Gaussian curvature and some other evaluation measures. The main problem in rough localization is the sensitivity of curvature to geometrical error. Trying to solve this problem, OuYang et al. [7] developed a robust initial matching scheme by matching the Delaunay pole sphere (DPS) as an orientation independent property rather than matching curvatures. OuYang's method is robust but demands four computationally expensive processes for initial matching including: triangulation, identification of characteristic points, checking of the DPS radius constraints and checking of the length constraints.

In the fine localization process, an accurate coordinate transformation matrix is obtained to optimally match the measurement points with the design surface. Since the transformation result achieved in rough localization is usually used as initial guess for the fine localization, the measurement coordinate system and the design coordinate system are close. In fine localization, the roughly localized measured points can be projected onto the design surface to find their corresponding points. In this research area, Besl and McKay [8] employed the iterative closest point (ICP) method through iteratively minimizing the sum of squared residual errors between the measured points and their closest points on the design surface. This ICP method and its variations have been primarily used in the past for fine localization. Research on fine localization focused on two aspects: (1) development of new fine localization methods to improve localization accuracy, and, (2) estimation of uncertainties of the localization results based on the uncertainties of the measurement points and/or uncertainties introduced in the fine localization process. In the first aspect, Li et al. [9] used least-median-of-square instead of least-squares on residual errors to improve the accuracy in local deformation detection for surface matching. Sharp et al. [10] developed the ICPIF method in which both the differences between the intrinsic geometric properties such as curvature and the residual errors were minimized to find the corresponding points. Orazi and Tani [11] developed a fine localization method based on the extended Gaussian curvature to compare the principal curvatures of the corresponding points. In the second aspect, Che and Ni [12] presented a generic approach to obtain the uncertainty in coordinate transformation from noisy measurements based on constrained optimization uncertainty analysis. Yan and Menq [13] developed a method to approximate the uncertainties of the obtained transformation parameters in the fine localization process based on measurement and manufacturing errors. Poniatowska [14] introduced a method to determine the uncertainty in the coordinate transformation parameters based on geometric deviations of the manufactured surface from the design surface. Mehrad et al. [3] studied the influences of measurement uncertainties and the uncertainties introduced in the localization process on the localized measurement points in freeform surface inspection.

The main problem in curvature-based localization methods is the sensitivity of curvatures to the manufacturing errors and/or measurement errors at the measurement locations. In curvature-based localization methods, the curvatures of the manufactured surface at measurement points are estimated and the design surface is searched to find the possible corresponding points. During this search process, when the acceptable difference between two similar curvatures is set too tight, the true corresponding points could be easily missed. On the other hand when the acceptable difference is assigned with a large value, many possible corresponding points, including wrong corresponding points, can be obtained. This problem is critical when the Gaussian curvature is used for comparison due to its small values especially in the flat regions of the surface. In addition, usually alignment of three pairs of corresponding points is used in the presently developed methods [5,7], leading to the alignment of two planes with the possibility of upside-down positions.

In this research, new robust localization methods are developed for both the rough and the fine localization processes. In rough localization, four or more measured points are selected and their corresponding points on the design surface are obtained in two steps: (1) identification of an initial list of possible corresponding points with similar curvatures based on curvature similarity constraints, and (2) elimination of non-feasible corresponding points based on distance constraints among measurement points. The calculated distances among measurement points are less sensitive to geometric errors on the freeform surface compared with the estimated curvatures. In fine localization, the uncertainties of finely localized measurement points are estimated from the uncertainties of roughly localized measurement points and the uncertainties of the six transformation parameters for the fine localization. The optimal design coordinate system is also identified to minimize the uncertainties of the finely localized measurement points.

The rest of this paper is organized as follows: in Section 2, the method developed for robust rough localization to match the measured points on the manufactured surface with the design surface is provided. In Section 3, a method to minimize the uncertainties of the finely localized measurement points is described through identification of the optimal design coordinate system. In Section 4, case studies are provided to show the effectiveness of the developed methods. In Section 5, major influencing factors on the computation efficiency of the developed methods are discussed. In Section 6, conclusions are summarized.

2. Robust rough localization to align measured points on the manufactured surface with the design surface

Before the rough localization, the measurement coordinate system and the design coordinate system are usually quite different. For each measured point, its corresponding point on the design surface needs to be identified to obtain the transformation parameters for localization. Geometric properties that are independent of the coordinate system, such as curvature, have to be used for identifying the corresponding points. The measures of curvature such as Gaussian and mean curvatures have been often used in the developed rough localization methods. The curvatures of points on the design surface can be accurately calculated based on the given mathematical model of the design surface. The curvatures of manufactured surface at the measurement points, however, can only be approximated using the coordinates of the measured points near this location. The approximated curvature for each measurement point contains the estimation error and is also sensitive to the manufacturing and/or measurement errors near this location. The maximum change in curvature occurs when a measured point moves towards or away from the center of curvature due to manufacturing and/or measurement errors. Fig. 1 shows three measurement points in a 2D case and the influence of the error in the radial direction on the approximated curvature. The curvature, C, is the reciprocal of the radius of curvature, R, and its value can be obtained by the Pythagorean theorem as shown in Eq. (1). The maximum sensitivity of the curvature to the geometric error at a measured point