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A Bi-Criterion Flexible Registration Method for Fixtureless Inspection of Compliant Parts

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Abstract

Manufactured mechanical parts such as sheet metal and thin-wall featured parts, often have significant geometrical differences compared to their nominal CAD models as they have a considerably different shape in a free state condition due to gravity and/or residual stress. Thus, expensive conformation fixtures are traditionally used during inspection operations. Naming such parts flexible (non-rigid or compliant), in this paper, a new method for avoiding fixtures is introduced. Validation was conducted on a virtual industrial case study typically produced with waterjet cutting. Obtained satisfactory results reflect the effectiveness and utility of this approach in precision detection of manufacturing defects.

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1. Introduction

Manufactured mechanical parts often have geometrical differences compared to their nominal CAD models and are often inspected for these differences during quality control. This inspection is typically performed in two steps: First, preliminary geometric data of the part in its state-of-use position (usually in the form of scanned point clouds or stereolithography (STL) files) are gathered. Next, the gathered data are processed using computer-aided inspection tools (CAI) designed to identify location and magnitude of a number of manufacturing defects (profile tolerance). Though this twofold inspection routine has gained considerable popularity, it is currently limited to parts that are reasonably rigid. Some parts such as skins, parts with thin walls, which are referred to as flexible (or nonrigid or compliant), have a considerably different shape in a free state compared to their nominal CAD models due to the effect of gravity and/or residual stress. In fact, the geometric deviation of flexible parts is mostly due to such elastic deformations rather than manufacturing defects. As a result, to correctly identify all or the majority of defects, traditionally, one is required to first set up standard or specialized conformation fixtures that would hold the part in the position defined in its nominal CAD model. It is only then that it becomes possible to gather the preliminary geometric data of the part for subsequent analysis in CAI software. A number of downsides exists in using fixtures such as: their time consuming set-up process, considerable acquisition and operation expenses, limitations of standard fixtures in some scenarios, etc. Disadvantages of this sort have led researchers to try to circumvent use of fixtures by digitally deforming (or better called *registering*) the gathered point cloud data of a flexible part in Euclidean space until it matches the part's corresponding nominal CAD model, thereby elastically deforming the data to reach an optimal assembly shape whilst avoiding neutralization of any existing manufacturing defect. In this paper the same goal is pursued as a hypothesis to investigate whether a *flexible* registration method for nonrigid transformation of preliminary point cloud data onto nominal shapes can be introduced or not.

A summary of the recent advancements and research trends in the field (automated inspection of freeform surfaces) are well presented in details in [1], accompanied with specific definitions, notions, and challenges of dealing with flexible

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parts. The literature that is directly related to the focus of this paper however, three dimensional point cloud registration methods, can be divided into two main categories: methods of rigid registration, and methods of nonrigid registration. Rigid registration approaches can only perform linear translations and rotations in the Euclidian space and as a result are not usable in the problematic of this study as the deviated shape of a flexible part's point cloud will not change (deform) under these linear operations. The second category, nonrigid registration approaches, is divided into quite a number of sub-categories ranging from semi-nonrigid methods restricted to affine transformations (shear, scale, etc.), to fully nonrigid (in a sense free-form deformation) methods capable of registering point clouds to almost any shapes given the right inputs were to be provided. Although introduction of all these sub-categories far exceeds the limits of this publication, a recent concise survey reviewing them is available in [2]. As for the purposes of this paper, the preference has been the Coherent Point Drift algorithm (CPD) [3] which is of state of the art status already adopted by many, and can register point clouds to almost any shapes. Despite the fact that nonrigid registration methods such as CPD can succeed where rigid registration methods fail (deforming point clouds), they are initially designed for applications such as registering medical images and have no regard for preserving the intrinsic material properties of the scanned part during the registration process (properties such as curvilinear distances, mesh size parameters, geodesic distance between nodes, etc.) and thus create unrealistic results which are not reliable for defect identification purposes (since such registrations in real life would in fact either add additional stress to the part or in some cases tear the material apart). To solve this issue, a new branch of nonrigid registration methods needs to be developed that would respect such intrinsic material properties during registration. We refer to these type of methods as *flexible* registration methods. It is also noteworthy to mention other types of deficiencies that most nonrigid registration methods often have: a lack of entirely automatic behavior (end-user is required to set key tuning parameters), a lack of automatic approximation of the noise/outliers level (even if the algorithm possesses dedicated tuning parameters to neutralize them), a costly runtime when registering large point clouds, etc. The only standalone flexible pointwise registration algorithm that has been introduced so far, to the knowledge of the authors, is that of Aidibe et al. [4] named Adapted CPD algorithm (ACPD). Whilst using the CPD algorithm at its core, the ACPD algorithm introduced a singular cost function composed of weighted sum of two elements to be minimized: First being a scalar distance criterion representing the average pointwise Euclidean distances between the source (scan data) and target (nominal CAD) point clouds. And second, an isometry conservation criterion representing the change in the average geodesic distance between each vertex to its neighbors on the point cloud after registration (similar to a criterion first described in [5]). By minimizing this cost function, ACPD algorithm attempts to conduct an optimal flexible registration that would respect the material properties of the source point cloud. This algorithm however, has some limitations such as: reliance on the end-user to provide the weights inside the cost function, not guaranteed to find the global optima, and not being accurate within its distance calculation in cases where the target point cloud data is incomplete. In this paper, a more generalized flexible registration method (and an algorithm based on it) is introduced that by design not only covers the limitations of ACPD, but also will introduce new capabilities. Resulting contributions include: a generalized wrapper based on the methodology that could be expanded to include future nonrigid registration algorithms and not remain limited to CPD, automatic selection of the tuning parameters of the nonrigid registration algorithm, implicit noise handling, a better route to optimality via using a bi-objective formulation as opposed to a singular formulation, and improving the distance calculation between the source and target point clouds. The algorithm developed based upon the proposed method has been named *BOFR1* where the acronym stands for the **1**st version of a **B**i-**O**bjective **F**lexible **R**egistration algorithm.

2. Methodology

As mentioned in section 1, the aim of this work is to develop a flexible registration method for compliant parts and an algorithm based upon it. The concept behind this method is *bi-objectively optimizing two key criteria that are the output of a black-box containing a nonrigid registration algorithm inside*. Main steps of the developed method (very similar to the code structure of BOFR1 algorithm) are presented in Fig. 1.

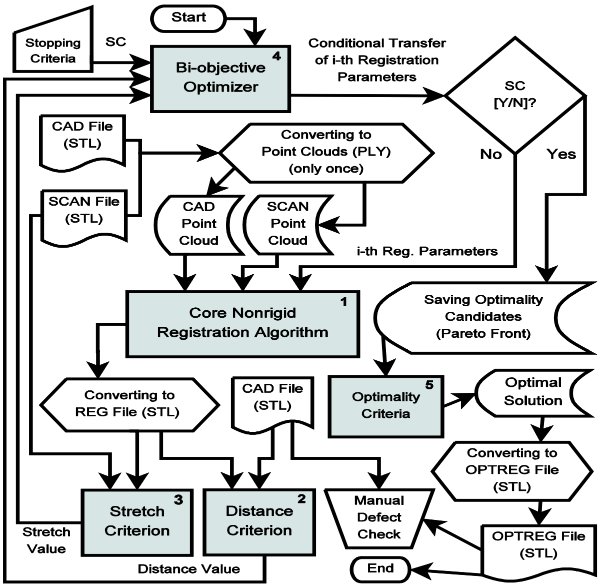

Fig. 1. Main steps of the proposed method

Theoretically, any branch of nonrigid registration algorithms capable of performing a free-form alike deformation can be used within the aforementioned black-box (block 1 in Fig. 1). In BOFR1, the latest version (v2.0) of the original CPD algorithm [3] was chosen. Motivations for this decision are the state of the art status of the CPD algorithm, its relatively good efficiency in registering large point clouds compared to other options, and an internal noise-canceling ability should the end-user manages to tune it properly. The inputs of the black-box (containing CPD) which are optimized include registration parameters λ and β, and noise handling parameter ω (enabling implicit noise handling in BOFR1). As for the optimization solver (block 4), BiMADS algorithm [6] was picked due its general superiority to a weighted single-objective scheme, its