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Efficient compensation of dimensional errors in robotic machining using imperfect point cloud part inspection data

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ABSTRACT

"Process-to-part" robotic machining using low-cost, off-the-shelf industrial robots is of interest for feature machining applications on large components where mounting on conventional machine tools is costly and presents a health and safety risk. For a range of well documented reasons, low-cost industrial robot-based machine tools are limited in terms of machining tolerance range. Work conducted by the authors in Barnfather et al. (2016a, 2016b, 2016c, 2017a, 2017b) investigates these capabilities as well as on-line dimensional error measurement and compensation using optical scanning methods, which have development potential for low cost dense error measurement. A key problem when optically scanning machined surfaces for error measurement is noise and localised data gaps due to reflectance. Robotic machining error compensation in this way can therefore be thought of as a two-part problem involving acquiring quality scan data and processing it optimally to compensate a machining trajectory. This paper contributes to the latter by presenting a dimensional deviation evaluation method for efficiently computing compensated robotic machining trajectories from aligned optically scanned point clouds without processing redundant data, as is typical in related works. Results validate this method, showing a ~96% improvement on dimensional error measurement time in comparison to conventional methods, and conclusions are drawn on direction for further development. This method is a novel contribution to the current state of the art of point cloud processing for on-line robotic machining error measurement and compensation, allowing the best to be made of imperfect point cloud inspection scans.

1. Introduction

Machining using off-the-shelf industrial robots is gaining interest in large volume manufacturing industries to reduce feature machining cost on large components. A barrier to adopting this technology is the low tolerances available from typical machine tools set ups based on low cost industrial robotics. In previous research publications, the underlying causes of dimensional error in robotic machined parts have been reviewed and experimentally investigated [1–5]. It is recommended that these are consulted for a more complete appreciation of the challenges discussed.

On-line measurement and compensation of systematic robotic machining errors accumulated in the part is investigated in [4], proposing an algorithm and machining strategy for utilising optically measured point clouds for this purpose. Results show that, although the idea of error measurement and compensation works in theory, challenges associated with the inspection point cloud quality restrict performance of the algorithm proposed. To investigate further, measurement performance is assessed, in depth, in [5]. Together [4,5], quantify challenges associated with inspection data gaps and measurement error, which are found to be relatively consistent over multiple scans and part geometries. Ultimately, the problem is that, when inspection point clouds, measured prior to the final robot cut, are aligned with nominal cutting points to determine the deviations from the desired dimensions, data gaps mean that these deviations either cannot be computed or are computed incorrectly. This results in a error-compensated trajectory that is not smooth and produces unacceptable machined geometry with little benefit to tolerance.

Focus on overcoming drawbacks of camera-based optical scanning for compensation is justified because it potentially allows lower cost, denser measurement of machining errors in the part, compared to other techniques, independently of robot errors, which is important due to the spatial variation of dimensional error in robotic machining. Also, camera-based optical scanning has future potential for low-cost integration into industrial robot machine tools in a machine vision-style system. These issues and other benefits over competing technologies are discussed in depth in [4]. In Section 1.1, key aspects of the prior art for tackling point cloud noise and data gap issues is reviewed and the

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purpose of the research documented in this paper is described in Section 1.2.

1.1. Prior art

In the literature, related problems have received significant attention as point cloud noise smoothing and interpolation between data gaps is common in typical optical inspection work-flows of commercially available software. Various algorithms can be employed for this purpose as reviewed in detail by Li et al. [6], who advance the state of the art by proposing and demonstrating a smoothing method based on image filtering techniques, suited to efficient sharp feature preservation in turbine blade scanning without meshing or curvature computation. Whilst this is proven to be effective, a downside of this approach for on-line robotic machined part error measurement and compensation is that it relies on processing a greater amount of data than is necessary for compensating tool path points. This issue is also evident in the work of Nagata et al. [7] who propose a system for computing smooth cutting locations from point cloud data to implement reverse engineering with robotic machining. The general problem of efficiency motivates the work of Li et al. [8], who demonstrate an improved approach to unordered point cloud de-noising by establishing order using the K-nearest neighbours algorithm. Lin and Hsu [9] and Yang and Xiao [10] also propose novel approaches, for the same purpose, based on supervised machine learning and grouping useful data using K-means clustering, respectively.

Tao et al. [11] proposes an alternative method of minimising point cloud data whilst keeping useful information based on bi-Akima spline interpolation, which is applied to on-line measurement using a machine tool's scanning system for re-machining and reverse engineering. Uniquely, this method preserves inherent point cloud density increases in high curvature regions and therefore reduces inaccuracy during interpolation. The choice of bi-Akima spline type is justified as it maintains an accurate representation of the point cloud whilst smoothing unnatural imperfections. Success is demonstrated with point cloud scans of a ~3 m ∅ semi-ellipsoidal irregular surface. Conversely, Morwald et al. [12] review the difficulties of fitting splines to point clouds of objects with complex contours, also finding inaccuracy due to data gaps, noise and clutter from surrounding data, and present and validate a solution based on B-spline surfaces that facilitate data reduction despite complexities. Rouhani et al. [13] make a similar contribution using B-splines, with particular focus on minimising computational cost. These issues are particularly relevant to robotic machining error compensation, when features to be machined have sharp edges rather than curves. Whilst efficiently solving point cloud noise and data gaps with surface spline interpolation has been widely researched (also see [14–16]) a conceptual drawback of these methods for robotic machining error measurement and compensation is still that they process more of the inspection point cloud than is necessary, thereby providing an over-engineered solution in this case.

Barazetti [17] and Lee and Bo [18] present methods for extracting and computing parametric CAD models from noisy point cloud data, which potentially eliminate problems with inaccurate spline representations of points clouds when primitive geometry types are correctly fitted. Although such capabilities add value in various applications, each of these works demonstrate the complexities of automating such tasks. Again, in robotic machining, a relatively small number of original tool path points, compared to the point cloud size, need compensating so it is questionable whether the complexity of recreating a whole "as-machined" CAD model is justified to solve this technological barrier. These issues are also considered in the work of Masood et al. [19] where the concept of direct machining is introduced for reverse engineering and a method to directly compute desired cutter locations from STL-format scans of a component is proposed to avoid the complexities of converting into a CAD format or surface fitting and then CAM programming.

1.2. Research purpose

The purpose of this paper is to build on the idea of direct machining for compensation as well as the basic compensation algorithm previously published by the author of this manuscript in [4]. The aim of this research is therefore to explore a concept for improved optical inspection-based robotic machining error compensation algorithm that efficiently reduces inspection point cloud data down to only what is needed, whilst reducing sensitivity to data imperfections, without the disadvantages of the methods described in the literature. This is based on restricting the measurement of dimensional errors to a single direction and then applying a simple smoothing filter to the compensated trajectory to produce a high quality robotic machined surface with improved tolerance, despite machining and measurement challenges.

To investigate the impact of the proposed method, the background and theory behind the concept is initially documented in Section 2 and the implementation and test methodology is discussed in Section 3. Results are presented in Section 4, where judgements are made on the ability of the method proposed to solve the underlying robotic machining problem. A final summary and conclusion is given in Section 5. This work builds on the previous research in [1–5], where problems in robotic machining error compensation have been analysed and attributed, to contribute to solving the problem of low-tolerance robotic machining capability. This is significant due the new understanding gained on how real world machined geometry can be approximated based on imperfect, noisy point cloud data and the potential impact on manufacturing.

2. Proposed approach

In this section, the proposed approach to efficient robotic machining error measurement and compensation using imperfect point cloud data is described. This is done by providing background details of prior attempts in Section 2.1 and then the recommended improvements in Section 2.2.

2.1. Background

The original method proposed for compensating dimensional errors in robotic machined parts [4] is based on quantifying these deviations as the minimum distance between the finish trajectory point and the inspection point cloud mesh taken after the semi-finish machining stage. These deviations are applied to the original semi-finish tool path to compute a finishing tool path that is adjusted according to whether there has been an under or over-cut at the semi-finishing stage, thereby preventing these errors from propagating to the final achieved dimensions. This concept is summarised in Fig. 1 for an under-cut case, inspired by [20]. In practice, errors would be of varying magnitude in both under and over-cut conditions.

The initial approach taken by the authors [4] is motivated by the surface comparison work of *Li and Gu* [21], who experimentally validate deviation inspection and compensation by looking for the closest

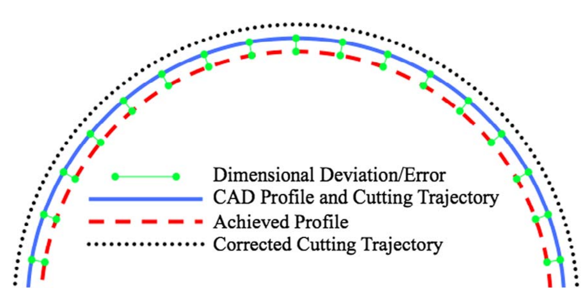

Fig. 1. Cutting path compensation based on dimensional deviations between the achieved profile after the semi-finish cutting stage and the desired final profile.