Measurement 94 (2016) 561–577

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Development and testing of an error compensation algorithm for photogrammetry assisted robotic machining

J.D. Barnfather [a,*], M.J. Goodfellow [a,b], T. Abram [a]

[a] The Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Pariser Building, Sackville Street, M13 9PL, UK
[b] Rolls-Royce Plc. Civil Nuclear, PO Box 2000, Raynesway, Derby DE23 7XX, UK

ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form 16 August 2016
Accepted 29 August 2016
Available online 1 September 2016

Keywords:
Machining
Robotics
Photogrammetry
Compensation
Error

ABSTRACT

Robotic machining of relatively small features on large components potentially offers an opportunity to reduce capital expenditure in various industries. A barrier to this is the inability of robotic machine tools to machine to the tolerances of conventional equipment. This paper proposes and tests a photogrammetry-based metrology assistance algorithm to compensate for robotic machining inaccuracy, as measured in the part, and investigates the associated measurement challenges. The algorithm is executed in a two stage process, whereby the closest point to nominal cutting coordinates on an aligned inspection surface is used for compensation, created a penultimate measured cut. Finally, the finishing program coordinates are compensated to correct under-cuts during the measured cut stage. Conceptual tests using simulated measurement data give confidence that the proposed approach works well. In experiments, a key area for further R&D effort is found to be uneven inspect point coverage, which results in alignment issues and a poor surface finish. Ultimately, direction is given to improve measurement system performance to enable the metrology assistance approach proposed to be implemented and therefore the benefits of "*process-to-part*" robotic machining to be realised.

1. Introduction

"*Process-to-part*" robotic feature machining potentially offers large component manufacturing industries a lower cost and flexible alternative to large machine tools, with less reliance on heavy lifting for mounting and alignment. This approach potentially reduces component costs [1–3] and health and safety risks when machining relatively small features on large components. However, a barrier to implementing robotic feature machining is the poor dimensional tolerances achievable when machining metals. See [4] for a brief application case study.

Attempts to tackle dimensional inaccuracy in robotic machining are typically associated with addressing individual error contributors. For example, kinematic modelling is widely researched as a means of accurately relating the programmed end effector positions to joint rotations and actuator extensions for program execution. An early research example is the work of Weill et al., where dimensional errors in links and joints are modelled in a serial arm robot for calibration purposes [5]. However, for machining applications, robots with parallel kinematic structures, such as hexapods, are of most interest due to their stiffness benefits, which offer improved chatter resistance and, potentially, accuracy compared to serial-arm alternatives [6–8].

Kinematic positional error compensation is challenging for unconventional parallel robot structures due to their complex configurations, which create a non-linear mapping between joint, actuator and machining coordinate spaces. This is investigated by Karimi and Nategh who model the resulting interpolation errors in a hexapod robotic machine tool and assess the effect of various parameters on tool path accuracy for optimisation [9]. Von Daake et al. also propose a hexapod kinematic calibration methodology based on significantly fewer pose measurements than is typical in other work [10]. An alternative approach is taken by Gong et al. who account for thermally induced dimensional change and joint compliance as well as geometric errors in kinematic models [11].

In other research, Antunes Simoes et al. improve robotic machining accuracy by optimising process variables, although this is done using plaster parts [12]. Also, Olabi et al. propose a trajectory planning technique that reduces non-geometric path error by providing a smooth feed rate profile with less jerk [13]. This issue and robot feed rate accuracy are investigated by Young and Pickin [14] to quantify advances in control methods, which ultimately impact final positional error.

* Corresponding author.
E-mail address: joshua.barnfather@manchester.ac.uk (J.D. Barnfather).

http://dx.doi.org/10.1016/j.measurement.2016.08.032

Dimensional error compensation in robotic machining is also commonly approached from the perspective of structural dynamics alongside efforts to improve productivity. In the work of Tunc et al. [8,15,16], this is proved to be a complex issue as it is shown that dynamic stiffness, and potentially machining error due to deflection, varies over the working envelope of a hexapod robot and that it may be necessary to machine with variable spindle speeds to adapt machining parameters to stiffness characteristics. Various other sources also highlight concerns over dynamic structural rigidity issues in robotic machining [17–19] and Matsuoka et al. optimise machining strategies for best force management to counteract their impact on dimensional errors in parts [20].

Work by Pan et al. relates cutting force and structural rigidity models to chatter mechanisms in robotic machining, presenting stability criteria for improved surface accuracy [21]. Zhang et al. achieve this by implementing a system to adapt the material removal rate on-line using in-process force feedback to a stiffness model to compensate for deflection error using a serial arm robotic machine tool [22]. A similar approach is taken by Pan and Zhang and Sornmo et al. who also counteract rigidity problems with adaptive force control and discuss how part inaccuracy is caused by excessive process forces that result in deviations from programmed paths [23,24]. Lehmann et al. build on such ideas by combining adaptive force control, strategy optimisation and off-line force compensation techniques for part accuracy improvement [25]. Olofsson et al. also considers machining force compensation by using a piezo-actuated micro-manipulator to directly compensate for tool deflection [26].

The underlying causes of dimensional inaccuracy in robotic machining are diverse and complex, as are the error compensation approaches that have been proposed and investigated. Further reviews of these issues can be found in [8,18,27,28]. The literature shows that the state of the art of robotic machining error compensation is largely based on the understanding and offsetting of specific root causes of error. Typically, the solutions proposed are not generically applicable to the wide variety of possible robotic machine tool implementations and are shown to be successful in only specific situations. The purpose of this paper is therefore to explore the feasibility of a novel, generically applicable, "black-box" approach to robotic machining error compensation. This measures the sum of all errors accumulated in the part to compute offsets, rather than focusing on a single characteristic, as suggested for the same purpose in conventional machine tools in [29]. This has the advantage of not being reliant on perfect knowledge of the complex underlying root causes of error.

Work done previously to quantify errors using a hexapod robotic machine tool, provides strong evidence that this approach would be successful because overall positional and machining errors are found to be mainly systematic rather than random. This means they can be offset when measured [4,30]. For example, aluminium machining trials show that when machining a cylindrical nozzle-type feature a mean diameter error of ~160 μm can be observed, with a maximum variance of ~10 μm from the mean, suggesting that ~150 μm can be offset, if it can be measured on-line. Although these values vary according to the specific geometry, potential is found to reduce total robotic machining error to only the random errors in the process, thereby implementing on-line calibration, effectively. This is useful because previous result have found that final part errors vary according to geometry, supporting observations made in the literature. A key question is therefore what advances are required to achieve the necessary measurement system capability, thereby approaching the problem from a dimensional metrology perspective.

Total error measurement for compensation is inspired by literature investigating metrology-assisted serial-arm robotic drilling in aerospace applications, which support the idea that considering the sum of errors is key. For example, work in this area was presented at the Coordinate Metrology Society Conference, San Diego in 2013, showing that positional tolerances of ~50 μm can be achieved in local work zones by laser tracking drilling robots to refine kinematic model parameters on-line [31]. Duin et al. [1] compares the achievable serial-arm robot drilling accuracies when using a laser tracker and an Infra-Red Global Positioning System (IRGPS) for robot positional error compensation. The approach taken by Duin et al. is to firstly position the tool at its final pre-cutting position using only the robot and then measure the error from the desired position using each metrology system to provide an offset for correction using a micro-positioning system at the end effector. Results show that drilling position accuracies of 16 ± 3 μm can be achieved using the laser tracker for compensation but that there is a mean variance of 432 μm when using the IRGPS, although it is noted that the accuracy of the latter option does not suffer with increased operating volumes as much as the former. DeVlieg and Szallay [2,3] also investigate the same issue but update kinematic and deflection model parameters using on-line laser tracker measurements and readings from a load cell integrated into the end effector. Wang et al. [32] build on the work of Duin et al. to some extent by experimentally comparing an Indoor Global Positioning System (iGPS) to a laser tracker in terms of trajectory tracking accuracy, which is more relevant to machining error compensation than drilling where only position is important. This work finds that speed and direction of motion are key influences on iGPS measurement error, with distances from the laser tracker trajectory being up to 5 mm.

A key downfall of these approaches for robotic machining applications is that they do not measure the part directly and only compensate for a deviation measured at particular points on the robot. Also, whilst [2,3] do consider deflection of the end effector, this is not considered at the tool tip, which is found to be a key error source due to deflection in robotic machining with industrial hexapods in the work of Tunc et al. [8,15,16]. Although evidence of success is found in robotic drilling, GPS or laser tracker error compensation is therefore not a complete solution for hexapod robotic machining and could reduce its potential economic benefits. These downfalls are also common to laser radar systems. In theory, an ideal solution would account for all possible systematic machining errors by measuring them in the part directly to compensate the final finishing cuts in reference to programmed geometry from CAD as suggested by ElMaraghy et al. [29], in the context of conventional machine tools.

Direct part measurement for compensation is supported by Guiassa and Mayer [33] who improve conventional machining errors in flexible parts with on-machine verification (OMV) probing to determine cut depths at various stages based on a deflection model of the entire system. Whilst OMV is easily robot integrated at a low capital expenditure, measurement interrupts machining by changing the cutter to a probe, increasing lead time, and is not practical or efficient for dense point cloud acquisition. The measurement of errors through surface reconstruction from a dense point cloud is desirable when attempting to compensate for the sum of robotic machining inaccuracies because it potentially allows errors to be understood across the whole part rather than just in localised areas. This is beneficial given the varying nature of part errors across a robotic machine tools working envelope.

Given the complex underlying contributors to systematic error and the conceptual limitations of similar metrology-assistance methods, this paper contributes to robotic machining by proposing and investigating a compensation concept more fully accounting for underlying error contributors in machined features using photogrammetry-based measurement. The research documented aims to expose the current benefits and limitations of a compensation algorithm and measurement technology to initiate develop-