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ScienceDirect

Procedia CIRP 52 (2016) 204 – 209

www.elsevier.com/locate/procedia

Changeable, Agile, Reconfigurable & Virtual Production

Improving Error Models of Machine Tools with Metrology Data

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Abstract

As the manufacturing community embraces the use of a variety of metrology solutions, the availability and quantity of measurement data is increasing. The tendency towards connectedness between manufacturing resources may also provide a mechanism for communication and exploitation of metrology data like never before. This research aims to provide an insight into the opportunities that are associated with accessible, abundant and communicable manufacturing metrology data. Issues are raised and critically discussed in relation to one particular aspect of manufacturing metrology, namely, machine tool accuracy verification and calibration. Specifically, a methodology for relating CMM part measurements to individual machine tool geometric error sources is described. A novel Monte Carlo simulation-based method is used to estimate previously unmeasured error values without the use of further testing. Using this method, the advantage of using previously captured verification and calibration data to identify likely causes of part defects is shown. It is envisaged that the proposed method can be used to instruct targeted machine tool verification and calibration routines to reduce the number of tests required to monitor a machine tool's health. By using targeted tests, the need to measure all machine error sources is reduced, which in turn can improve productivity by reducing machine tool downtime.

Peer-review under responsibility of the scientific committee of the Changeable, Agile, Reconfigurable & Virtual Production Conference 2016

Keywords: CMM; Metrology; Machine Tool Calibration; Monte Carlo Simulation

1. Introduction

In 1987, McKeown et al. [1] identified automated assembly, reduced scrap and rework, and improved part performance as being key motivators for precision in manufacturing. Statistical process control (SPC) is a widespread quality control methodology for moderate part quantities [2] and is an adequate tool in meeting the objectives set out by McKeown et al. [1]. However, reactive quality control methods such as SPC are unable to alleviate scrap and rework in low-volume production, where it is impossible to acquire a meaningful sample size. Hence, there is a requirement for information-rich, model-based approaches to achieve predictive quality control in these scenarios e.g. [3].

Machine tool accuracy is a key component in quality control for low-volume production. Industrial and academic developments in machine tool calibration and verification have helped to significantly improve machine tool accuracy via compensation of errors [4,5]. The true cost-benefit of introducing metrology into manufacturing operations is complex [6]. As such, there is a general drive to minimize the non-productive time associated with acquiring metrology data. This paper describes a new methodology for relating CMM part measurements to machine tool error sources. Heightened connectivity between manufactured parts and individual machine tool error sources forms the basis of a targeted machine tool verification / calibration methodology. By identifying machine errors that are likely to have resulted in part defects, fewer time-consuming tests will be needed to monitor a machine tool's health, increasing productivity.

Peer-review under responsibility of the scientific committee of the Changeable, Agile, Reconfigurable & Virtual Production Conference 2016
doi:10.1016/j.procir.2016.07.053

2. Machine Tool Error Sources, Calibration and Verification

There are a wide variety of error sources that can manifest themselves in the final machined part. Schwenke et al. [4] categorized error sources as either being kinematic (geometric), thermo-mechanical, static load, dynamic forces, motion control and control software related. Incorrect tool dimensions, poorly selected cutting parameters, inconsistencies in workpiece material and inadequate fixturing of the workpiece also affect machining accuracy. This paper focuses on the kinematic (geometric) errors, where errors result from imperfect geometry within or between machine tool axes and structural elements. It is therefore assumed that all other error effects are negligible at this time.

2.1. Geometric Errors in Machine Tool Axes

An axis of motion has six possible components to its error motion. ISO 230-1:2012 [7] defines the geometric errors of linear and rotary axes as either being component errors or location errors. Component errors are a function of commanded axis position. Location errors on the other hand are constant across the range of axis travel, describing an offset or orientation errors (e.g. squareness). The location and component errors of an exemplary three-axis machine tool are detailed in Table 1.

2.2. Error Measurement – Calibration vs. Verification

'Direct' error measurements measure a single error component in one axis. This is traditionally conducted using displacement sensors with artefacts, laser interferometers with different optics, and encoder gratings [4]. Conversely, 'indirect' measurement methods are influenced by multiple error components, perhaps from several axes [5]. Instruments include the ballbar, nested sensor arrays (e.g. R-Test) and on-machine probing of artefacts etc. Quantifying the measurement uncertainty of direct techniques is generally more straightforward than with indirect techniques [4]. Furthermore, separation of individual errors from measurement data can be highly complex with indirect methods [5]. However, indirect methods typically have the advantage of shorter testing durations as a result of fewer set-ups, resulting in less machine tool downtime.

Machine tool calibration and verification are not always clearly differentiated and seem to lie on a spectrum. The previous work of Muelaner et al. [8] describes machine tool verification as a facility to establish a 'Go/No-Go machine capability criteria', where there is 'no requirement to separate errors, diagnose faults or compensate errors'. Conversely, calibration focuses on the measurement and separation of axis motion into individual error components, which are often removed via adjustment or compensation [4]. Some indirect error measurement techniques sit between these two ends of the spectrum as they separate measurement data into individual error sources, assigning a value to each. Often, errors identified using these methods are only a subset of all possible errors (e.g. only location errors) [5].

To extend beyond just a subset of machine tool errors is challenging due to trade-offs. For example, pursuing more detailed error source information has traditionally meant: (i) greater capital investment in advanced instrumentation and /or artefacts, and greater levels of operator expertise; (ii) more machine tool down-time due to multiple apparatus set-ups and data processing stages, which reduces productivity.

Laser trackers and 6-DoF laser interferometry systems can provide a means through which to acquire detailed error source information with reduced machine tool downtime [4,5,9]. However, care must be taken regarding measurement uncertainty, which can be a complex issue in e.g. multilateration techniques [5]. Additionally, the cost of these instruments suggests that overcoming technical trade-offs often only strengthens the impact of financial trade-offs in machine tool metrology [9]. The University of Bath has targeted different areas of the machine tool calibration-verification spectrum. Flynn et al. [10] focused on the use of the ballbar to rapidly identify location errors in 5-axis machine tools using a single experimental set-up.

Table 1. The location and component errors of an exemplary three-axis machine tool as per the definitions of ISO 230-1:2012 [7] (using Y-axis as reference)

Location Error Definitions for a 3-axis Machine Tool				3-Axis Machine Tool Diagram
E_{C0X}	Squareness of X to Y			
E_{A0Z}	Squareness of Z to Y			
E_{B0Z}	Squareness of Z to X			
Component Error Definitions for a 3-axis Machine Tool				
E_{XX}	Linear positioning of X	E_{AX}	Angular error of X about X	
E_{YX}	Straightness of X in Y	E_{BX}	Angular error of X about Y	
E_{ZX}	Straightness of X in Z	E_{CX}	Angular error of X about Z	
E_{XY}	Straightness of Y in X	E_{AY}	Angular error of Y about X	
E_{YY}	Linear positioning of Y	E_{BY}	Angular error of Y about Y	
E_{ZY}	Straightness of Y in Z	E_{CY}	Angular error of Y about Z	
E_{XZ}	Straightness of Z in X	E_{AZ}	Angular error of Z about X	
E_{YZ}	Straightness of Z in Y	E_{BZ}	Angular error of Z about Y	
E_{ZZ}	Linear positioning of Z	E_{CZ}	Angular error of Z about Z