Expert Systems with Applications 42 (2015) 3005–3015

Contents lists available at ScienceDirect

Expert Systems with Applications

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

Multi-objective optimisation of machine tool error mapping using automated planning

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ARTICLE INFO

Article history:
Available online 9 December 2014

Keywords:
Machine tool error mapping
Uncertainty of measurement
Automated planning
PDDL
Multi-objective optimisation

ABSTRACT

Error mapping of machine tools is a multi-measurement task that is planned based on expert knowledge. There are no intelligent tools aiding the production of optimal measurement plans. In previous work, a method of intelligently constructing measurement plans demonstrated that it is feasible to optimise the plans either to reduce machine tool downtime or the estimated uncertainty of measurement due to the plan schedule. However, production scheduling and a continuously changing environment can impose conflicting constraints on downtime and the uncertainty of measurement. In this paper, the use of the produced measurement model to minimise machine tool downtime, the uncertainty of measurement and the arithmetic mean of both is investigated and discussed through the use of twelve different error mapping instances. The multi-objective search plans on average have a 3% reduction in the time metric when compared to the downtime of the uncertainty optimised plan and a 23% improvement in estimated uncertainty of measurement metric when compared to the uncertainty of the temporally optimised plan. Further experiments on a High Performance Computing (HPC) architecture demonstrated that there is on average a 3% improvement in optimality when compared with the experiments performed on the PC architecture. This demonstrates that even though a 4% improvement is beneficial, in most applications a standard PC architecture will result in valid error mapping plan.

1. Introduction

A machine tool is a mechanically powered device used during subtractive manufacturing to cut material. The design and configuration of a machine tool is chosen for a particular role and is different depending, amongst other things, on the volume and complexity range of the work-pieces to be produced. A common factor throughout all configurations of machine tools is that they provide the mechanism to support and manoeuvre the functional position, and sometimes the orientation, between the cutting tool and work-piece. The physical manner by which the machine moves is determined by the machine's kinematic chain (Moriwaki, 2008). The kinematic chain will typically constitute a combination of linear and rotary axes.

Fig. 1(a) shows an example of a five-axis gantry machine tool that has three linear and two rotary axes which are used to move the tool around the work-piece. Typically, this configuration of machine will be used to machine heavy, multi-sided, large volume work-pieces. Fig. 1(b) shows an alternative design of a three-axis C-frame machine tool. This particular machine tool configuration consists of three linear and no rotary axes and is typically used to machine smaller work-pieces than the five-axis machine.

In a perfect world, a machine tool would be able to move to predicable points and orientations in three-dimensional space, resulting in a machined artefact that is geometrically identical to the designed part. However, due to tolerances in the production of machine tools and wear during operation, this is very difficult to achieve mechanically. Pseudo-static errors are the geometric positioning errors resulting from the movement of the machine tool's axes that exist when the machine tool is nominally stationary. Machine tool error mapping is the process of quantifying these errors (Schwenke et al., 2008) so that predictions as well as improvements of part accuracy can be made via numerical analysis and compensation.

The significance of the error mapping process is dependent on application; manufacturers machining high value parts to tight tolerances, usually in the order of less than a few tens of micrometres, should have their machines regularly error mapped otherwise they are at risk of producing non-confirming parts. Manufactures with broader tolerances may calibrate less frequently. There are many

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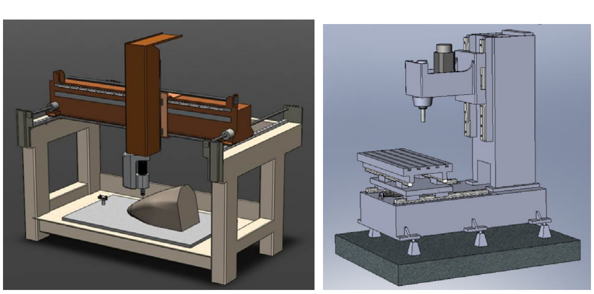
http://dx.doi.org/10.1016/j.eswa.2014.11.066
0957-4174/

error components that collectively result in deviation of the machine tool from the nominal. For analytical and correction purposes, it is important to measure each error component. For example, as seen in Fig. 2(a) a machine tool with three linear axes will have twenty-one geometric errors. This is because each linear axis will have six-degrees-of-freedom and a squareness error with the nominally perpendicular axes (Mekid, 2009; Schwenke et al., 2008). Therefore, a three-axis machine tool will have a total of twenty-one geometric errors. Additionally, as seen in Fig. 2(b) a rotary axis will have six motion, two location errors, and two squareness errors (Bohez et al., 2007; Khim and Keong, 2010; Srivastava et al., 1995). Therefore, a five-axis machine tool will have a total of forty-one geometric errors.

The measurement of each error will involve the use of a test method and a measurement device. The selection of equipment will usually be done in unison with the test method, influenced by the engineer's preference. However, there are many cases where many different instruments can be used for performing the same test method, where each require a different duration to install and perform the test. For example, both a laser interferometer and a granite straight edge can be used to measure the straightness of a linear axis. The laser interferometer might take longer to set-up, but if the machine has an axis with a long travel, the granite straight edge might need to be repositioned multiple times to measure the entire axis, therefore, taking more time to perform. For most manufacturers, removing a machine tool from manufacturing has large financial implications. Downtime can be in excess of £120 per hour (Shagluf et al., 2013). Therefore, the accumulative cost for a manufacturer with many machines can be large. For example, consider a manufacturer with 10 machine tools, each of which undergoes a 12 h error mapping exercise per year. The estimated downtime cost would be £14,400. However, this is a conservative figure for many high value manufacturing companies.

The estimated uncertainty of measurement is a parameter associated with the result of a measurement that characterises the dispersion of the values that could reasonable be attributed to the measurand (BIPM, 2008). The uncertainty of measurement is calculated for each individual measurement and the accumulative estimated uncertainty of measurement has a direct effect on tolerance conformance of parts manufactured using the machine. Therefore, from the manufacturer's perspective, it is desirable to reduce the estimated uncertainty of measurement. The estimated uncertainty of measurement is affected by change in environmental temperature. If the same calibration plan was carried out at different times throughout a working-day while the temperature is continuously changing, the accumulative estimated uncertainty would also change.

Depending upon the manufacturer's motivation for performing the error map, they may want to optimise the error map plan to either minimise financial cost, or maximise the quality of the error mapping exercise. The following different optimisation criteria



(a) Five-axis machine tool (b) Three-axis machine tool

Fig. 1. Example three- and five-axis machine tools.

considered in this paper are: (1) the reduction of machine tool downtime, (2) the reduction of the estimated uncertainty of measurements, and (3) balancing the two parameters with the possibility of customising their individual weighting. The change in environmental temperature throughout a measurement, as well as between interrelated measurements, will have a significant impact on estimated uncertainty of measurement ISO230-9 (2005). The decision making process involved for construction optimal error maps plans is exhaustive. However, computational intelligence in the form of domain-independent Artificial Intelligence (AI) can be used to provide optimal solutions when given a model of the problem (Ghallab et al., 2004).

In this paper, a description of individual factors that affect a machine's downtime and estimated uncertainty of measurement during error mapping are defined. This leads to a discussion of a previously developed model (Parkinson et al., 2012a, 2012b) that can be used by state-of-the-art domain-independent AI planning tools to find optimised solutions (Russell et al., 1995). The development of this model to produce measurement plans that are optimised to reduce machine downtime and the estimated uncertainty of measurement due to the plan order is presented and discussed. This multi-objective optimisation is motivated by the desire to reduce both machine tool downtime and the uncertainty of measurement, which to some extent are competing as a temporally optimised plan will generally have a high estimated uncertainty of measurement. Following the development of a multi-objective model, twelve different case-study examples are presented and described to show the ability to generate plans that are optimised for (1) downtime, (2) uncertainty of measurement, and (3) the arithmetic mean of them both. The generated calibration plans are then examined and discussed to evaluate their fitness-for-purpose. It is then identified that computational resources are restricting the planner's ability to find optimal solutions in ten minute time allocation. This leads to a further investigation into the produced measurement plan when solving the planning problem on both personal and High Performance Computing architectures.

2. Related work

The complexity associated with machine tool geometric error measurement (Mekid, 2009; Schwenke et al., 2008) and the desire to reduce measurement uncertainty (Bringmann and Knapp, 2009; Bringmann et al., 2008) and machine tool downtime are well known for individual measurements. However, surveying the literature suggests that less well known is the potential to reduce machine tool downtime and the uncertainty of measurement by intelligent construction of the multiple-measurement plan.

Bringmann and Knapp (2009) and Bringmann et al. (2008) have identified that current ISO 230 part 2 (ISO230, 2006) is based on sequential testing of single geometric component errors. However, an exception is made for ISO 230 part 4 (ISO230, 2005) where several machine errors are tested together while the machine tool is performing multi-axis movement. Bringmann and Knapp (2009) then continue to describe the importance of interrelated errors using the example of linear yaw deviation effecting the non-orthogonality measurement at different positions in the plane of non-orthogonality measurement. The authors identify that this process is time consuming, and in response have shown the calibration of a machine tool using a 3D-ball plate where the amplification of interrelated measurements can be identified. However, when such approach cannot be used, they suggest using a Monte Carlo simulation that uses an approximation of the machine tool, the measurement and the machine's performance after calibration to estimate the uncertainty of measurement. Performing the