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Automated planning to minimise uncertainty of machine tool calibration

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ABSTRACT

When calibrating a machine tool, multiple measurement tasks will be performed, each of which has an associated uncertainty of measurement. International Standards and best-practice guides are available to aid with estimating uncertainty of measurement for individual tasks, but there is little consideration for the temporal influence on the uncertainty when considering interrelated measurements. Additionally, there is an absence of any intelligent method capable of optimising (reducing) the estimated uncertainty of the calibration plan as a whole. In this work, the uncertainty of measurement reduction problem is described and modelled in a suitable language to allow state-of-the-art artificial intelligence planning tools to produce optimal calibration plans. The paper describes how the continuous, non-linear temperature aspects are discretized and modelled to make them easier for the planner to solve. In addition, detail is provided as how the complex uncertainty equations are modelled in a restrictive language where its syntax heavily influences the encoding. An example is shown for a three-axis machine, where the produced plan exhibits intelligent behaviour in terms of scheduling measurements against temperature deviation and the propagation of error uncertainties. In this example, a reduction of 58% in the estimated uncertainty of measurement due to intelligently scheduling a calibration plan is observed. This reduction in the estimated uncertainty of measurement will result in an increased conformance zone, thus reducing false acceptance and rejection of work-pieces.

1. Introduction

Machine Tool calibration is the process to map the geometrical error of the machine tool in order to correct its systematic geometric errors (Schwenke et al., 2008). The significance of this 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, will require their machines to be calibrated regularly, whereas manufactures with broader tolerances may calibrate infrequently. There are many 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, a machine tool with three linear axes will have 21 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). Additionally, a rotary axis will have six motion errors and two location errors (Bohez et al., 2007; Seng Khim and Chin Keong, 2010; Srivastava et al., 1995).

Measuring an error component consists of selecting suitable instrumentation and test methods. The selection process is not as simplistic as it first appears. In order to make the best selection, many constraints need to be examined. Previous work in applying automated planning to machine tool calibration planning has shown that calibration plans can be optimised in terms of duration (Parkinson et al., 2011). This work involved modelling the process of machine tool calibration in the Planning Domain Definition Language (PDDL). This model can then be used alongside state-of-the-art planning tools to find the most efficient calibration plan, reducing the overall calibration time. Industrial case studies were then performed to validate the ability to produce complete and optimal calibration plans using this technique. This work resulted in the verification of the model's ability to automatically produce calibration plans with a duration saving of 10.6% over industrial and academic experts (Parkinson et al., 2012). This 10.6% equates to a £134 saving for a single machine tool, and a £2680 saving for a company with 20 machine tools. Optimising a calibration plan to minimise machine tool down-time is important from a production point-of-view. However, the effect on the measurement's quality is not currently taken into consideration and is important for high precision manufacturing. The main aim of the work presented in this paper is to expand the temporal model to be able to produce calibration plans that minimise uncertainty of measurement due to the schedule of the calibration plan.

Uncertainty of measurement is a parameter associated with the result of a measurement that characterises the dispersion of the

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Nomenclature

E_{C0Y}	squareness deviation of *X*-axis in *Y*-axis direction in micrometers per metre (μm/m)
E_{XY}	straightness deviation of *Y*-axis in *X*-axis direction in micrometers per metre (μm/m)
E_{YX}	straightness deviation of *X*-axis in *Y*-axis direction in micrometers per metre (μm/m)
k	coverage factor
$U_{CALIBRATION}$	uncertainty of the calibration according to the calibration certificate in micrometers per metre (μm/m) or parts per million (ppm)
u_c	uncertainty of uncorrelated contributor in micrometers (μm/m)
$u_{DEVICE\ DTI}$	uncertainty due to the Dial Test Indicator (DTI) in micrometers (μm)
$u_{DEVICE\ SQR}$	uncertainty due to the mechanical square in micrometers (μm)
$u_{E,DEVICE\ POST}$	uncertainty due to thermal expansion of the mounting post in micrometers (μm)
$u_{E,MACHINE\ TOOL}$	uncertainty due to thermal expansion coefficient of the machine tool, in micrometers (μm)

values that could reasonable be attributed to the measurand (BIPM, 2008). Uncertainty of measurement is an essential part of metrology. Every measurement has uncertainty, the value of which must be reported along with the measurement. In the manufacturing industry, the uncertainties will be calculated to evaluate whether tolerances can be met. High accuracy and precision manufacturing such as the aerospace industry have tight tolerances, therefore reducing the estimated uncertainty of measurement will have an effect on tolerance evaluation, and can help reduce repeating tasks and false rejections.

Fig. 1 illustrates the conformance (green) and non-conformance (red) zones based on the uncertainty value and the lower and upper tolerance limits (Forbes, 2006). The remainder is uncertain. From this illustration false acceptance and rejections can be visualised. False acceptance could occur if the measurement value is out-of-tolerance but the uncertainty of measurement brings it into tolerance. Conversely, false rejection could occur if the measured value is in tolerance but the uncertainty of the measurement makes it out-of-tolerance. Therefore, only measurement values that fall within the conformance zone are certain, within the given confidence level, to be within the tolerance. Minimising the uncertainty of measurement can increase the conformance zone reducing false acceptance and rejection.

It is possible to calculate the estimated uncertainty for each measurement individually either before or after the measurement has been performed. The estimated uncertainty is dependent on many temporal factors such as the prevailing environmental temperature and the duration for which an electronic instrument has been active. The existent environmental temperature will affect the thermal expansion and distortion of the machine tool and the measuring device. In this work, the environmental temperature profile for a machine tool is assumed to be repeatable; this is often referred to as the normal daily cycle.

The literature suggests that there are few tools available to aid with reducing the estimated uncertainty of measurement for machine tool calibration planning. Bringmann et al. (2008) correctly identified that there is little correlation between the selection of a measurement and the machine tool's configuration. However their work is concentrated on improving the selection of the best instrument and the test method to use for geometric calibration (Bringmann, 2009). Muelaner et al. (2010) produced a piece of software that aids with the instrumentation selection based on the dimensional characteristics of a large artefact. Although this method is not aimed at optimising the sequence of measurements, it does help to optimise the selection of instrumentation for measuring each dimensional characteristic. The limitation of this tool is that it requires human intervention and does not guarantee completeness and optimality.

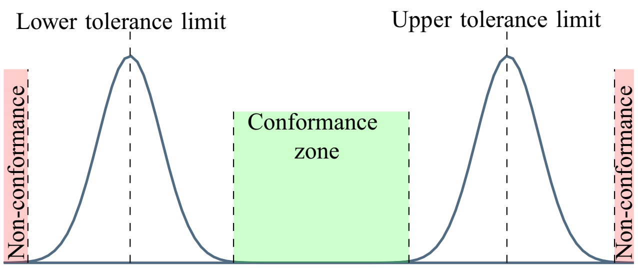

Fig. 1. Conformance and non-conformance zones for two-sided tolerance. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

Co-ordinate measurement machines (CMMs) are similar to a machine tool in physical design and movement, however they are used to accurately measure dimensional features of a work-piece. CMMs are designed to provide measurements to micrometre-level accuracy, and require regular calibrating. The geometric error components of a CMM are the same as a machine tool and the same measurement principles can be applied, albeit using more precise instrumentation. There is a wealth of the literature on measurement techniques that can reduce the uncertainty of measurement when calibrating a CMM (Aggogeri et al., 2011; Beaman and Morse, 2010). However, there is an absence of any literature detailing methods of reducing the uncertainty of measurement for the entire calibration plan. This is most likely because CMMs often operate in temperature controlled environments, meaning that during calibration there should be minimal change in environmental temperature.

In summary, work has been carried out to reduce estimated uncertainties based on measurement criteria, such as instrumentation, temporal factors and measurement techniques. However, there is an absence of any literature indicating the uncertainty reduction of multiple, consecutive interrelated measurements, in this case machine tool calibration. In addition to the uncertainty reduction of calibration plans, there is an absence of the literature indicating that work has been undertaken to intelligently produce calibrations plan that can help minimise uncertainty of measurement.

Automated planning and scheduling includes domain-independent planners that can solve large planning problems that contain continuous, non-linear effects (Klöpper et al., 2012). However, due to the complexity of the dynamics of such models, they are restricted to solving small scale problem instances with the implementation of a domain-specific heuristic (Fox et al., 2011).

COLIN (Coles et al., 2009) is a planner capable of handling continuous, linear numeric change through the use of linear programming. However, COLIN does not support PDDL+ process and events, instead it is limited to continuous change as expressed through the durative action (Coles et al., 2012).

UPMurphi (Della Penna et al., 2009) provides a "discretize and validate" approach to continuous planning and supports the full PDDL+ semantics. Although, this planner is both powerful and novel in its approach, it performs an exhaustive breadth-first