Automation as a Solution for Machine Tool Calibration Planning

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ABSTRACT

Understanding a machine tool's capability is fundamental for applications where a high level of accuracy is required, such as aerospace manufacturing. Therefore, calibrating machine tools to International Standards is an important process and should be executed thoroughly. The calibration process requires firstly identifying the errors component of a machine tool, followed by the selection of an appropriate test method and instrumentation. The emphasis on minimising machine down-time requires expert knowledge to ensure that the calibration process is both complete and optimal. The paper shows the process of planning a machine tool calibration and is followed by a description of how using automated planning techniques will improve machine too calibration planning.

Keywords machine tool calibration automation

1. INTRODUCTION

The continuing desire to manufacture artefacts to a higher degree of accuracy, while decreasing the production cost, has resulted in the requirement for more accurate machine tools [1-3]. This is because excess error within a machine tool's positioning capability will translate to the artefact during machining, possibly resulting in out-of-tolerance parts that are scrapped or require re-work. By calibrating a machine tool, the asset owner can gain an understanding of the machine's capability [4, 5]. Great effort has been spent by many researchers to improve the process of machine tool measurement to correctly identify the machine's error components. International Standards [6] and best-practice guides provide guidance regarding the selection of test methods for individual error components. These are critical for performing meaningful measurements on machine tools. However, even with this rich knowledge there is still a great deal of interpretation, selection and planning to be done to develop a good strategy for measuring a specific machine tool [5]. For example, ISO 230-2 [6] contains a section regarding test specification parameters that need to be "agreed" between the calibration supplier, manufacturer and the user. Often the user does not have the sufficient level of experience to make this decision and sometimes the interests of the manufacturer and user can conflict. This results in the need for "independent" expert knowledge to make the best compromise to suit all. A major consideration in this decision is that down-time for calibration is a cost to manufacturing, so optimising the workflow has distinct commercial advantages. For example, the machine downtime cost for a large company operating a production line could be in excess of a £1000 per hour.

In this paper we describe the evolution of an automated planning system for machine tool calibration using computational intelligence. We start by describing the factors that influence machine tool calibration planning. Following this, we present our work of using Artificial Intelligence techniques to derive the optimal calibration plan, which minimises machine downtime. We conclude by discussing the direction in which this work should continue to produce a complete solution for optimal machine tool calibration planning.

2. MACHINE TOOL CALIBRATION

As highlighted in the introduction, machine tool calibration is based on many influencing factors. This section contains a detailed description of these factors, providing examples of how their difference can significantly change the calibration process.

2.1. MACHINE CONFIGURATION

A machine tool can be designed and constructed in many different ways to perform its task. Figure 1 shows a C-frame machine tool with three perpendicular linear axes, while Figure 2 shows a gantry machine tool with three perpendicular linear axes and two rotary axes. Different configurations are required for manufacturing components of different size and material. For example, it is less efficient to use a machine configuration where the workpiece is situated on a cross-table for the manufacturing of large, heavy parts. This is because the machine would be required to move the workpiece during manufacturing. Conversely, a gantry machine would move around the workpiece, reducing the amount of energy required to machine the item as well as reducing the structural strain on the machine from the workpiece, but has a larger overall footprint.

In addition to the number of linear and rotary axes, the configuration (stacking) of these axes can cause errors to propagate differently throughout the machine. The configuration of a machine tool will determine how many error components it has. While there are few common machine configurations, there are a lot of different configurations that require in-depth consideration to identify all of their error components. The configuration is heavily dependent on the item that will be manufactured, meaning that the variety of machine tool configurations in somewhat proportional to the variety of items that they manufacture. It is also possible that a machine tool might have additional axis, for example, a parallel W-axis, which would also have errors that require calibrating.

Each error component will have an effect on the overall geometric accuracy of machine tool. However, depending on the machine configuration, each error component has a different significance. For example, taking the three-axis machine as seen in Figure 1, the roll of the vertical Z-axis can be regarded as having a lower importance when compared to the roll error of the Y- and X-axis. This is because any Z about Z (roll) movement along the Z-axis will only affect the rotation of machine's tool position (which during milling rotates anyway), whereas any roll in the X- and Y-axis would result in the rotation of the workpiece. However, the significance of the Z about Z error component for a five-axis gantry machine, as seen in Figure 2 is greater. This machine has a kinematic chain where the C-axis is mounted on the Z-axis and the A-axis is mounted on the C-axis. Any error of the Z-axis roll will be propagated down the kinematic chain resulting in the incorrect orientation of the A-axis, which would be directly evident on any machining procedures that involve the rotation of the A-axis.

The configuration of the machine’s constituent parts determines the potential geometric errors that a machine might have. The geometric errors associated with linear and rotary axes are well known [7]. Each linear axis will have the following quasi-static errors (not including spindle errors). For example purposes we are referring to the X-axis of a Cartesian machine as illustrated in Figure 3.

- **EXX** Linear positioning
- **EXZ** Vertical straightness
- **EXY** Horizontal straightness
- **EBX** Yaw (X about Y)
- **EAY** Pitch (X about Z)
- **ECX** Roll (X about X)

In addition to the six-degrees-of-freedom errors, there will the cross-axis errors of:

- **EXY, EXZ, EYZ** Squareness with each perpendicular axis

If we consider the addition of rotary axes to the machine's kinematic chain, the following error components, as seen in Figure 4 are introduced for the C-axis:

- **ECC** Angular positioning error
- **EYC** Radial error motion in X and Y
- **EAC** Tilt error around both the X and Y axis
- **EZC** Axial error

In addition to error components, there are also location errors in respect to the machine's coordinate system. For the same C-axis, these are:

- **XOC** X position of C
- **YOC** Y position of C
- **AOC** Squareness of C to Y
- **BOC** Squareness of C to X

From this it is possible to deduce that a three axis machine tool as seen in Figure 1 will have in total 21 geometric errors [3], and that a five-axis machine tool as seen in Figure 2 has the error count of 41. A machine tool will, however, actually experience more error sources such as thermal, dynamic and non-rigid [8]. For the scope of this paper, only the calibration planning problem for pseudo-static geometric errors in machine tools is considered.

2.2. ERROR MEASUREMENT

The measurement of an error component will involve setting-up the equipment and the movement of the associated axes during measurement. However, when performing the measurement it is essential that axes not being tested are kept stationary. This is because any movement of the machine could result in non-rigid and dynamic errors affecting those geometric errors that are being tested. It is an important fundamental of metrology to maintain a high level of measurement repeatability, and systematically ensuring that only the relevant parts of the machine are moving can help achieve this. In addition to maintaining a quality measurement process, other factors such as instrument interference require the ordering of measurements to be sequential. However, there are conditions which would allow for multiple error components to be measured concurrently, while ensuring that a high level or repeatability is maintained. For example, it could be possible that the linear positioning error component, using laser interferometry, and the roll error component, using an precision level, could be tested concurrently. This is providing that the machine's axis has enough physical capacity to locate both the instruments, and that the test parameters are identical.

2.3. INSTRUMENTATION

The extensive variety of instrumentation available for performing a machine tool calibration adds complexity to deciding the optimum solution when measuring each error component. There are many different reasons why a specific instrument might be selected. The following list supplies some criteria which would influence the instrumentation selection.

- The time to install and align the equipment may be lower, which could help to minimise machine downtime.
- The resolution and accuracy of the instrument might be greater, making it a better choice to improve the quality of the calibration.
- The instrument can measure multiple degrees-of-freedom concurrently, allowing for the simultaneous measurement of multiple error components.
- The instrument might be better suited to the machine's physical characteristics which could place restrictions on the available space

It is important to ensure that the instrumentation chosen can help to reduce the overall calibration time because, for most organisations, machine downtime can significantly reduce or even halt manufacturing. Therefore, identifying where the use of certain instrument can reduce the set-up and measurement time is regarded as a beneficial quality. For example, measuring the Y-axis linear positioning error using the Renishaw XL-80 laser interferometer would require the configuration of the optics as seen in Figure 5. Next, measuring the Y-axis pitch error would require the use of the optics aligned as seen in Figure 6. However, because the optics and the laser are already aligned, it is possible to carefully exchange the optics and the laser will still be aligned parallel with the axis under examination. In addition to the consideration taken towards the setup time, the instrument's ability to measure multiple error components (degree-of-freedom) concurrently is considered. For example, the test setup involving two displacement sensors in Figure 7 can be used for the test procedure as seen in Figure 8. Even though the second procedure will require the movement of the X-axis, meaning that it cannot be carried out simultaneous to the first, the instrumentation will not require any repositioning or adjustment.

So far, we have described the requirements on instrumentation selection based on the improving the calibration process and reducing the overall time. However, there are logistical reasons as to why the distribution of instrumentation is important. A machine tool calibration company might have many concurrent calibration jobs for many different clients. In this situation, the optimisation of instrumentation selection should take consideration to the overall distribution of instrumentation as well as for each calibration job. It could be that selecting the most efficient instrumentation for one job could lead to a greater decrease in efficiency for another calibration job, so company-wide instrumentation allocation should be considered.

3. CURRENT WORK

To improve the quality and efficiency of a machine tool calibration it is essential to model the problem. Work has been carried out to model the problem in such a way that allows calibration planning to take advantage of computational intelligence. The following section describes the work that has carried out through the evolution of this project. Planning a machine tool calibration is dependent on many influencing factors. The fundamental factors can be established as being (1) the machine's configuration, (2) known geometric error components, (3) known test methods, and (4) the available instrumentation which can be used for the selected test method. Using this information, it was possible to create an inference engine using PROLOG [9] which engineers could use as a support tool to aid with decision making when producing a calibration plan. The tool also provides a basic evaluation function to estimate the amount time that is required for each measurement. However, the engineer is still responsible for ordering the tests into the most suitable sequence.

To overcome the requirement for the engineer to order the tests, a model was created which can optimise the sequence based on the estimated instrumentation setup, adjustment and measurement time. The model was created as a Hierarchical Task Network (HTN) because machine tool calibration can naturally be expressed as a sequence of tasks, where each one requires the setup of an instrument, measurement of an error component, and finally the removal of the instrument. The HTN was implemented and tested in the SHOP2 environment [10]. The HTN model was then tested using two different calibration problem scenarios. The first is for a machine tool with three perpendicular linear axes (Figure 1), and the second for a five-axis gantry machine tool (Figure 2). It is evident in Figure 9 that the computation time for solving both the HTN problems is low, where in both cases a valid plan is found in less than one second. It is also evident from the graph that the number of three-axis plans generated is greater than the number of five-axis plans. This is because a five-axis machine has more error components from the addition of two rotary axes, therefore increasing the problem's complexity. Figure 10 shows the reduction in the total estimated calibration plan time relative to the previously identified lowest cost plan.

The introduction of the branch-and-bounds algorithm will ensure that the plan with the lowest cost is found within a given time frame [11]. Table 1 shows that when enabling optimisation for sixty second a calibration plan was produced which has a total efficiency saving of 205 minutes for the three-axis machine and 74 minutes for the five-axis machine. The results are shown for a sixty second period even though the experiment was executed for ten minutes because after sixty-seconds no plans were discovered that have a lower cost. It is also evident in Figure 11 that the number of complete plans generated in the allocated time frame is much lower with the addition of the branch-and-bound optimisation. It is also noticeable in Figure 11 that the number of optimised plans for the three-axis machine increased quickly, peaking at 22 before rapidly dropping to 6 where it stabilises. For the five-axis machine, the number of plans fluctuates between a maximum of 6 and a minimum of 2. This behaviour is because the branch-and-bound optimisation is continuously trying to identify partial plans of a lower cost. Once a lower cost partial plan is identified, the algorithm will then explore it to find a complete plan that is of an overall lower cost than the previous plan. Figure 12 shows the increase in efficiency for the discovered plans. It is evident that the time saved for both the three- and five-axis machines increases gradually within the first 10 seconds. The time saved then stabilises for both the problems until 25 seconds for the three axis machine, where it reaches an efficiency saving of 19 minutes. The five axis problem increases rapidly until it stabilises with an efficiency gain of 74 minutes in 50 seconds of execution time.

So far, a planning method has been developed which can produce a machine tool calibration plan. However, limitations of the planning algorithm (HTN) mean that tasks cannot be executing concurrently, meaning that potential efficiency gains are not realised. The model was then implemented in PDDL (Planning Domain Definition Language). The domain-independent LPG-TD planning tool [12] was used to solve the same three- and five-axis machine problems as solved by the HTN.

An experiment was then performed testing both the HTN model in the SHOP2 environment, and the PDDL model using the LPG-TD tool. Twelve different calibration problems were tested with each model [13]. The twelve problems consist of the following two three-axis machine configurations and two five-axis machine configurations:

1. **XYtZ** Three-axis C-frame
2. **tZXY** Three-axis gantry
3. **tBCZXY** Five-axis gantry
4. **XYBCtZ** Five-axis cross- and rotary-table

For each of these machine configurations we have the following three different calibration scenarios:

i) A company with a good variety of equipment, which establishes the base line scenario.
ii) A company who are more proficient with their instrumentation, therefore reducing the time required to setup and take the measurement.
iii) A company who are more experienced with machine tool geometry so assign a different level of priority to each error.

The results from conducting these experiences [13] show that both planning techniques can find good solutions, and that no planner is an outright winner in terms of the estimated plan length. However, once concurrency was enabled the estimated plans using LPG are much shorter; in some cases only halve that of the HTN. From this experiment it can be deduced that while different planning techniques can find good quality solutions, using a planning algorithm that can plan for concurrent tasks results in a significant timesaving.

CONCLUSION AND FUTURE WORK

The work undertaken so far has shown how automated planning techniques can provide a method to aid with calibration planning by finding both complete and optimal calibration plans. We have shown that the developed HTN model is capable of producing complete plans. However, consideration to concurrent measurements highlighted the limitations of using a HTN model. This led to the creation of a PDDL model which could then solve problems by allowing the possibility of concurrent measurements. So far only few simplistic comparisons have been made between an expert's 'hand-crafted' plan and the automatically generated plan. The reason behind this is that the current models used for automatic plan generation are not entirely complete. There are some parameters and constrains that have been omitted to allow for the quick development of a simplified model that could be used for verifying that the use of automatic calibration plan generation is feasible. Since the work presented in this paper verifies this, a comprehensive model needs to be created to include all parameters and constraints that will not only allow for the optimisation of time, but for the improvement of measurement traceability and repeatability.

Another aspect of using an automated model for automatic plan generation is that for every different calibration job, a corresponding problem model must be created using the model's language. To make the process more user-friendly, an interface will be required to provide a suitable level of abstraction between the real-world calibration problem and the encoded problem.

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Table 1: Experimental results

	No optimisation		With optimisation		
Plan	**First plan**	**Lowest cost after 60 seconds**	**First optimised plan**	**Lowest cost after 60 seconds with optimisation**	**Difference between first and best after 60 second plans**
3-axis	2745	2546	2559	2540	205
5-axis	4777	4759	4777	4703	74

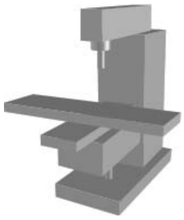

Figure 1: Three-axis machine tool

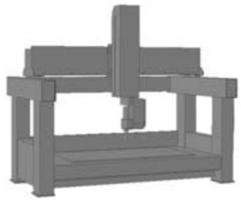

Figure 2: Five-axis machine tool

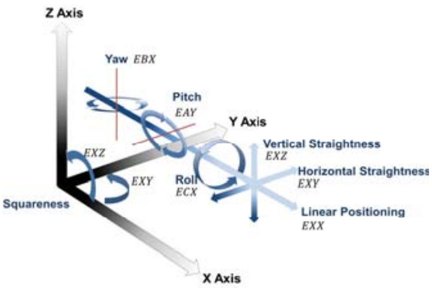

Figure 3: pseudo-static errors of a linear axis

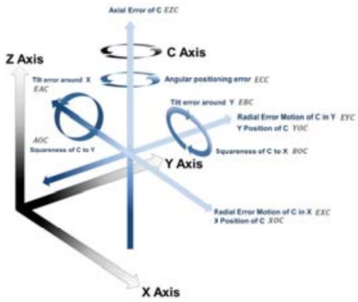

Figure 4: Pseudo-static errors of a rotary axis

Figure 5: Linear Position Optics

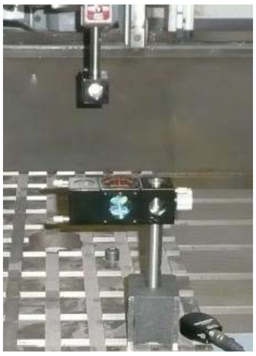

Figure 6: Pitch Optics

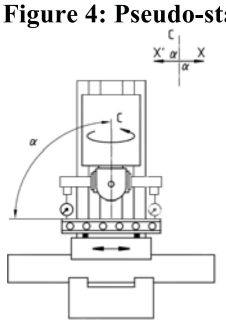

Figure 7: Checking squareness between the axis of rotation and the XY plane

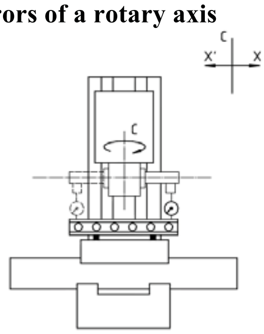

Figure 8: Squareness between C-axis and X-axis motion

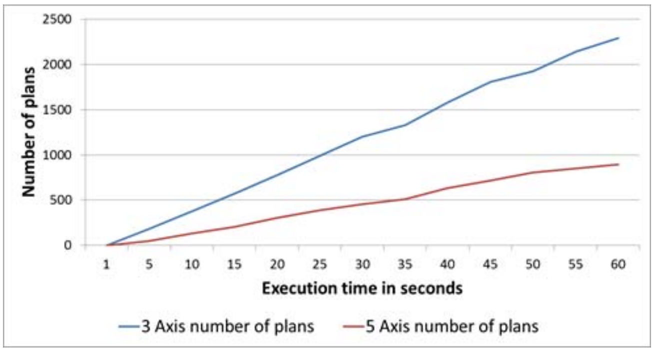

Figure 9: Plan exploration

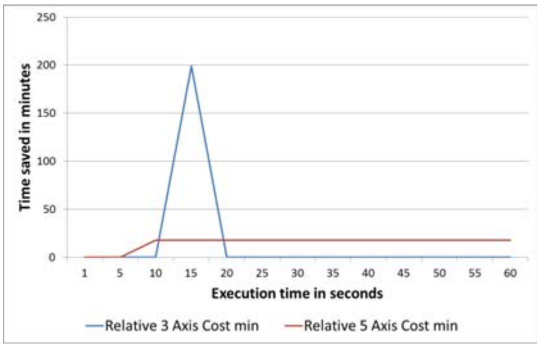

Figure 10: Time saved relative to previous plan

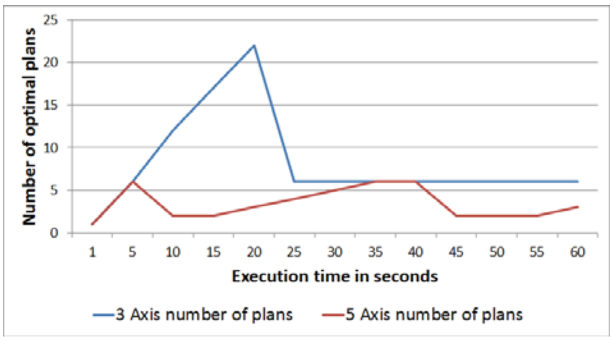

Figure 11: Plan exploration (optimised)

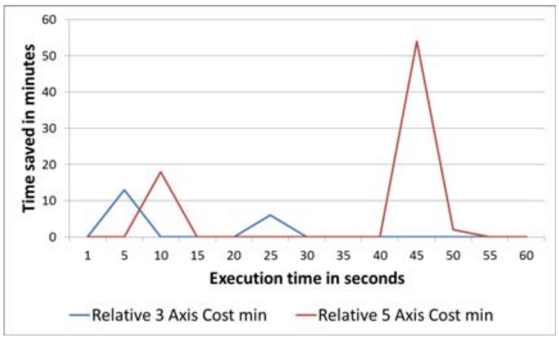

Figure 12: Time saved relative to previous plan when using the branch-and-bounds optimisation