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Geometric error measurement and compensation of a PKM type CNC machine

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Abstract
For most multi-axis CNC machine tools, direct measurement of errors is straight forward, and the data can be applied directly in the controller for compensation. Non-cartesian machine tools such as hybrid Parallel Kinematic Machines (PKMs) also require regular calibration but direct measurement of error motions may not correlate to the build/joint errors and the associated parameters that need updating in the controller. The measurement procedure and calculation of the errors can be very different and not covered by any standards. In the case of the Exechon Parallel Kinematic Machines (PKM), they provide a custom calibration routine that uses a portable measuring arm to measure the position and orientation of the spindle nose at a variety of poses. The existing process typically requires some manual intervention and has limited scalability depending on the size and orientation of the PKM relative to the workpiece and available metrology arms. This paper describes a similar measuring routine but uses a laser tracker, SMR and data fitting to generate the measurement points efficiently. The generated data was used successfully by Exechon in their optimisation software to create a new set of parameters. A simple Ballbar routine was then created that excited all the axes as a fast verification method, showing a 60% reduction in the magnitude of the error after compensation.

Parallel kinematic machine, geometric errors, laser tracker, machine calibration

1. Introduction

The direct measurement of geometric errors using artefacts or laser interferometry is typical for most CNC machine tools and many international standards exist to facilitate the process, including the use of the data for error compensation. Non-cartesian machine tools such as hybrid Parallel Kinematic Machines (PKMs) also require regular calibration but direct measurement of error motions may not correlate to the build/joint errors and the associated parameters that need updating. The measurement procedure and calculation of the errors can be very different and not covered by any standards, often requiring research into custom solutions [1]. The Exechon XT700R PKM is an example configuration comprising three linear axes (legs) and two rotary axes to enable 6DoF position and orientation of the tool [2] with high stiffness [3]. The popularity of these machines in high value manufacturing is increasing. Figure 2 (inset) shows an example configuration of the machine axes from the manual, but there are variations in size and orientation. The standard method of calibration includes the use of a portable measuring arm to measure the position and orientation of the spindle nose at a variety of positions. The existing process typically requires some manual intervention and has limited scalability depending on the size and orientation of the PKM relative to the workpiece and available metrology arms. One of the advantages of the smaller PKMs is the ease with which they can be moved or oriented on different sub-frames, some of which have their own axes for increased cell flexibility for which a flexible and non-contact calibration method is required. This paper describes a similar measuring routine but using a Laser Tracker (LT), SMR and data fitting to generate the measurement points efficiently with the potential for full automation of the process. The research builds on work completed at the Manufacturing Technology Centre (MTC), a High Value Manufacturing Catapult centre, using a LT for Exechon PKM calibration.

In this work, a Leica AT960 was used to extract calibration data on a XT700R PKM machine and processed to be suitable for use in Exechon's proprietary optimisation software, which calculates more than 30 parameters. Due to the complex working volume these machines generate [2, 3], traceable validation of the performance using standard cartesian methods such as laser interferometry can be limited. Additional rapid R-Test and Ballbar routines were therefore created that excited all the axes as fast verification methods. This measurement showed the magnitude of the error was reduce from ±0.3 mm to ±0.1 mm after the tracker calibration.

It should be noted that the reference result is not necessarily optimal for the existing Exechon calibration method with the arm, but it was a calibrated machine. The primary goal of the work is to provide a valid alternative that can achieve a result within the specification required by the machine user. The method can assess the accuracy faster, is robust and can generate compensation files to improve the PKM accuracy.

2. Methodology

Modern laser trackers have very good 3D measuring range and the accuracy is typically less than 50 µm at 3m distance between reflector and tracker. This was the maximum distance used in this work. When using a standard SMR or cat-eye reflector, the LT only provides 3D position. In order to obtain the orientation of the tool, as per the standard arm-based calibration, a planar feature was required from which a normal vector can be extracted. Typically, the spindle on a CNC machine has very small motion errors relative to the geometric errors of the machine therefore the spindle was used as a reference to create circular trajectory by offsetting the SMR on a rigid bracket attached to the spindle. Measurement of spindle runout using a digital displacement sensor (DTI) and spindle mounted test bar confirmed a runout of the spindle of less than 5 µm. Most machines can control the orientation of the spindle programmatically to automate the circle generation.

The fixture installed in the tool holder is shown in Figure 1, the length of which was a compromise. A larger radius provides greater orientation sensitivity but also limits the range of angular motion of the rotary axes due to collision with the structure. A radius of 125mm was chosen for this machine but future work is required to balance uncertainty from reduced circle size vs increased number of poses. Figure 1 also shows the method used to measure the tool length offset required for the accurate calculation of the position of the spindle nose required for the Exechon optimisation software. It should be noted that in this work, only a standard SMR was available and an optical cat-eye reflector with ultra-wide acceptance angle could improve efficiency, and this is part of ongoing research.

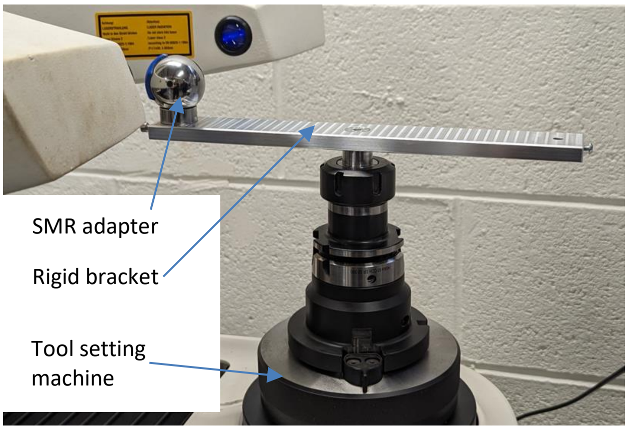

Figure 1. Tool length measurement

The Exechon calibration routine used a NC program to drive the machine to 242 different poses. For simplicity, the same poses were used but the NC program adjusted to support static point capture using the Spatial Analyser software. Some poses had to be trimmed to prevent collisions resulting in 155 poses for the calibration. This speeds up the calibration but has the potential to reduce accuracy in the optimisation. Figure 2 shows the tracker positioned on the rotary table of the machine (not used in this work) in front of the machine at a distance that was approximately 1.5m when the spindle was at a mid-position in the working volume. Reducing this distance increases the measurement accuracy of the tracker but also increases the number of adjustments of the SMR due to the limited acceptance angle. A problem which should be eliminated using a cat-eye reflector. The semi-automated measurement took approximately 4 hours to complete.

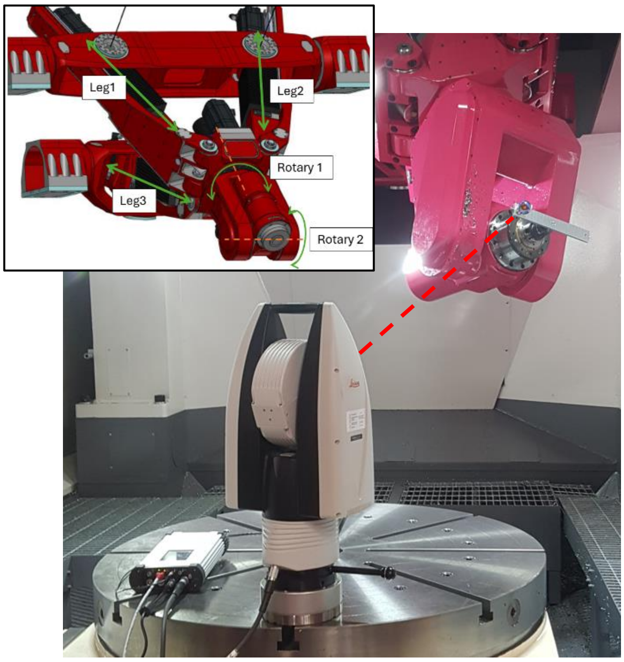

Figure 2. Laser tracker measuring SMR on spindle (inset shows overview of machine configuration)

2.1 Data processing method

The LT data was processed using an algorithm (written in MATLAB) to extract the set of 4 points for every circle, best fit a circle to those points, and calculate the normal vector. Circle fitting was achieved using SVD to convert 3D points to 2D, and generate the normal, then least square fitting a 2D circle. Any normal vectors are flipped if they point away from the tracker. This was checked by generating a reference point roughly central to the arched working volume these machines generate. Knowing that the spindle face always points away from this point, we compare the circle normal to the vector generated a line between the reference point and the centre of each circle. If the difference is less than zero, then it is flipped. Figure 3 shows all the points for each circle and their normal vectors all pointing away from the reference point.

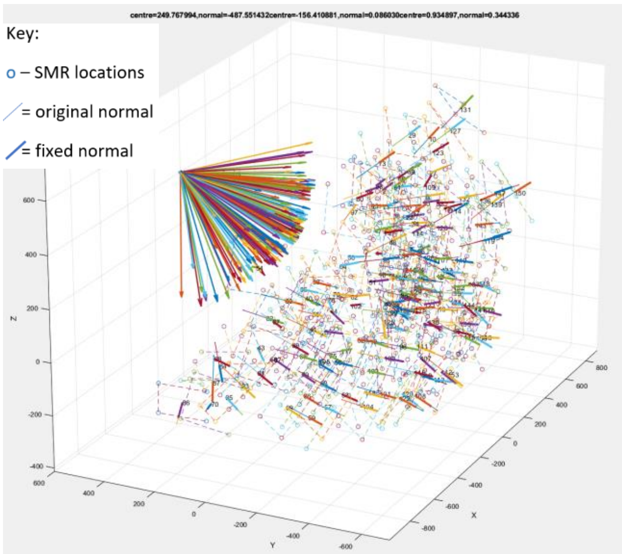

Figure 3. Visualisation of all poses

The performance of the measurement is dependent on the accuracy of the 3D points and the stability of the rotation reference (the spindle axis in this case) which are used to generate the circles. An indicator of this is the maximum radial deviation of any of the 4 points from the circle. Figure 4 shows that the maximum deviation is typically less than 4 μm with the maximum being 4.6 μm.

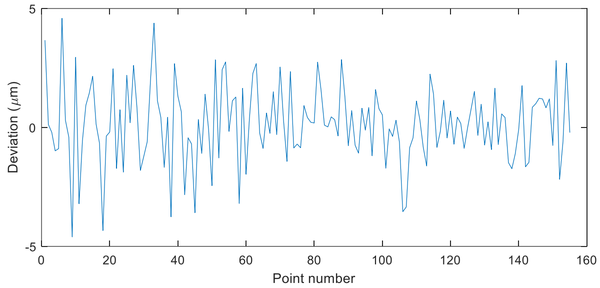

Figure 4. Point deviation from best fit circles

The last phase of the process is sending the processed pose and machine position data to Exechon for generation of a calibration file which was then uploaded to the machine as per the existing standard method.

2.2 Pre/post compensation verification method

Three measurement systems were employed to measure the motion errors. The first is linear axis error motion measurement using a Renishaw XM-60 in accordance with ISO 230-2. This is a traceable measurement but is not well suited to the PKM machine due to the curved working volume. Measurement of tool error motion during tool-centre-point motion is an efficient method for rapid verification of machine performance when rotary axes are involved. Motion around the virtual C and A axes requires movement of all the axes providing a better representation of the machine position errors therefore the second method chosen was tool-centre point rotations around a static point using an IBS Precision R-Test system which can capture movement in 3-axes dynamically [4].

Some of the testing, according to ISO 10791-6 [5], can be completed using a Ballbar with time-based data capture. These systems are probably the most common for regular machine verification, and previous research has shown how useful and rapid the testing can be on multi-axis CNC machines [6]. In this work, a Renishaw QC-20 Ballbar and Ballbar Trace software was used to capture data continuously. A combination of TCP motion and partial arcs provides even more excitation of the axes compared to interferometry or R-Tests. The range of motions is indicated in the results plot in Figure 9.

3. Verification results

The results from the three methods introduced in section 2.2 are provided in this section.

3.1 Renishaw XM-60

The Renishaw XM-60, shown in Figure 5 setup to measure the Z axis, captures all 6 motion errors of an axis simultaneously. Only linear positioning motion error results are reported for brevity in Table 1 (in accordance with IS0 230-2 as provided by Renishaw Carto Explore software), which shows that the positioning error is reduced significantly using the new method compared to the reference state of the machine. During linear motion, all the axes are being used, but the range of motion is quite limited, so additional verification methods are also included in the following sections.

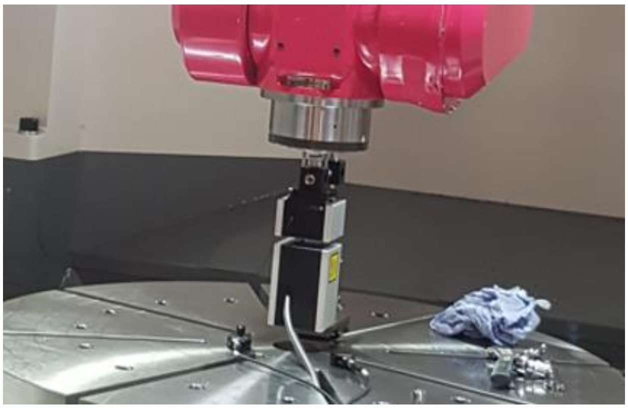

Figure 5. Renishaw XM-60 setup to measure X axis motion error

Error motion	Reference state	UoH method
EXX	384.9	58.2
EYY	33.9	34.1
EZZ	189.4	69

Table 1. XM-60 linear positioning error motion results

3.2 R-Test

The second method uses TCP rotations around a static point as shown in Figure 6. Motion around the virtual C and A axes requires movement of all the axes providing a good representation of performance but does not cover all the working volume. Figure 7 shows the time series data captured from the R-Test duration 180 ° rotation of the A and C axes. The error range after the new calibration is 0.105, 0.172 and 0.087 mm in the X, Y and Z axes respectively.

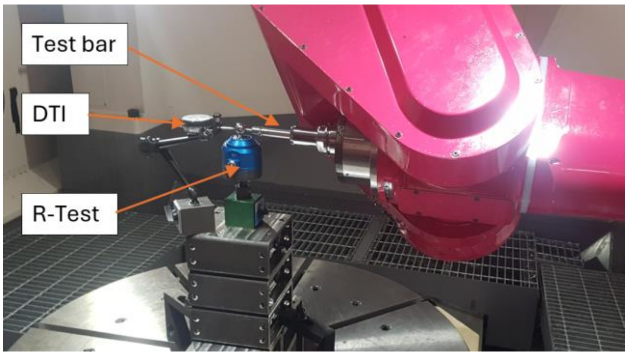

Figure 6. R-Test used to capture tool centre point motion error

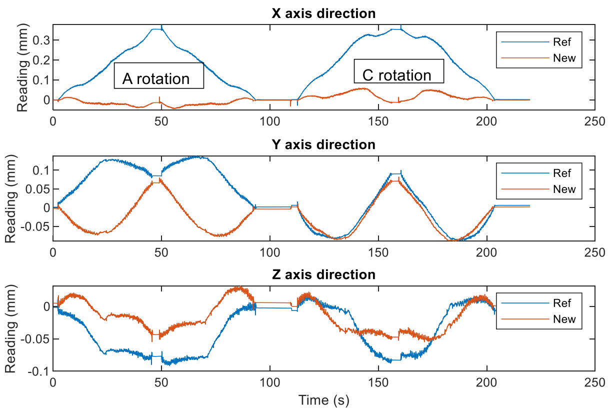

Figure 7. IBS R-Test measurement result

3.3 Ballbar

The Ballbar routine was used to measure the tool centre point deviations. To focus on the geometric errors, a slow feedrate of 500mm/min was used for all tests.

The blue section in the trace indicates error in the Z axis direction, Red is X and Green is Y. The black sections are transitions changing the Ballbar orientation. The labels in each step describe the axis that is changing, for example in the first step the label is Z, A0>>A-90, C90 indicating that the Ballbar is sensitive to error in the Z direction and that the A axis changes from 0° to 90° while the C is at 90° and does not change.

The verification measurement takes less than 5 minutes to complete and excites more than 70% of the available motion of all the axes. Figure 9 shows the Ballbar readings with the reference and new parameters, with the range of error reading reducing from +/-0.3 mm to +/- 0.1 mm.

Five measurements were completed and the first run subtracted to see variability across the runs, indicating the repeatability of the machine to perform these synchronous movement. The standard deviation across all runs is 2 µm.

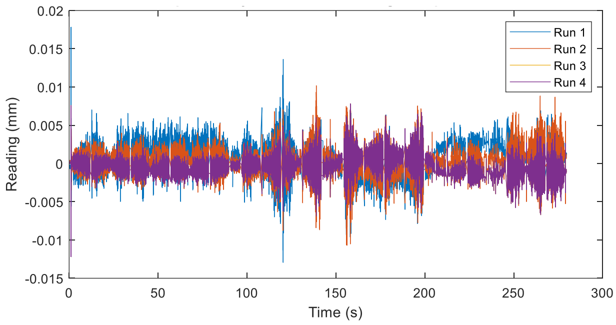

Figure 8. Repeatability of Ballbar tests

4. Conclusions

An Exechon PKM machine was successfully calibrated using a LT efficiently and resulting in good calibration performance compared to the standard method provided by Exechon. Occasional manual intervention was required to reorient the standard SMR due to its limited acceptance angle, however it is likely that the method can be fully automated if a cat-eye reflector is used.

The position errors of the machine need to be verified, but the non-cartesian nature of the machine means that traditional measurements are not ideal therefore three measurement solutions were used including a bespoke Ballbar routine. The first is traceable linear axis measurement using a Renishaw XM-60, the second is a TCP measurement using a IBS Precision R-Test and the third was a hybrid TCP with synchronous circular motion using a Renishaw QC-20w Ballbar.

The average residual errors from new verification were within ± 0.1 mm which was the target for the machine user.

4.1 Further work

To increase the efficiency of the routine, further optimisation of the number of poses is required using an IK model of the machine coupled with an accurate CAD model to maximise pose variation (location and orientation) using both cat-eye and SMR reflectors, while avoiding any collisions and occlusions. Another area could be development of application-specific poses (e.g. for working on a flat plane or small area of the working volume).

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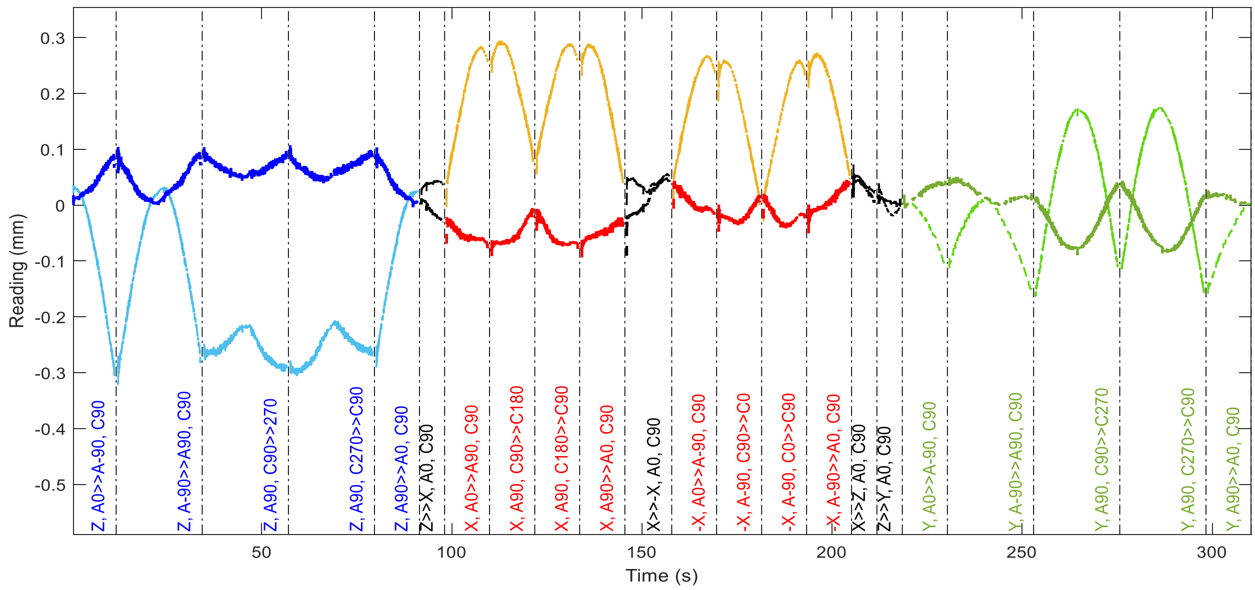

Figure 9. Ballbar trace result with reference and new calibration parameters