euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Calibration of grid plates bearing a high density of targets

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Abstract
The rapid take up by industry in the use of portable 3D point cloud measuring equipment, such as fringe projectors and laser scanners, raises the issue of the traceability of the measurements they make. A number of fringe projection suppliers currently use 2D grid plate reference artefacts that they employ to calibrate their systems, both in the factory and out in the field. The calibration of these reference artefacts involves the measurement of the absolute location of each target. At NPL, this is performed using a high-specification vision CMM supported by error separation algorithms and software developed by NPL. Unlike low density grid plates bearing of the order of less than 200 targets that can be calibrated very quickly, the projector calibration plates have many thousands of targets and, because of the large number of measurements the CMM needs to take, the CMM warms up and its geometry changes during the measurement cycle. The new challenge that needs to be overcome for calibration of these high density plates is to account for the dynamic self-heating effect of the CMM in addition to other machine errors in the calibration exercise. This paper presents a novel method for calibrating high density grid plates and details an approach to overcome the dynamic self-heating effect experienced when measuring some 12,000 targets over a 24 hour period. The paper also discusses the computational challenges arising from analysing the data from the measurement of such a large number of targets and how they have been addressed.

Keywords: Keywords: calibration, error separation, fringe projector, two-dimensional grid plate

1. Introduction

Two dimensional grid plates bearing targets have been employed for calibrating optical dimensional coordinate measuring machines for many years. Most commonly they are used to calibrate and verify the performance of Cartesian-type vision-based coordinate measuring machines (CMM) where the overall geometrical errors of a machine are corrected for using data stored in an electronic look-up table. This typically consists of a list of correction values which are applied depending on the position of the CMM's stages. The density of the matrix is based on pairs of correctors (dx, dy) aligned nominally on an XY grid having a common pitch in X and Y of 25 mm, for example. For a machine having a stage travel of 300 mm × 300 mm, a suitable square grid plate would bear 13 × 13 targets (169) targets. Correction values for stage positions that do not align with the chosen calibration pitch are determined by interpolation. At NPL, such plates are calibrated using an optical Cartesian CMM employing fast-accelerating, high-velocity, lead screw driven stages traversing on mechanical bearings. The time period to measure 169 targets is of the order of 10 minutes and during this period both the CMM and the grid plate are nominally dimensionally stable. Error separation algorithms and software developed by NPL [1,2] can be deployed to ascertain the positions of the targets together with their associated measurement uncertainties. The error separation algorithms remove all the stable systematic errors associated with the CMM so that the uncertainties associated with the estimated target locations depend primarily on the repeatability of the CMM.

A requirement to calibrate similar plates, but with a considerably higher density of targets to support, for example, the calibration of commercial white light fringe projection and similar instruments, presents a problem due to CMM dimensional drift issues. An example of such a high density grid plate could be one having targets on a 3 mm pitch placed over an area filled for example by 67 × 51 (3417) targets and printed on a rectangular plate nominally 300 mm × 260 mm in size. With the machine time required to calibrate this design of grid plate in five different orientations being in excess of 20 hours, significant heat is generated by the stage's motors and by friction from the bearing surfaces. This causes the CMM to become dimensionally unstable and the resultant data shows significant systematic effects that change over the measurement cycle.

This paper describes in section 2 a measurement procedure employed at NPL for calibrating grid plates and discusses the effects of instrument drift observed during the calibration of high-density plates. Section 3 discusses how the instrumented drift can be compensated while section 4 discusses the computation challenges associated with analysing over 40 000 measurement results. Our concluding remarks are given in section 5.

2. Grid plate measurement procedure

A grid plate to be measured is located kinematically and centrally on a vision-based CMM and with the targets aligned as well as possible with the axes of the measuring machine. In the case of the NPL CMM and procedure, positions of the targets are always measured in the machine's coordinate system, moving the probe from left to right in a raster scan, progressively moving it from the top left-most target to the bottom right target. The XY positions of the targets are recorded. The plate and its mount are then both rotated clockwise by 90° and placed so that the targets align as closely as possible with the same machine coordinate system as used when the plate was in its original zero degree orientation. The plate is then measured again. This process is repeated for the plate being measured in at least two other orientations and then it is finally measured with the plate translated along the X-axis by a known number of inter-target pitches. For the purpose of determining the geometry of the plate, the vision CMM itself does not need to be in good absolute calibration, but it's measurement capability at each target position must be reproducible. In the same way, the plate must be stable too. The NPL error separation algorithm sets out to enhance the measurement results beyond the normal capability of the measuring machine and simultaneously determines the machine errors at the grid nodes. The basic philosophy behind the error separation technique [3] is that the machine errors at a particular measuring location remain constant throughout the measurement, regardless of the orientation of the plate on the CMM. By measuring the plate in different orientations and positions on the machine the algorithm is able to determine simultaneously the locations of the plate targets and the machine errors at each measuring location [1,2] up to a global scale correction. This global scale correction is determined from the measurement of selected targets on the plate using a high precision linear optical measuring machine which derives its traceability to the metre directly via laser interferometry.

3. Compensation for CMM thermal drift

The above procedure works very well when employing the NPL vision CMM to measure grid plates with a low density of targets (less than 200). In such cases the measurement cycles, each only last some 11 minutes and issues of self-generated thermal effects do not arise. For high-density plates, the measurement cycles are of the order of 20 hour during which time heat generation becomes significant but unpredictable, partly due to the differences in the kinematic behaviour of the X and Y axes due to different masses, stage bearings and lead screws.

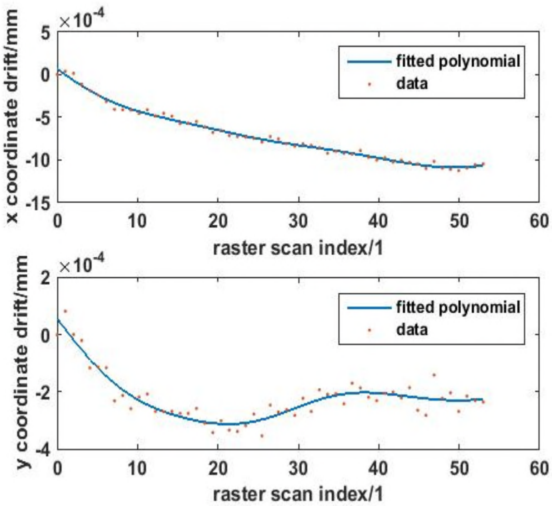

Figure 1. Graph showing grid plate drift in the Vision CMM

Since during the capture of positional data from a grid plate bearing a high density of targets, the reproducibility of the NPL's Vision CMM becomes temporally degraded, it became necessary to monitor the apparent drift in the position of targets associated with the grid plate. To achieve this, the positions of the four corner targets on the plate were re-measured after each single line of the raster measurement process has been completed. In practice this meant that the drift of the plate was monitored nominally after every fifty measurements. Figure 1 shows a plot of the apparent change in the position the plate with respect to the NPL Vision CMM machine over one set of 53 raster scans. Analysis of this data showed coordinate system of the CMM appeared to be undergoing a (two dimensional) rigid body transformation that was tracked by the measurements of the corner points.

The drift in plate position was modelled by a polynomial functions of order 20 (degree 19) with a pre-assigned spatial correlation to smooth out the response of the system [4]. Using this model, all the measurement data was transformed to a single coordinate system and to which the NPL error separation algorithms could be applied successfully. The impact of the drift correction was to reduce the standard deviation of the residual errors of the fit of the model to the data from 150 nm to 100 nm. More importantly, the residual errors for the drift-corrected data showed none of the systematic effects that were present for the uncorrected data.

4. Computational challenges

A second challenge presented by high-density grid plates relate to the number of observations m and model parameters n, in this case over 40 000 measurements and approximately 15 000 parameters. The error separation software solves a nonlinear least squares problem using the Gauss-Newton algorithm that solves a sequence of linear least squares involving the $\boldsymbol{m} \times \boldsymbol{n}$ Jacobian matrix. However, only about 0.07 % of the elements of the Jacobian matrix are nonzero and the sparse matrix linear least squares solver LSQR [5] can be used effectively in a Gauss-Newton setting.

While estimates of the target estimates can be determined efficiently because the Jacobian matrix is sparse, the variance matrix associated with the targets is full and it is not feasible to compute it directly. However, uncertainties associated with the measured data can be propagated through to uncertainties associated with the target estimates using a linearised model and Monte Carlo techniques [6] which, for each sample of the input data, evaluates the change in the parameter estimates by solving a linear least squares problem using the LSQR algorithm. A sample of a few hundred parameter estimates is sufficient to determine the standard uncertainties associated with the fitted target locations and inter-target distances, etc. Standard uncertainties (k = 1) associated with the target estimates were of the order of 50 nm to 80 nm, depending on the location of the target.

5. Conclusions

Grid plates are used as two-dimension reference artefacts to calibrate and/or assess the performance of a range of coordinate measuring systems. The calibration of high density grid plates brings new challenges relating to the stability of the measuring system performing the calibration and computational feasibility. This paper has described how both challenges can be overcome.

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