Investigating the volumetric performance of multi-axis measurement arms

J.Singh, M.Hughes & J N Petzing
Wolfson School of Mechanical & Manufacturing Engineering
Loughborough University, UK

Abstract

Multi-axis Measurement Arms (MMAs) are a unique subset of Coordinate Measuring Machines (CMMs). They incorporate a large number of degrees of freedom and compact design based on multi-element arm construction, which provides tremendous versatility of movement and access around an object being measured. The consequences of the flexibility of the MMAs is that the volumetric accuracy and repeatability specifications are substantially inferior to those of more traditionally designed CMMs.

The work reported here has examined in detail the volumetric performance of a ‘Faro Bronze Series’ Multi-axis Measurement Arm, with repeated systematic measurements of a calibrated reference sphere. The results show that regions of poor accuracy, repeatability and variance occur within the measurement volume, and these regions are found to encroach into the normal measurement positions of the instrument.

1 Introduction

Knowledge of the performance levels of any item is of importance to give confidence in its use and application. In the metrology world this knowledge has to be stated in compliance with an appropriate standard to give the statement recognisable credibility. To arrive at this statement, usually there are procedural tests carried out to definitive standards formulated by national and international bodies. There are currently no recognized international standards of test specifically for MMAs in existence, hence there is much debate due to variation in the tests carried out of the accuracy performance of MMAs by different manufacturers. However, it should be noted that standards such as
BS EN ISO 10360 [1] do not preclude the assessment of MMAs, although the formulation of standards such as this one have been based on more traditional CMM mechanical build formats.

MMAs consist of two arms jointed at six places, each of the joints housing its own encoder for indicating position of the arm. The joints have six degrees of free movement providing vast flexibility in accessing features to be measured. Although there are no fixed slideways as in the case of traditional CMMs with three orthogonal axes, the arm with its six joint movements generates a three axes system similar to that of the traditional CMM. The accuracy performance testing of the MMA is therefore unique in that there are no axes moving specifically and uniquely in X, Y or Z directions which may be tested in the traditional manner for parametric errors. The freedom of movement on the six joints means that there are a semi-infinite number of variations that can generate a point in the working volume of the arm.

In the main MMA manufacturers state the two sigma point measurement repeatability of the arm, the linear displacement accuracy and the volumetric accuracy. The first is typically performed either by repeated measurement of a reference sphere, or measuring points repeatedly by locating the probe in a hole smaller in diameter than the probe. In both cases the artefact is measured in one location only. The linear displacement accuracy is tested by measuring a step gauge in an undefined number of positions. Similarly the volumetric accuracy is tested using a ball bar, again the number of positions and the locations are left to the discretion of the operator.

These methods give an indication of the arm's ability to measure points in the particular part of the volume that the test has been carried out. It does not offer any indication as to the performance with regards to the complex measurements that are carried out with the arm, or of any variation that may occur, in particular parts of the volume. The feedback of a coordinate position from the stylus tip to the operating software, is a complex combination of the multiple encoder positions. At any position, inherent encoder errors will combine to a varying extent, whereby a simple statement of volumetric accuracy may not truly reflect the actual accuracy at any point within the working volume [2].

The work reported here is the result of volumetric measurements made in the normal work volume of the arm. In addition to highlighting the accuracy level of the arm, the work also indicates the likely performance in particular locations of the volume.

2 Possible errors with MMAs

The uncertainty of measurement of an MMA is the result of the interaction of the systematic errors which are errors of the individual machine components and can potentially be assessed and compensated for, and random errors,
comprising the influences exerted by the object under test, the environmental conditions and other operational influences. When a position in space is determined, these errors result in the measured point being surrounded by a three-dimensional area of uncertainty within which the true value lies [3]. It is extremely important in measurement to reduce errors to the minimum possible level and to quantify the maximum possible error which may exist in any reading. It is therefore obviously necessary to analyse any sources of error which may exist. The random errors which are unpredictable variations in the measurement, can largely be compensated for by calculating the mean or median of a data set. It should be noted that any quantification of the measured value and statement of error bounds remains a statistical quantity. Due to the nature of random errors the measured value can only be expressed in probabilistic terms; i.e. there is a 95% confidence that the measured value is within ±1%. Furthermore, due to the often unknown manner which random errors may interact they are very difficult to compensate for.

If the thermal expansion coefficients of the probe head and the measured component are different then a change in temperature will affect the dimensions of the probe and the measured part differently, thus causing an incorrect measurement to be taken. As a corrective measure, the metrology laboratory temperature was controlled at a steady state, (20°C±1/2deg C). It should also be noted that MMAs manufactured by Faro have internal temperature compensation units which measure any change in temperature and compensate for any dimensional change, although details of the compensation mechanism and its effectiveness have not been identified.

The probe should be calibrated using the manufacturers recommended routine [4] prior to every measurement session. Good probe calibration is essential for accurate results. A poorly calibrated probe may lead to an unreal probe calibration error, which will lead to inaccurate results. The result from calibration should be better than the single point accuracy of the MMA.

The main components of MMA systems are the encoders and the bearings. It is important that good quality encoders and precision bearings are used to minimise the factors such as interpolation errors, resolution errors, over-velocity errors, and mechanical/electrical/electronic reliability or integrity.

All of these encoder errors are typically quantified in the MMA specifications, which for the FaroArm Sterling or Bronze series is stated as ±0.3048mm within the company literature [5].

3 Test to determine the volumetric performance of a FaroArm MMA

The primary assessment of the performance of a CMM is, where practicable, a length measuring task [6]. However, during this work it was not practicable, as the consideration that would need to be given to the orientation of the length
standard would add further uncertainties, making the test too complex and hence not viable. Therefore a traceable spherical material standard was used, which was not the sphere used for the CMM probe system qualification. The MMA used for the work was a FaroArm Bronze series device.

A 50.7810mm calibration sphere used on a DEA Omicron CMM for stylus qualification was utilised for this work and was repeatedly measured at predetermined positions within the working volume of the MMA. Hence, repeatability conditions were applied, i.e. where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time.

3.1 Measuring the test sphere

Two preliminary tests were conducted in order to establish the best method of measuring the test sphere. The first test was to determine how many points needed to be digitised on the sphere in order to obtain an accurate result, and the second to determine if the results from measuring half the sphere and three quarters of the sphere were accurate. After assessment of the test data it was decided to use 11 points and it was concluded that the spread of points over the area of sphere used affects the result, therefore where it was not possible to measure the whole sphere the result would be compensated.

3.2 Division of the working volume of the MMA

The working volume of the MMA was broken up into eight levels, each 100mm apart, as shown in Figures 1 and 2. The Arm is restricted by mechanical design to a swept volume of just over one quarter of a sphere if mounted at the side of a reference surface table. Consequently, one quarter of the sphere volume was analysed during this work. Three methods of dividing each level of the quarter sphere into segments were considered, Grid, Rosette and Paving. The paving technique was used because it gave an even distribution of segments and a good concentration of data points would be achieved. The detail of the measurement points using the paving technique are shown in Figure 3.
4 Results of volumetric performance test

The data was visualised graphically by generating two sets of graphs using Matlab. The first set illustrated the measurement accuracy throughout the working volume and the second set illustrated the measurement variation throughout the working volume. These graphs were analysed in tandem to obtain a full understanding of the operating performance. Three measured values for each segment were averaged, the minimum and maximum values were found and used to calculate the range.
The three measurements taken were averaged to give an average measurement value. The problem with this approach is that it can be misleading unless the measurement variation is described. For example, for data taken from Level 8, Band 6, Segment 11, the three measured values were 50.6064mm, 50.5070mm, and 50.9978mm. The average of these values is 50.7031mm, which is just 0.0779mm below the nominal value of the reference sphere, which appears to make this measurement an accurate segment of the spherical volume. However, analysing the measurement variation, which is 0.4888mm, it becomes clear that the segment accuracy statement requires the additional variance qualifier.

The deviation from the nominal value was calculated using the formulation:

\[ \text{Nominal Value} - \text{Measured Value} = \text{Deviation} \]

The majority of deviations generated were therefore positive, as the MMA tended to produce values less than the calibrated sphere diameter. Thus positive deviations actually represent a measured value that is smaller than the nominal value.

5 Analysis of Level 0 measurements

The accuracy of the MMA on Level 0 was very good and on average it was well inside the manufacturers accuracy limits of ±0.3048mm. There were no residual data points on this level. Points of particular interest were to be found in segments (B9/S5 - 11 and B8/S6 - 10) having small negative deviations, this is at the extremities of the MMAs working volume. The measurement variation...
on this level confirmed that the accuracy statements generated from the majority of the data conformed to the manufacturers statement of accuracy.

5.1 Analysis of Level 1 measurements

The graphical results from Level 1 have been reproduced here, to act as an example of the expected output of the work. The first observation was that all but two of the segments recorded positive deviations, indicating that all the averaged measured values on this level were reading lower than the nominal value. The second point to note was that the deviations appeared to be randomly distributed, but as with Level 0 there was an area of high variation around B9/S11. Figure 4 shows that the areas at 45° and 135° appeared to have an increased accuracy. This was confirmed by Figure 5 which shows that in the same areas there was minimal variation.

Figure 4: Level – Positive Deviations from Nominal Value
The trend of the measurement data for all Levels, showed that as the reference sphere was moved down through the measurement volume (Figure 1 and 2) the variance increased and the MMA tended to display regions of volumetric measurement where the output did not conform to the manufacturers statement of quality. Of particular note and interest is that there were regions of conformity and non-conformity, which were located in similar position on each Level. This would suggest that certain combinations of arm and encoder positions may cause the MMA to produce less reliable data.

6 Conclusions

The aim of this study was to highlight the accuracy performance level throughout the working volume of an MMA. Analysis of the data has shown that the accuracy varies as the arm extends vertically upward from the centre of the work volume. The changes in deviation were highlighted well by the data derived from Band 6 Segment 6, Band 5 Segment 6 and Band 4 Segment 5. Up to Level 4 the deviation averaged 0.16 mm increasing to 0.426 mm through the higher levels. This was also the case when the arm extended in the horizontal direction from the centre of the work volume. The effects of increased variation at the extremes of the arm were seen at Level 5 with points of high variation in Band 4 and Band 9, at segments 5 to 15 or 45 deg to 135 deg.
The results of this study show that the MMA tested experienced problems of inaccuracy and variation in certain areas of its working volume. This information would enable users to apply the arm more effectively by avoiding the inaccurate areas and measuring parts of high accuracy in the volume zone that is most accurate. However, the data generated relates only to a one quarter sphere of the swept volume and is only truly representative of the MMA tested. Identification of this matter as a generic problem of MMA CCMs will require further testing of additional units.

References


Bibliography

1. J.A. Bosch, Coordinate Measuring Machines and Systems, Marcel Dekker, Inc. New York, 1995