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PRACTICAL APPLICATION OF A MODULAR SPACE FRAME FOR VERIFICATION OF CO-ORDINATE MEASURING MACHINES (CMMs)

Joao Bosco de Aquino Silva
Department of Mechanical Engineering, Federal University of Paraiba,
João Pessoa -Pb, Brasil. E-mail: jbosco@ct.ufpb.br

Abstract. In the present investigation, a new form of space frame for rapid verification of co-ordinate measuring machines (CMMs) is proposed and applied. This space frame has the form of a tetrahedron and is referred to as a modular space frame as different configurations of tetrahedron can be obtained easily and rapidly. The modular space frame comprises magnetic ball links and a ball plate. A typical magnetic ball link consists of two magnetic cups and a carbon fibre link, connecting magnetically, two high accuracy spheres. A technique based on a laser interferometer system was developed to calibrate the magnetic ball links and the ball plate. The volumetric error data obtained when a CMM measures the calibrated modular space frame can be used to verify whether a CMM maintains the manufacturer specifications. The experimental results have demonstrated that the modular space frame system has an acceptable repeatability and provides a practical and cost effective mechanical artefact to determine the volumetric accuracy of small/medium sized CMMs. The developed technique can be applied for calibration, verification, periodic reverification and acceptance test of any type of CMM.

Keywords: **Calibration, Verification, Co-ordinate Measuring Machines**

1. INTRODUCTION

Over the past two decades there has been a significant increase in the use, in the manufacturing
industry, of three axis co-ordinate measuring machines (CMMs). These machines are capable of measuring a large number of critical features of complex components, often in a single operation. This contributes to reduced time in inspection and permits the identification of errors from the manufacturing process more efficiently and rapidly. To satisfy traceability requirements of most industrial quality system, CMM must be periodically evaluated. That is an essential condition for analysing whether the CMM maintains the manufacturer specifications. Also, evaluation of CMM performance is necessary for obtaining correct measuring results. However, it is important to note that CMM performance evaluation is rather complicated as CMMs are more complex measuring device then most conventional measuring instruments.

Many techniques to assess volumetric accuracy of CMMs have been proposed and applied over the last two decades. Basically, the methods can be classified into three groups of common techniques. They are: kinematic reference standard technique (Bryan,1982), (Burdekin and Park, 1988), (Burdekin and Jywe, 1992); parametric calibration technique or synthesis method (Pahk and Burdekin, 1991), (Huang and Ni, 1995) and transfer standard technique (Kunzmann et al, 1993; Zhang, 1991). Unfortunately, none the existing techniques meet all requirements in terms of consumed time, simplicity to use and measure, diagnosis of errors, thermal stability, ease to transport and inexpensive. Therefore, a critical need exists in order to overcome disadvantages that existing techniques, to assess accuracy of CMMs, present. In this regard, it is necessary to developed a new technique that is capable of assessing the performance of modern CMMs that incorporate software compensation systems. Also, the technique must be able to carried out both verification and calibration of any type of CMM. Additionally, a new technique should require a minimum number of mechanical transfer standard and should be simple to use.

2. MODULAR SPACE FRAME FOR RAPID VERIFICATION OF CMMs

In order to verify the performance of CMMs a novel form of space frame was designed and manufactured, as part this research (Silva, 1997). This space frame has the form of a tetrahedron which contains a sphere at each apex. The base of the tetrahedron comprises a ball plate that contains three spheres. Each tetrahedron contains three magnetic ball links. A simple magnetic ball link comprises a link, connecting magnetically, to two spheres. One sphere is located on the ball plate and the other at a space point where three links are connected together, as shown in figure 1. This space frame will be referred to as a modular space frame as different configurations of tetrahedron can be obtained easily and rapidly. The number of possible configurations for a given three ball plate is a function of the number of available links of different length.

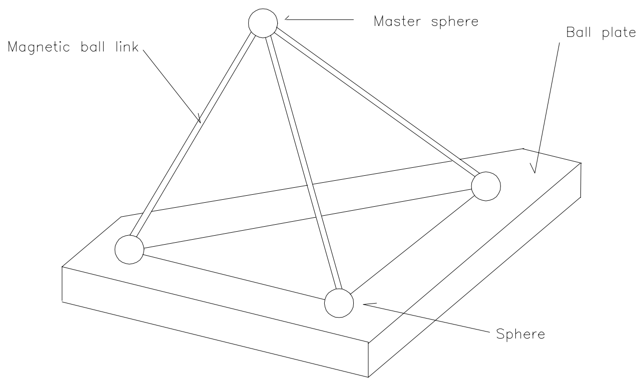

Figure 1 Typical modular space frame

A mechanical artefact before being used to measure the volumetric error of a CMM must be calibrated. Unlike other types of mechanical artefacts, the modular space frame developed in this research is very simple to be calibrated. That is because the modular space frame itself needs not be calibrated. The calibration process only involves in calibrating the elements that define the modular space frame, i.e. magnetic ball links and the ball plate. Then, a computer program calculates the co-ordinates of the apices of the tetrahedron by using the calibrated data. A calibration technique based on a laser interferometer system, which is capable of calibrating both magnetic ball links and ball plate, was developed at UMIST (Silva, 1996).

Although a CMM has its own co-ordinate reference system, it is useful to establish a local co-ordinate reference system on the component to be measured. The main role of the local reference system is to establish a relationship between the CMM and the component being measured. Thus, a program to measure a particular component can be developed by considering the local reference system instead of using the CMM co-ordinate reference system. Once a program to measure a component has been developed, identical components can be measured by using the same program. An analogous principle has been applied to develop a program to measure the modular space frame.

3. PRACTICAL APPLICATION OF THE MODULAR SPACE FRAME

The approach developed in this research was applied on a LK CMM. It is a computer numerically controlled co-ordinate measuring machine of the moving bridge type. The machine has XYZ travels of 600x500x400 mm, respectively.

The machine incorporates air bearing and DC power drives on all axes. Also, the LK CMM incorporates a Renishaw PH9 probe system and a Windows based software to control the measuring process of the machine. This software is called Visual CMES and facilitates the development of a computer program with which the LK CMM performs the measuring tasks. This software eliminates the need for specialist part programming skills by the use of graphical representations or icons rather then text. Visual CMES provides a full suite of teach/learn facilities to the user, as for example, learn sphere measurement, learn circle measurement, etc. In this research, a computer program to measured the modular space frame has been developed, by using the programming facilities provided by the Visual CMES software. The program that measures the modular space frame provides instructions to assist the CMM operator to set-up the ball plate on the CMM table and to build up each tetrahedron configuration.

3.1 Test to check the repeatability of the modular space frame.

A method has been applied to verify the repeatability of the modular space frame by using the CMM itself. Primarily, the method consists in measuring three different tetrahedron configurations of the modular space frame. Each different tetrahedron was measured three times. The first and the second measurements were taken without removing the links. However, before taking the third measurement the links were removed and set-up again, keeping the same tetrahedron configuration. Table 1 shows the results of the repeatability test. By analysing table 2 it can be observed that there is no significant variation between the length values which were measured before and after the links being removed. This indicates that the modular space frame has an acceptable repeatability which was within the repeatability of the CMM.

Table 1 Analysis of repeatability of the modular space frame

Frame number	Measurement	L1 [mm]	L2 [mm]	L3 [mm]
4	1	170.148	202.272	180.752
	2	170.148	202.271	180.752
	3	170.146	202.270	180.752
16	1	255.984	170.146	91.764
	2	255.984	170.146	91.764
	3	255.984	170.147	91.764
33	1	301.067	202.271	180.749
	2	301.067	202.270	180.748
	3	301.067	202.271	180.749

Note: L1, L2 and L3 (in millimetres) = measured length of the links that comprise the modular space frame

3.2 Using the modular space frame for volumetric error measurement of a LK CMM.

The modular space frame has been applied to measure the volumetric error components of a LK CMM. The measuring process is facilitated by the computer program which was developed on the Visual CMES environment. The process of setting-up the modular space frame, which comprises in mounting the ball plate on the CMM table and building up the different tetrahedron configurations, is simple and non-time consuming.

Before starting the measuring process, the LK CMM was warmed up for a one hour period. This procedure contributes to achieve the thermal stability of the machine. Some preliminary thermal drift tests were carried out by probing the spheres of the ball plate at interval of one hour after switching on the machine. The results showed that the drift was on an average of 3 μm in X, 5 μm in Y and 2 μm in Z. During one hour after the initial warm up period, the drift reduced significantly to 1 μm in X, 1.2 μm in Y and 1 μm in Z, as shown by (Silva, 1996). This confirms that the warm up period for one hour before taking measured data is desirable. Additionally, before measuring the modular space frame, the re-qualification of the probe was undertaken.

In this practical application, six calibrated links of different lengths, were used to construct the modular space frame. A computer program uses the calibrated data in order to generate all possible tetrahedron configurations of the modular space frame based on the above data.

Two data files are generated by the computer program that measures the modular space frame. One contains the measured length of the links that form each tetrahedron configuration of the modular space frame. The other one contains the measured co-ordinates of the master sphere of each tetrahedron and the measured co-ordinates of the spheres of the ball plate. Most CMMs have file accessing facilities such as disk drivers in their own computer. Thus, data files generated by the computer program that measures the modular space frame can be saved onto either the hard disk or a floppy disk. Then, those data files can be import, as input data, by a computer program in order to establish the volumetric accuracy analysis of CMMs. This indicates that the analysis of the measured data can be performed off line. In other words, the CMM is used only to measure the modular space frame as the measured data can easily be transferred to other computers or imported by a computer program.

By comparing the calibrated and measured tetrahedron configurations of the modular space frame it is possible to determine the volumetric error components (Ex_i,Ey_i,Ez_i) of the machine under test. The volumetric error at each point defined by the modular space frame is given as follows:

$$Ex_i=X_{mi} - X_i \quad (1)$$

$$Ey_i=Y_{mi} - Y_i \quad (2)$$

$$Ez_i=Z_{mi} - Z_i \quad (3)$$

where,

X_i,Y_i,Z_i, are the calibrated co-ordinates of the points generated by the calibrated modular space frame.

X_{mi},Y_{mi},Z_{mi}, are the measured co-ordinates of the points generated by the measured modular space frame.

The volumetric error components (Ex,Ey,Ez) of the LK CMM, in which the proposed modular space frame was applied can be used to fit a mathematical model to represent each volumetric error component of the machine. Response Surface Methodology (RSM) was used to obtain such a mathematical model as described by (Silva and Burdekin). Response surface methodology, or RSM, is a collection of mathematical and statistical techniques that are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimise this response. In practice, most response surface methodology problems can be established by utilising either a first order model such as:

$$g(X,\beta) = \beta_o + \beta_1 + \beta_2 + \ldots + \beta_k X_k \qquad (4)$$

or a second order model such as:

$$g(X,\beta) = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_{ii}^2 + \sum_{i=1}^{k} \sum_{i=1}^{k} \beta_{ij} X_i X_j \qquad (5)$$

Hence, a response Y, which is approximated by a polynomial function, can be written as

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \varepsilon \qquad (6)$$

or

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_i X_j + \varepsilon \qquad (7)$$

and,

$$\beta = (X^T X)^{-1} X^T Y \qquad (8)$$

where

β = Vector that contains the coefficients of regression or coefficients to be estimated (β_o, β_1, ..., β_k)
X= Matrix of independent variables
X^T = Transposed of X
Y = Vector of observed or measured values
ε= error or discrepancies

Also, by using the calibrated and measured data obtained by using the modular space frame it is possible to evaluate the three-dimensional uncertainty of length measurement of the CMM under test as shown in section 4.

4. APPLICATION OF THE MODULAR SPACE FRAME TO EVALUATE THREE-DIMENSIONAL UNCERTAINTY OF LENGTH MEASUREMENT

According to British Standard (BS 6808, part 2, 1987), uncertainty of length measurement is the uncertainty with which the minimum (i.e. straight line) distance between any two points within the working volume of the CMM can be determined with the machine probe and measuring system. Three-dimensional uncertainty of length measurement is, also, defined as the difference between the measured length and the true length of a mechanical reference artefact.

British Standard(BS 6808, part 2, 1987) [13] establishes a procedure to evaluated the three-dimensional uncertainty of length measurement. This procedure consists of measuring the true dimensions of a mechanical artefact such as gauge block, step gauge, etc., which is located at different positions and orientation within the measuring volume of a CMM. The difference between the measured and the true dimensions of the artefact defines the uncertainty of length measurement. The expression U=±(A+KL)≤B is used to represent the three dimensional (3D) uncertainty of length measurement of a CMM. The constants A, K and B are supplied by the CMM manufacturer. Thus, the length measurement uncertainty specified by the manufacturer can be checked.

In this research a method to evaluate three-dimensional (3D) uncertainty of length measurement of an arbitrary type of CMM has been developed. Primarily, the method consists in taking into account the calibrated and measured dimensions of the modular space frame. To achieve this objective the following steps should be performed. First, the distances between the points generated by the calibrated modular space frame are calculated. Second, the modular space frame is measured by the CMM under test. Third, the distances between the points generated by the measured modular space frame are calculated. Finally, the difference between the measured and calibrated distances is calculated. That difference represents the 3D error of length measurement and is given by the following equation:

$$\Delta L_i = L_{mi} - L_{ci} \tag{10}$$

but,

$$L_{mi} = ((X_{mj} - X_{m(k+j)})^2 + (Y_{mj} - Y_{m(k+j)}{}^2 + (Z_{mj} - Z_{m(k+j)})^2)^{1/2} \tag{11}$$

$$L_{ci} = ((X_{cj} - X_{c(k+j)})^2 + (Y_{cj} - Y_{c(k+j)})^2 + (Z_{cj} - Z_{c(k+j)})^2)^{1/2} \tag{12}$$

where,

j=1,2, . . . , n_p-1; k=1,2, . . ., n_p-j

n_p = number of points generated by the modular space frame

L_{mi} = ith measured length

L_{ci} = ith calibrated length

X_{mj},Y_{mj},Z_{mj} = measured co-ordinates of the points generated by the measured modular space frame.

X_{cj},Y_{cj},Z_{cj} = calibrated co-ordinates of the points generated by the calibrated modular space frame.

In this particular practical application, six calibrated links of different length were used to construct the modular space frame which provides thirty-six points. Thus, the number of distances (or lengths) that can be generated by these points is 630 and is given by the following equation:

$$N_d = \frac{n_p!}{(n_p - 2)!2!} \tag{13}$$

where,

N_d= number of distances or lengths (generated by the modular space frame)
n_p!= factorial of n_p
n_p= number of points generated by the modular space frame.

Generally, the uncertainty of length measurement can be defined as a linearized curve, that is,

$$U=A+KL\leq B \quad (14)$$

where,
U = uncertainty of length measurement
A, K, B = constants to be determined
L = measured length

As already mentioned, according to British Standard (BS6808, part 2, 1987) the constants A, K and B are supplied by CMM manufacturers. Thus, after determining the 3D error of length measurement by using the method proposed in this research the user can verify whether a CMM meets the manufacturer specifications. The modular space frame can also be used by CMM manufacturers when performing acceptance tests in order to establish the specifications of a manufactured CMM. British Standard 6808 (part 2, 1987) does not define how to calculating the constants A and K in equation 14. Thus, it is worth providing a criterion which can be applied by manufacturers to define the values of those constants. In this research, a method proposed by Pakh and Burdekin (1991) to determine the constants A and K has been followed. This method provides two approaches to evaluate the slope K which are: least squares slope over all data and least squares slope over maximum error data (data of "envelope" points). The former is to evaluate the least squares slope considering all the data in the error versus measured length plot. The latter is identical to the former except that it considers the maximum data ("envelope" point data) at every measured length. In both cases, the constant A can be determined as the maximum intercept by shifting the evaluated best fit line, so that the shifted straight line may contain all the error data in the plot.

A computer program, which is described by (Silva, 1997), has been developed in order to calculated the error of length measurement (ΔL) and the constants A and K of equation 14. Figures 3 and 4 show the 3D uncertainty of length measurement plotted against the measured distances, related to the LK CMM on which the modular space frame has been applied. The curve of uncertainty of length measurement shown in figures 3 and 4 was calculated following the method proposed by Pahk and Burdekin (1991) and are given as follows:

- Considering all data points (figure 8).

$$U= \pm(5.8 + 0.0173\ L) \quad (15)$$

- Considering the maximum data or "envelope" data points (figure 9).

$$U= \pm(3.5 + 0.0335\ L) \quad (16)$$

where,
L= measured distance, in millimetres, between any two points generated by the modular space frame.
U= 3D uncertainty of length measurement, in micrometers.

From figures 8 and 9 it can be seen that the slope, K, calculated considering all data points is smaller than the slope, K, calculated considering the maximum data or "envelope" data points. However, the intercept, A, calculated considering all points is greater than the intercept, A, calculated considering the maximum data or "envelope" data points.

The comparison of the above mentioned constants (A and K) with the manufacturer limits is shown in figure 10. From this figure it can be seen that all errors of length measurement are within the linearized curves defined by equation 15, which is $U_2=\pm(5.8+0.0173\ L)$, and the equation 16, which is $U_1=\pm(3.5+0.0335\ L)$. However, there exist points that are outside of the manufacturer tolerance limits, which is $U_3=\pm(2.5+0.0067\ L)$. This indicates that the CMM is out of the manufacturer specifications.

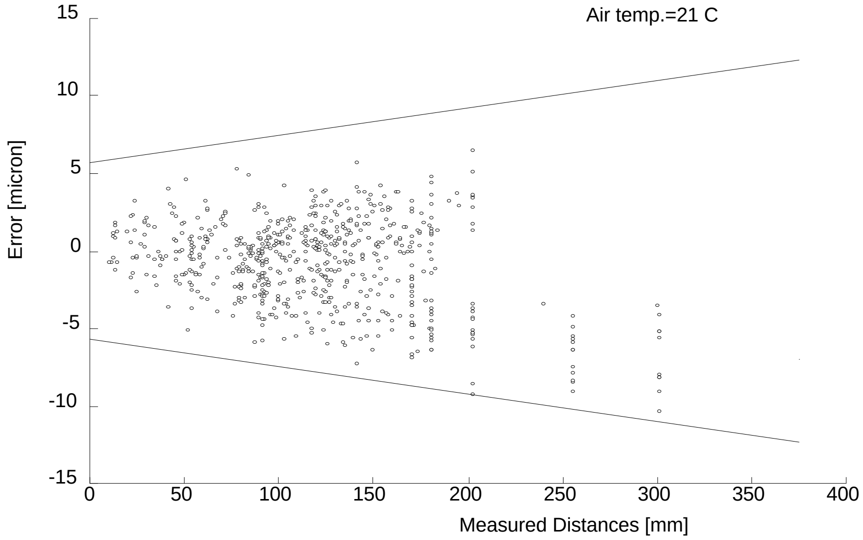

Figure 8 Three-dimensional uncertainty of length measurement (LK CMM)
U= ±(5.8 + 0.0173 L)

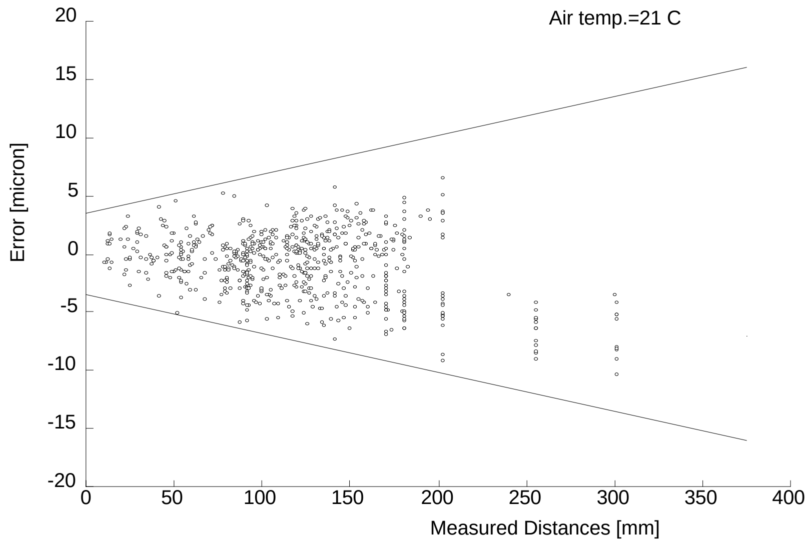

Figure 9 Three-dimensional uncertainty of length measurement (LK CMM)
U= ± (3.5 + 0.0335 L)

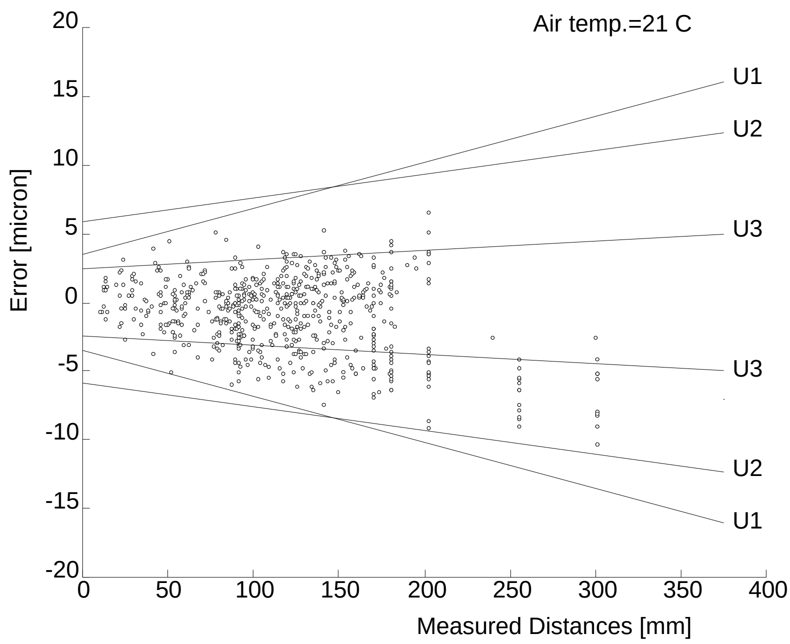

Figure 10 Three-dimensional uncertainty of length measurement (LK CMM)

$U_1 = \pm (3.5 + 0.0335\ L)$

$U_2 = \pm (5.8 + 0.0173\ L)$

$U_3 = \pm (2.5 + 0.0067\ L)$

5. CONCLUSIONS

Primarily, this work had as objective to developed a new technique for volumetric accuracy measurement and analysis of CMMs. The main conclusions of this work can be outlined as follows:

i) The modular space frame provides a practical and cost effective mechanical artefact to determine the volumetric accuracy of small/medium sized CMMs.

ii) Unlike most traditional mechanical artefacts, the modular space frame can be easily handled, transport and stored. It is also lightweight and is thermally stable.

iii) This technique developed in this research provides an efficient approach for measurement and analysis of volumetric accuracy of CMMs.

iv) Once a CMM, under test, measures the calibrated modular space frame and the volumetric error are obtained, both verification and calibration of the CMM can be established.

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