TECHNIQUE FOR PERFORMANCE ANALYSIS OF FIVE-AXIS COORDINATE MEASURING MACHINES

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Abstract. In this paper, a new technique for performance analysis of five-axis Co-ordinate Measuring Machines (CMMs) is presented. The investigation of five-axis machine accuracy is a problem much more complex compared to investigating three-axis machine accuracy as extra sources of error are introduced by added degrees of rotacional freedom. In the first part of this research a novel form of space frame for error evaluation and uncertainty analysis of four-axis Coordinate Measuring Machines (CMMs) was proposed and applied. The novel space frame comprises a ball plate that incorporates seven high accuracy spheres. The volumetric error data obtained when a CMM measures the space frame, in different angular locations, can be used to verify whether a CMM maintains the manufacturer specifications. The experimental results have demonstrated that this space frame provides a practical and effective mechanical artifact to assessing the volumetric performance of four-axis CMMs. Therefore, the purpose of this research is to extend the application of this technique for performance analysis of five-axis CMMs.
Keywords: Five-axis Coordinate Measuring Machines, Ball Plate.

1. INTRODUCTION

Five-axis machine tools and Co-ordinate Measuring Machines (CMMs) are in widespread use as precision machining and measurement tools. These machines are very useful in particularly when the component to be machined and measured has a complex shape. They have attracted much attention due to their ability to machine and measure geometrically complex work-pieces efficiently and with higher dimensional accuracy. In the past decades, much work has focused on three–axis machine tool and CMM accuracy under the influence of geometrical errors and thermal deformation (Srivastava et al., 1995). Basically, the existing methods to assess volumetric accuracy of three-axis machine can be classified into three groups of common techniques. They are: kinematic reference standard technique (Bryan, 1982; Ziegert and Mize, 1994; Lee and Ferreira, 2002); parametric calibration technique or synthesis method (Pahk and Burdekin, 1991; Kunzmann et al., 2005; Umetsu et al., 2005) and transfer standard technique (Zhang and Zang, 1991; Silva and Burdekin, 2002; Chiffre, et al., 2005). The kinematic reference standard technique, such as ball bar, is particularly simple for acquiring data, however, it is difficult to cover all of the measuring volume as well as it is difficult to interpolate between the measured points. The parametric technique has the advantages of providing information for the error diagnosis of the machine. However, this technique is time consuming, requires expensive equipment and special skill to operate that equipment, for instance a laser interferometer system. The transfer standard technique presents some limitations. First, it is difficult to manufacture mechanical artifacts that have the following proprieties: lightweight, high thermal stability, easy calibration and non-expensive. Second, various sizes of the standards are required for various machine sizes and the problem of storage, handling as well as transporting may also arise. Despite such limitations, the transfer standard technique has the advantage of getting measuring data very similar to the way in which the CMMs perform their measuring tasks (Silva and Burdekin, 2002). Therefore, a critical need exists in order to overcome disadvantages that existing techniques to assess accuracy of three-axis CMMs present and most important it is necessary that a new technique to be capable of assessing the performance of five-axis CMMs. That new technique must be able to carry out the accuracy assessment of any type of five-axis CMM and it should require a minimum number of mechanical transfer standards and should be simple to use and measure. The literature survey shows that work in the area of five-axis machine is rather sparse. Among the existent works it can be mentioned: Srivastava et. al (1995) developed an analytical method, based on rigid body kinematics, to obtain the volumetric error at the tool throughout the workspace due to geometric and thermal errors of individual components on a five-axis CNC machine tool; Florussen et. al. (2001) presented a method for assessing geometrical errors of multi-axis machines based on volumetric three-dimensional length measurements by using a double ball bar; Lei and Hsu (2003) used a measurement device called 3D probe ball to measure the position errors of five-axis machine tools. Lin and Shen (2003) developed and implemented a matrix summation approach for modeling the geometric errors of five-axis machine tools. Bring and Knapp (2006) developed a R-test, a new device for accuracy measurements on five-axis machine tool, which incorporates three kinematic ball bar; Terrier et. al. (2005) applied a double ball bar probe coupled with a plate equipped with three spheres to assessing a five-axis parallel kinematics milling machine.

2. DESCRIBING PARAMETRIC ERRORS OF FIVE-AXIS MACHINES.

The investigation of five-axis machine accuracy is a problem much more complex compared to investigating three-axis machine accuracy as extra sources of error are introduced by the added degrees of rotational freedom. The interaction of all of the axes complicates the relationship between the sources of error and the final error at the tool or probe tip. Five-axis machines usually have both translational axes and rotational axes (Florussen et al., 2001). When a five-axis machine moves on the machine guideway it will experience geometric errors as result of existing inaccuracy between the machine component and the guideway, figure 1. In addition, it will experience geometric errors associated with the geometric inaccuracy of the two rotary stages, figure 1. Additionally, these rotary stages may be removable which further complicates the machining accuracy. In this research, for convenience of notation, the translational errors are represented by δ and the angular errors by ϵ. In addition, two characters are used. The first one indicates the direction of the error and the second one indicates the direction of the movement. For instance, $\delta_x(y)$ means the straightness error component in the direction X when moving along the Y axis.

A five-axis machine has three translational axes. For each one six parametric errors are identified such as: 1 positioning error ($\delta_x(x)$), 2 straightness errors ($\delta_y(x)$, $\delta_z(x)$) and 3 angular errors (roll, $\epsilon_x(x)$; pitch, $\epsilon_y(x)$; yaw, $\epsilon_z(x)$). Figure 1 shows these six parametric errors associated with a prismatic joint (X-axis). Similarly, there are positioning errors $\delta_y(y)$ and $\delta_z(z)$, straightness errors ($\delta_x(y)$, $\delta_z(y)$) and ($\delta_x(z)$, $\delta_y(z)$) as well as angular errors (roll, $\epsilon_y(y)$; pitch, $\epsilon_x(y)$; yaw, $\epsilon_z(y)$) and (roll, $\epsilon_z(z)$; pitch, $\epsilon_x(z)$; yaw, $\epsilon_y(z)$), along the Y and Z axes, respectively.

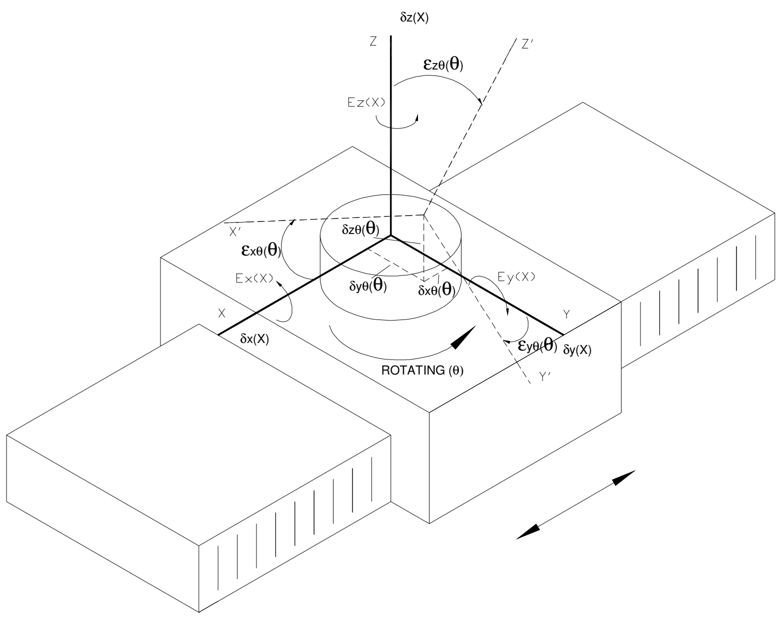

Figure 1. Six parametric errors associated with a prismatic joint (X-axis) plus rotary stage errors

For a rotary joint, the nominal motion is the rotation about its axis. There are also six-degrees-of-freedom error motions associated with this type of joint, i.e., three translational errors and three rotational errors (Florussen et al., 2001). As shown in figure 1, for the rotary stage the translational errors are: $\delta_{x\theta}(\theta)$ and $\delta_{y\theta}(\theta)$ radial errors in X and Y direction, respectively, and $\delta_{z\theta}(\theta)$ axial error in Z direction. The three angular errors are: $\epsilon_{x\theta}(\theta z)$ and $\epsilon_{y\theta}(\theta)$ tilt errors about X and Y axis, respectively, and $\epsilon_{z\theta}(\theta)$ angular positioning error. Similar geometric errors exist for the tilt stage too. When the multi-axis movement is introduced, the misalignment of each axis gives the squareness or orthogonality error. In a generic five-axis machine seven squareness errors are defined. The planar squareness error, between X and Y axis, is defined as the out of squareness, α, between axes X and Y. The vertical squareness error, $\beta_{1,}$ is defined as the out of between the axes X and Z. The vertical squareness error, β_2, is defined as the out of squareness between the axes Y and Z. By considering the rotary and tilt stages, a five-axis machine presents four more squareness errors. They are: $\alpha_{x\theta}$ and $\alpha_{y\theta}$ out of squareness of θ with the X and Y of the reference coordinate system, respectively (rotary stage); $\alpha_{y\varphi}$ and $\alpha_{z\varphi}$ out of squareness of φ with the Y and Z of the reference coordinate system, respectively (tilt stage).

Therefore, thirty-seven parametric error components have to be considered in a five-axis machine. They are fifteen translational errors, fifteen rotational errors and seven squareness errors. In order to determine the accuracy of five-axis machines, basically, there are two approaches. One, as mentioned in the section 1, it is called parametric technique which consists in measuring all parametric error components of the machine, then, using the kinematic rigid body mathematical model of the machine to calculate the volumetric errors components. However, this technique is time consuming and very expensive, as it requires that all thirty seven parametric error components of a five-axis machine to be measured. Other approach that can be used to determine the machine accuracy is to measure the volumetric error components, directly, by using a reference artifact. In the first part of this research (Silva et al., 2009) a novel 3D artifact was developed and applied for assessing the accuracy of four-axis Coordinate Measuring Machines. The present research aims to extend that approach for five-axis Coordinate Measuring Machines. The novel 3D artifact that has been designed and developed will be described in the following section.

3. USING A 3D SPACE FRAME FOR ASSESSING THE PERFORMANCE OF FIVE-AXIS COORDINATE MEASURING MACHINES (CMMS).

In order to verify the performance of five-axis CMMs the novel form of space frame that was developed in the first part of this research (Silva et al., 2009) can be used. This 3D artifact comprises a ball plate that incorporates seven high accuracy spheres which diameter is approximately 19 mm (3/4"), figure 2. Three spheres (2, 4 and 6) are located on the plate surface, the sphere 1 is on the central position and the other three spheres (3, 5 and 7) are set up on steel stems which are fixed to the plate. The main requirement that the spheres should meet is high accuracy in terms of shape. Also, the spheres must be resistant to wear and corrosion. This project incorporates chromium steel spheres whose sphericity is better than 0.1 µm. Unlike the space frame proposed in previous work (Silva and Burdekin, 2002), the artifact developed in the present research does not have ball links. For that reason it is called virtual space frame. Also, it is not necessary to be calibrated as the self-calibration technique is applied. The important advantages of self-calibration include the fact it does not require the preparation and maintenance of an accurate artifact or sensor systems (Lee and Ferreira, 2002).

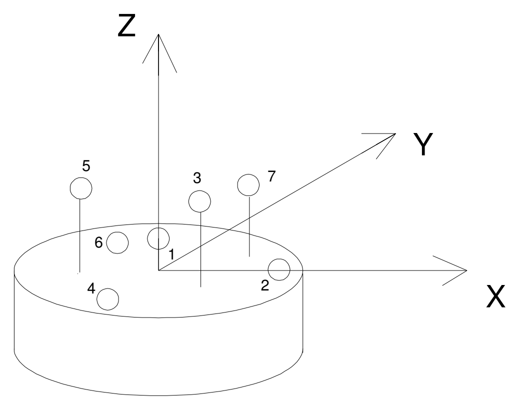

Figure 2. Proposed space frame

3.1 Map of calibration points

The proposed 3D artifact can be rotated along the Z axis (angle θ) and along the X axis (angle φ) as can be seen in figure 1. The range of the angles θ and φ is from 0 to 360 and from -90 to 90 degree, respectively. In order to establish the calibration map which is generated by the proposed 3D artifact, a computer program has been developed. Basically, the input of that program consists of the measured coordinates of the center of the seven spheres at the initial position of the artifact for which the value of the angles θ and φ are assumed to be zero. Once the initial coordinates (X,Y,Z) of the center of the seven spheres are defined it is possible to calculate the nominal coordinates values of the seven spheres at any location of the artifact. The relation between the coordinates (X,Y,Z) of the spheres at the ith+1 location and those at the ith location when the artifact is rotated by θ and tilted by φ is given by:

$$[C_{i+1}]=[RotTilt]^{*}\,[C_i] \qquad (1)$$

where,

the matrix, $[C_{i+1}]$, represents the coordinates of the center of the spheres 1, 2, 3, 4, 5, 6 and 7 at the i+1 location of the artifact and is given by:

$$[C_{i+1}] = \begin{bmatrix} X_{i+1}^1 & X_{i+1}^2 & X_{i+1}^3 & X_{i+1}^4 & X_{i+1}^5 & X_{i+1}^6 & X_{i+1}^7 \\ Y_{i+1}^1 & Y_{i+1}^2 & Y_{i+1}^3 & Y_{i+1}^4 & Y_{i+1}^5 & Y_{i+1}^6 & Y_{i+1}^7 \\ Z_{i+1}^1 & Z_{i+1}^2 & Z_{i+1}^3 & Z_{i+1}^4 & Z_{i+1}^5 & Z_{i+1}^6 & Z_{i+1}^7 \end{bmatrix}$$

the matrix, $[C_i]$, represents the coordinates of the center of the spheres 1, 2, 3, 4, 5, 6 and 7 at the i location of the artifact and is given by:

$$[C_i] = \begin{bmatrix} X_i^1 & X_i^2 & X_i^3 & X_i^4 & X_i^5 & X_i^6 & X_i^7 \\ Y_i^1 & Y_i^2 & Y_i^3 & Y_i^4 & Y_i^5 & Y_i^6 & Y_i^7 \\ Z_i^1 & Z_i^2 & Z_i^3 & Z_i^4 & Z_i^5 & Z_i^6 & Z_i^7 \end{bmatrix}$$

The [RotTilt] is the rotation and tilting matrix when the artifact is rotated along the Z axis, by an angle θ, and the artifact is tilted along the X axis, by an angle φ from the ith to the ith+1 location and is given by,

$$[RotTilt] = \begin{bmatrix} \cos(\theta) & \sin(\theta)\,\mathrm{Cos}(\varphi) & \sin(\theta)\sin(\varphi) \\ -\sin(\theta) & \cos(\theta)\cos(\varphi) & \cos(\theta)\sin(\varphi) \\ 0 & -\sin(\varphi) & -\cos(\varphi) \end{bmatrix}$$

The proposed space frame can be applied to any configuration of coordinate measuring machines as the only requirement is to establish a local reference system before getting the nominal coordinates of the center of the spheres in different locations of the proposed artifact defined by the angles θ and φ. By considering the practical application which was carried out in the first part of this research (Silva et al., 2009), figure 3, the nominal coordinates (X, Y, Z) of the center of the seven spheres of the space frame, at initial location (θ=0, φ=0), are shown in table 1.

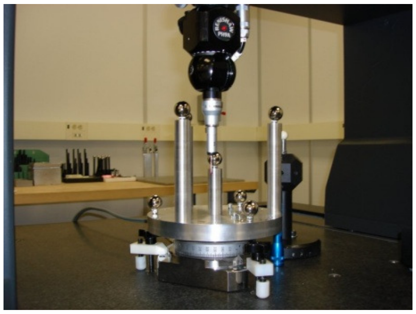

Figure 3. Set up of the proposed space frame on the CMM under test.

Table 1. Nominal coordinates (X, Y, Z) of the spheres at location (θ=0, φ=0).

Sphere	X(mm)	Y(mm)	*Z(mm)*
1	-0.0170	-0.2243	*73.6373*
2	0.1266	-102.977	*0.1119*
3	-88.1763	-51.6103	*149.8827*
4	-88.4696	50.0995	*-0.0242*
5	-2.3838	101.2081	*150.2041*
6	86.5175	51.0002	*0.0012*
7	*88.7260*	*-52.6343*	*150.1732*

The calibrated map of the points generated by the artifact when it is rotated from the position θ=0 to 0=360 at step=45 degree and tilted from position φ= -90 to φ= 90 at step=45 the points generated are shown in figure. Thus, by considering all locations after rotating and tilting the artifact the calibrated map is shown in figure 4.

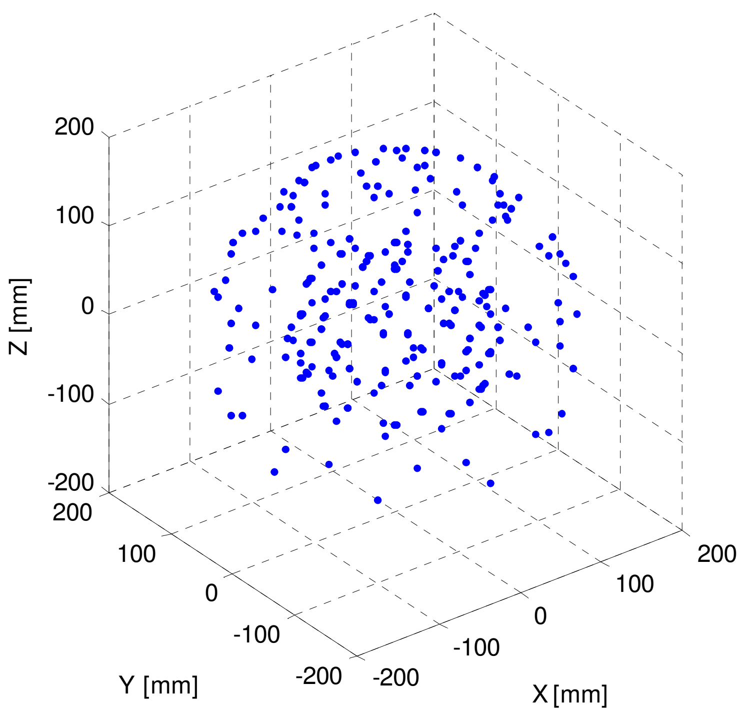

Figure 4. Location of points in the calibration map (space frame rotated and tilted)

4. APPLICATION OF THE PROPOSED TECHNIQUE TO EVALUATE THREE-DIMENSIONAL UNCERTAINTY OF LENGTH MEASUREMENT

In this research a method to evaluate three-dimensional (3D) uncertainty of length measurement of an arbitrary type of CMM developed in the first part of this research (Silva et al., 2009) is applied. Primarily, the method consists in taking into account the nominal and measured dimensions distances of the points generated by the proposed space frame. To achieve this objective the following steps should be performed. First, the distances between the nominal points generated by the space frame are calculated. Second, the space frame is measured by the CMM under test. Third, the distances between the points generated by the measured space frame are calculated. Finally, the difference between the measured and nominal distances is calculated. That difference represents the 3D error of length measurement and is given by the following equation:

$$\Delta L_i = L_{mi} - L_{ni} \tag{2}$$

but,

$$L_{mi} = ((X_{mj} - X_{m(k+j)})^2 + (Y_{mj} - Y_{m(k+j)}{}^2 + (Z_{mj} - Z_{m(k+j)})^2)^{1/2} \tag{3}$$

$$L_{ni} = ((X_{nj} - X_{n(k+j)})^2 + (Y_{nj} - Y_{n(k+j)})^2 + (Z_{nj} - Z_{n(k+j)})^2)^{1/2} \tag{4}$$

where,
$j=1,2, \ldots, n_p-1$
$k=1,2, \ldots, n_p-j$
n_p = number of points generated by the space frame
X_{mj},Y_{mj},Z_{mj} = measured co-ordinates of the points generated by the measured space frame.
X_{nj},Y_{nj},Z_{nj} = nominal co-ordinates of the points generated by the space frame.
L_{mi} = ith measured length obtained by considering the co-ordinates of the points generated by the measured modular space frame.
L_{ni} = ith nominal length obtained by considering the nominal co-ordinates of the points generated by the space frame.

In this particular practical application, when the space frame is rotating from θ=0 to θ=360 deg., at step of 45 degree, and tilting from φ=-90 to φ=90, at step of 45 degree, 315 points are generated, as shown in figure 4. Thus, the number of distances (or lengths) that can be generated by these points is 49455 and is given by the following equation:

$$N_d = \frac{n_p!}{(n_p - 2)!2!} \tag{5}$$

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

The figure 5 shows the frequency of the lengths generated by the space frame. As can be seen from this figure, a considerable number of lengths are generated by measuring the seven spheres that comprise the proposed space frame at different locations (θ, φ). That is an important advantage of the proposed method in comparison to traditional methods, such as step gauge, to establish the uncertainty of length measurement of CMMs. Additionally, the space frame technique is not time consuming, it does not require expensive equipment and special skill to operate and it is particularly simple for acquiring data. In this research a computer program has been developed in order to calculate the error of length measurement (ΔL). Figure 6 shows the 3D uncertainty of length measurement plotted against the measured distances which was obtained by measuring the proposed space frame. From this figure it can be seen that all errors of length measurement are within the linearized curves defined by the expression U=±(A+KL), According to British Standard (BS 6808, part 2). This indicates that the CMM under test meets the manufacturer specifications.

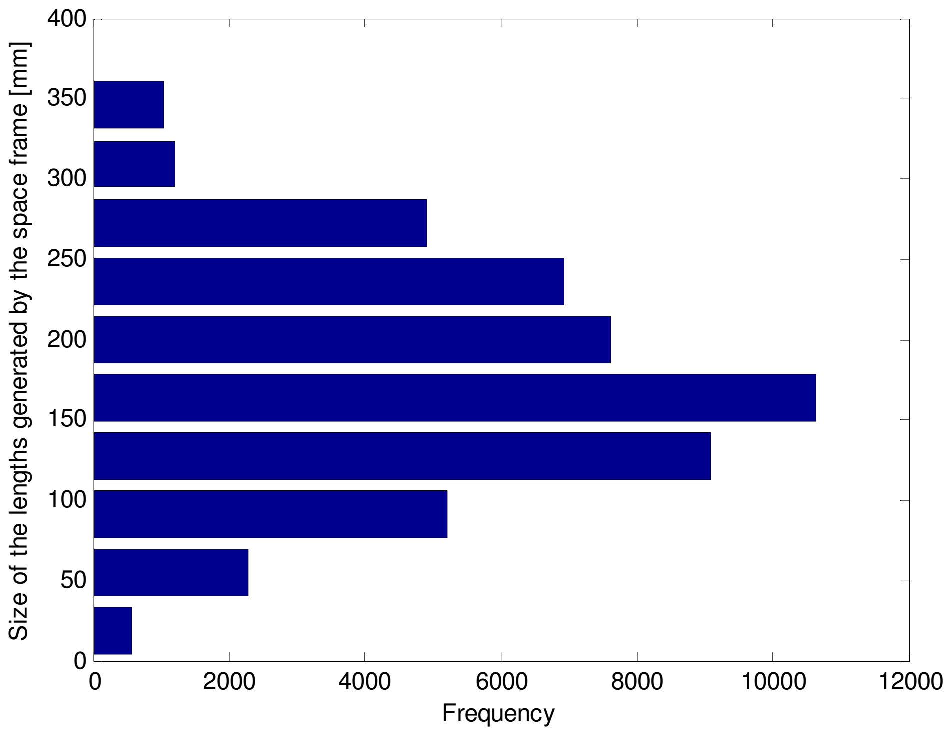

Figure 5 Frequency of length sizes

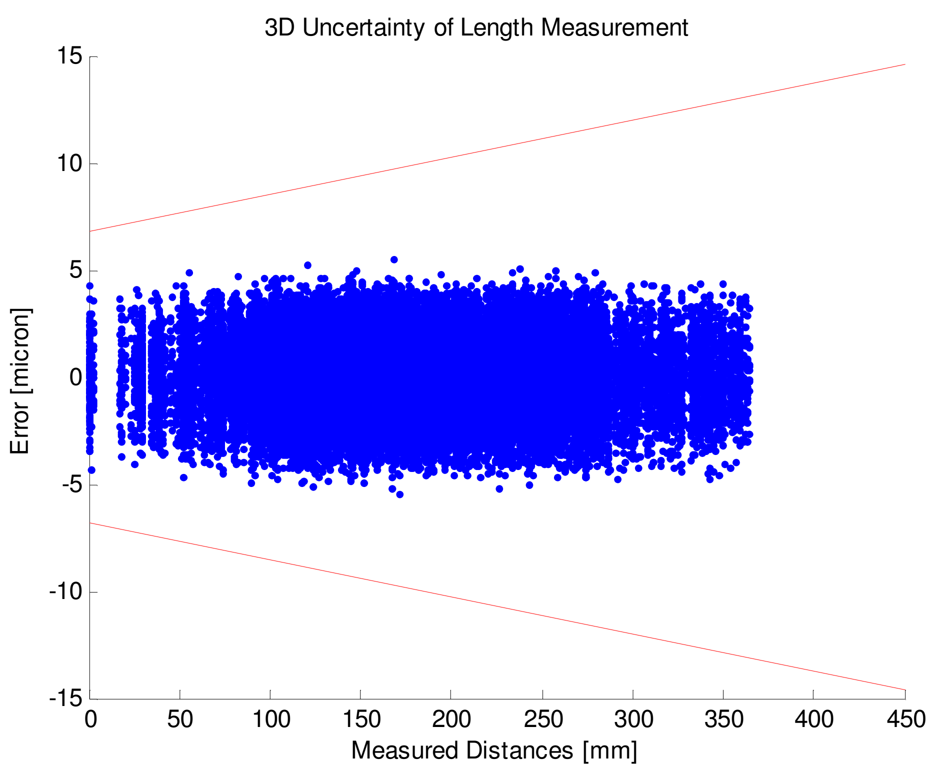

Figure 6. Three-dimensional uncertainty of length measurement

5. **CONCLUSIONS.**

This paper presented a new technique for performance analysis of five-axis coordinate measuring machines. Results showed that the proposed approach provides a practical, non-time consuming and cost effective technique to evaluate three-dimensional uncertainty of length measurement of these type of machines. Also, the volumetric performance test of a five-axis CMM has been established by comparing the nominal and measured coordinates of the points generated by the proposed space frame when it is located at different angular positions within the measuring volume of the machine under test. By rotating and tilting the 3D space frame for different locations, the number of points generated by the seven spheres of the space frame is 315. The number of distances (or lengths) that can be generated by these points is 49455. That is an important advantage of the proposed method in comparison to traditional methods, such as step gauge, to establish the uncertainty of length measurement of CMMs. Further research work is to be carried out to extend the present approach for determining the parametric errors of the five-axis machine from the volumetric error components obtained by measuring the 3D space frame in different locations.

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