Uncertainty analysis of volumetric errors of machine tools – Type A approach

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INTRODUCTION

Quantifying the volumetric performance of machine tools is a vital part of efficient precision engineering. Different metrology techniques are applied to determine the accuracy of the tool path, either directly or indirectly. Extensive industrial and academic efforts have previously been dedicated to establishing models that demonstrate the link between machine errors and deviations from specified geometric features on workpieces in the 3D space. Besides an error model, an uncertainty model is also needed to show both the deviations and variations simultaneously. In other words, the uncertainty model facilitates demonstration of the volumetric performance of a machine tool for manufacturing parts with tight dimensional and geometrical tolerances. Such analysis has not previously been presented. An uncertainty model based on two approaches was developed: a statistical approach (Type A) with the Monte Carlo Method (MCM); and an analytical method using boundary values (ABM) from statistical analysis of individual measurements. Both methods are novel and currently rely on the scattering of the data measured on a 3-axis vertical machining centre (VMC). The numerical results of the uncertainty estimation for a specific target position, located almost at the central part of this VMC used as a benchmark in this research work, were presented and visually demonstrated according to both MCM and analytical methods. Furthermore, characteristics of MCM and the analytical method in estimating uncertainty were explained and compared to each other.

For this research work, an error model based on Rigid Body Theory and Homogeneous Transformation Matrices (HTM) was established for a 3-axis VMC with a kinematic chain of [w X' Y' b Z (C) t]. All six error motions of its three linear axes were measured by a laser system according to ISO 230 series. Assembly errors of these axes, mutual squareness errors between axes, were also measured with granite square and dial gauge according to ISO 10791-2:2023. Having all these geometric errors of the machine and synthesising them into HTM calculations results the error vectors in the working volume of this 3-axis machining centre.

ERROR MODEL

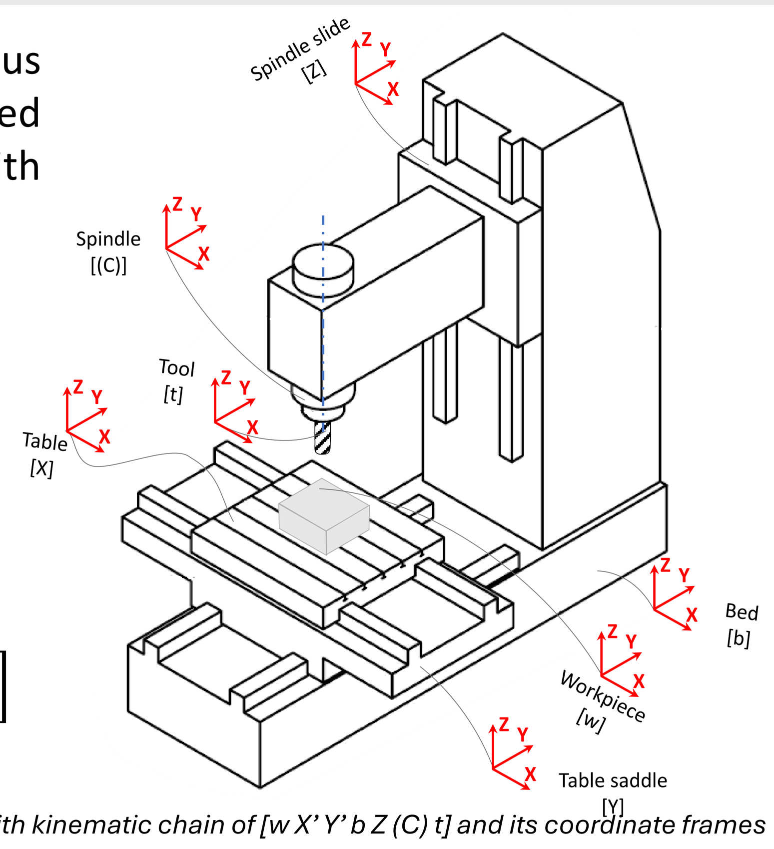
To derive volumetric errors, Homogeneous Transformation Matrices (HTM) method was applied to a 3-axis vertical machining centre (VMC) with kinematic chain of [w X' Y' b Z (C) t].

$${}^{b}_{t}T = \left({}^{b}_{Z}T\right)\left({}^{Z}_{(C)}T\right)\left({}^{(C)}_{t}T\right)$$

$${}^{b}_{w}T = \left({}^{b}_{Y}T\right)\left({}^{Y}_{X}T\right)\left({}^{X}_{w}T\right)$$

$${}^{w}_{t}T = \left({}^{b}_{w}T^{-1}\right)\left({}^{b}_{t}T\right)$$

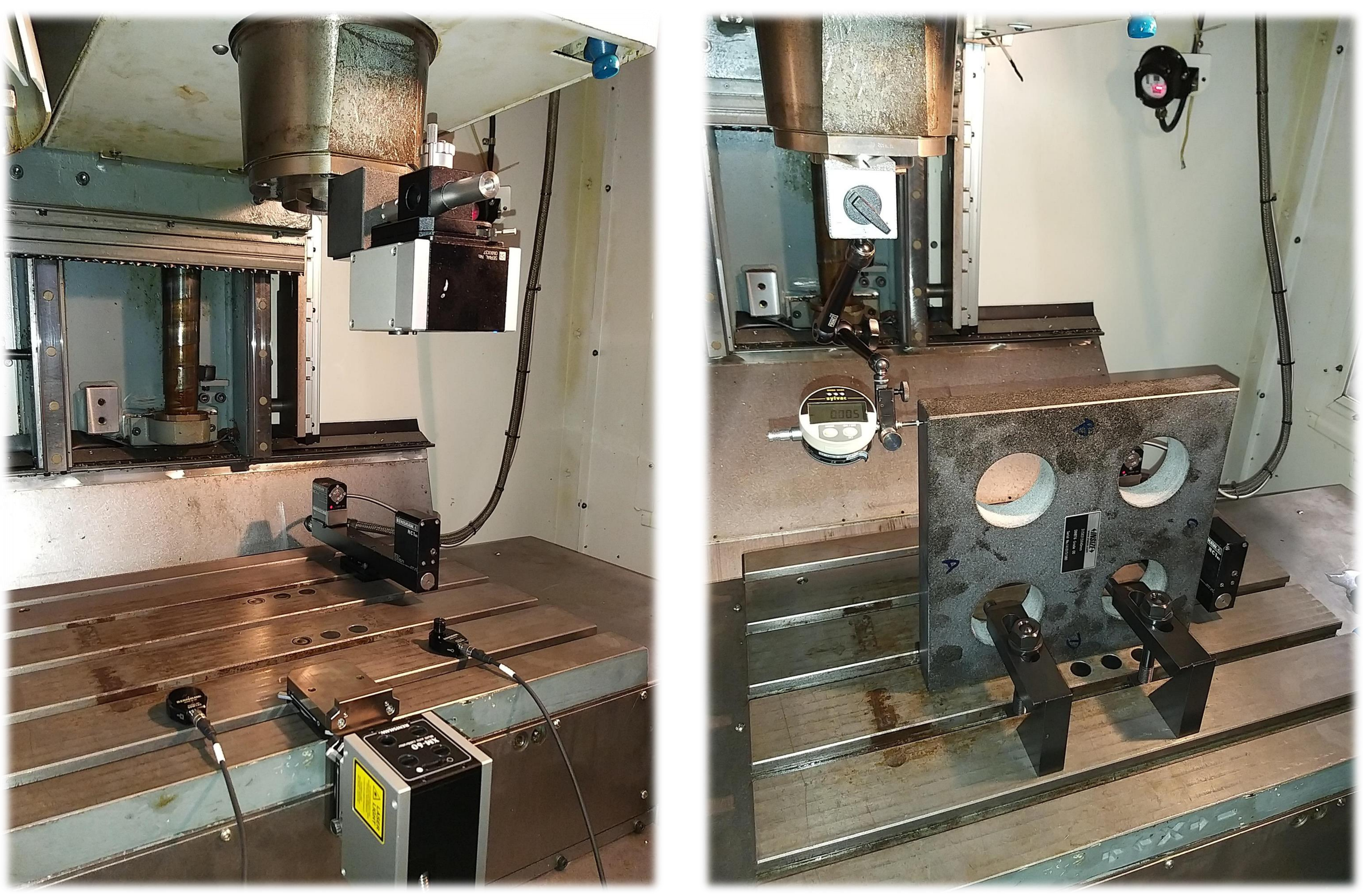
$${}^{w}_{t}T = \left[\left({}^{b}_{Y}T_a\right)\left({}^{Y}_{X}T_a\right)\left({}^{X}_{w}T_a\right)\right]^{-1}\left[\left({}^{b}_{Z}T_a\right)\left({}^{Z}_{(C)}T_a\right)\left({}^{(C)}_{t}T_a\right)\right]$$



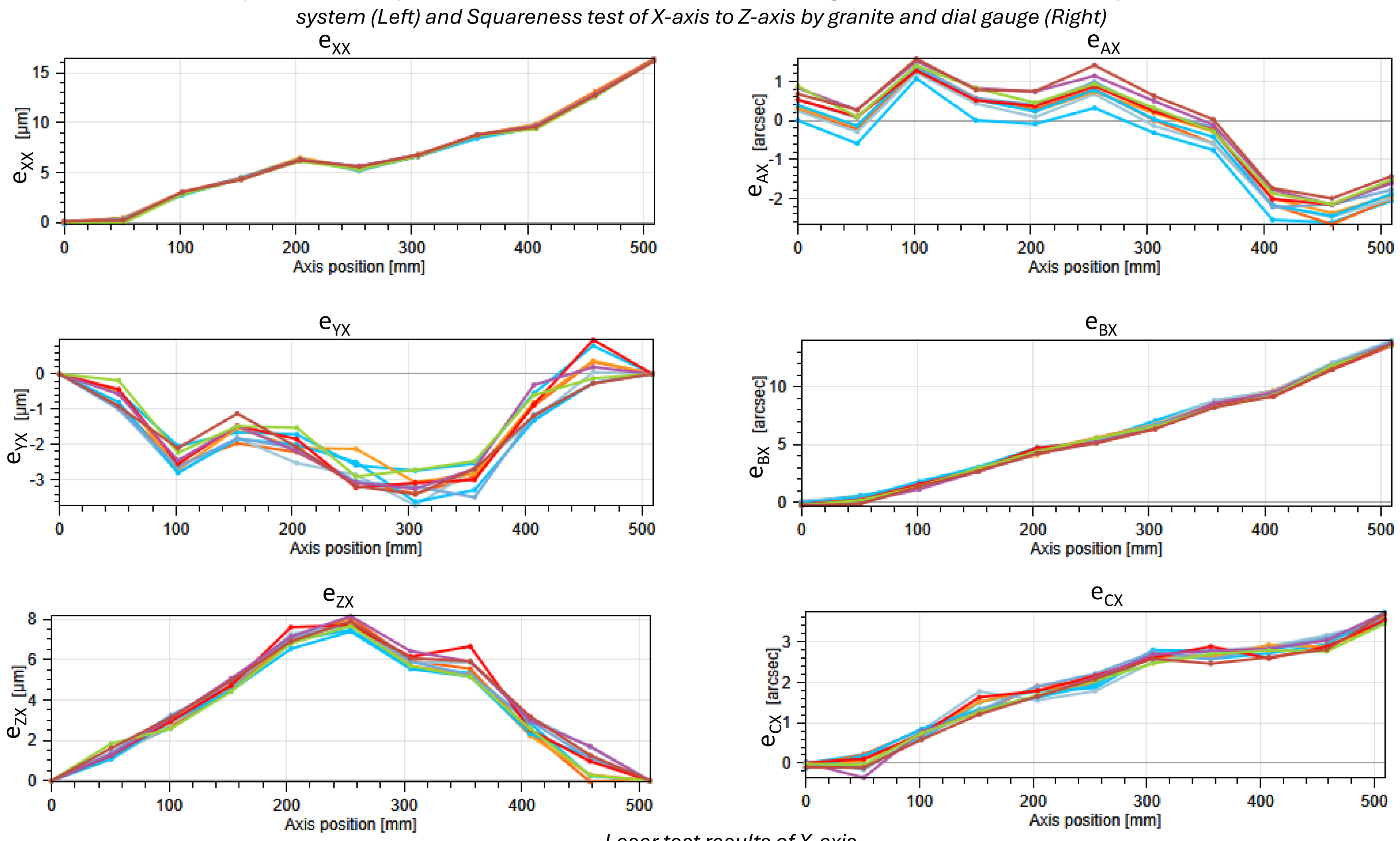
VMC with kinematic chain of [w X' Y' b Z (C) t] and its coordinate frames

EXPERIMENTS

All error motions of the machine with the same kinematic chain of [w X' Y' b Z (C) t] were extracted by Renishaw XM-60 laser system, a granite square and a dial gauge.

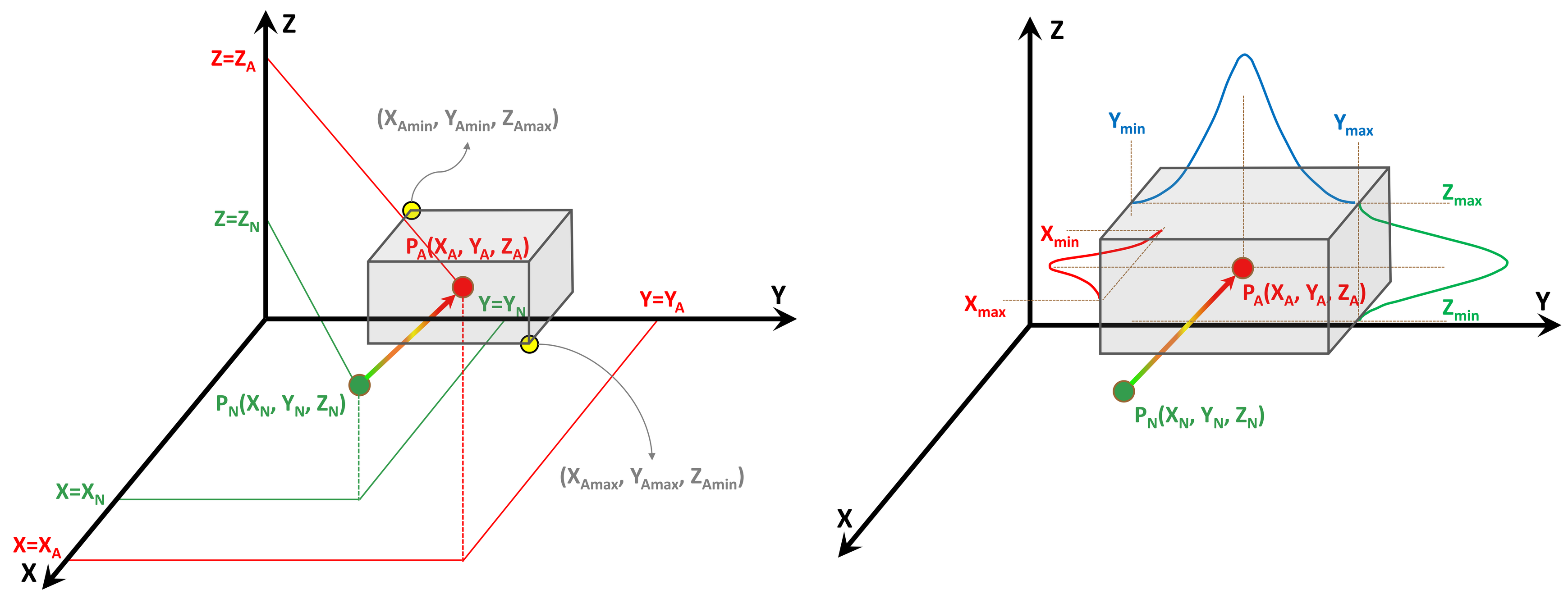


Experimental setup on Cincinnati Arrow500 VMC: linear and angular error motions of Z-axis by laser system (Left) and Squareness test of X-axis to Z-axis by granite and dial gauge (Right)



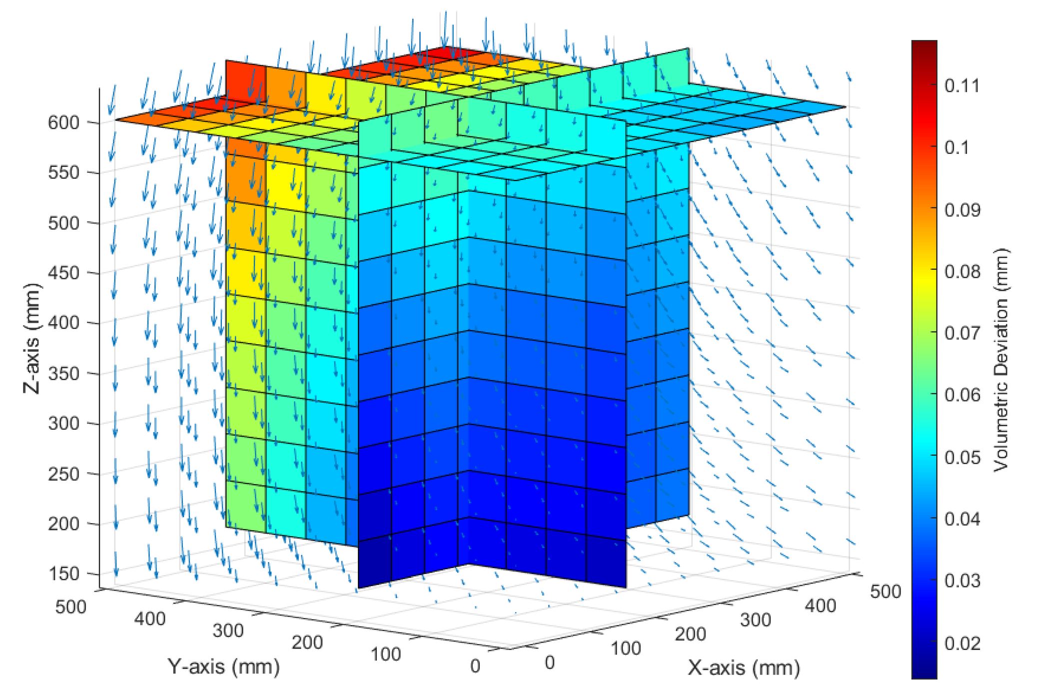
Laser test results of X-axis

UNCERTAINTY MODEL

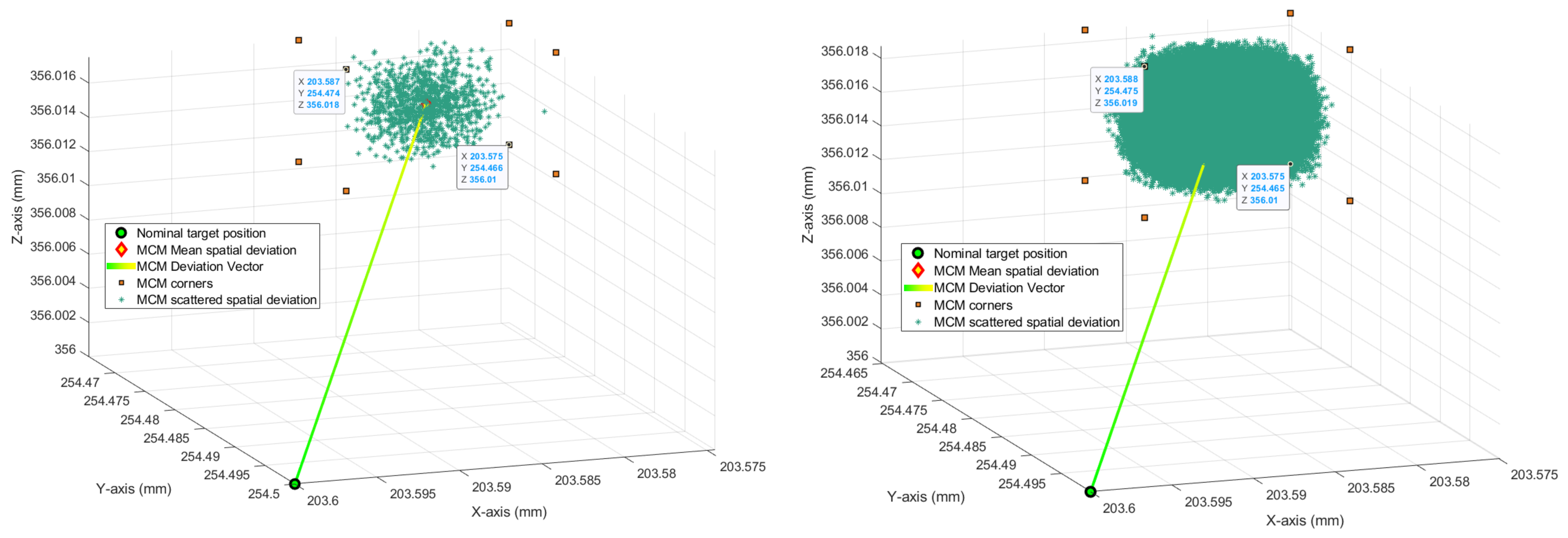


Volumetric variation of the endpoint of the deviation vector (Left) and Normal distribution of deviation vector elements along X, Y, and Z-axes based on central limit theorem (Right)

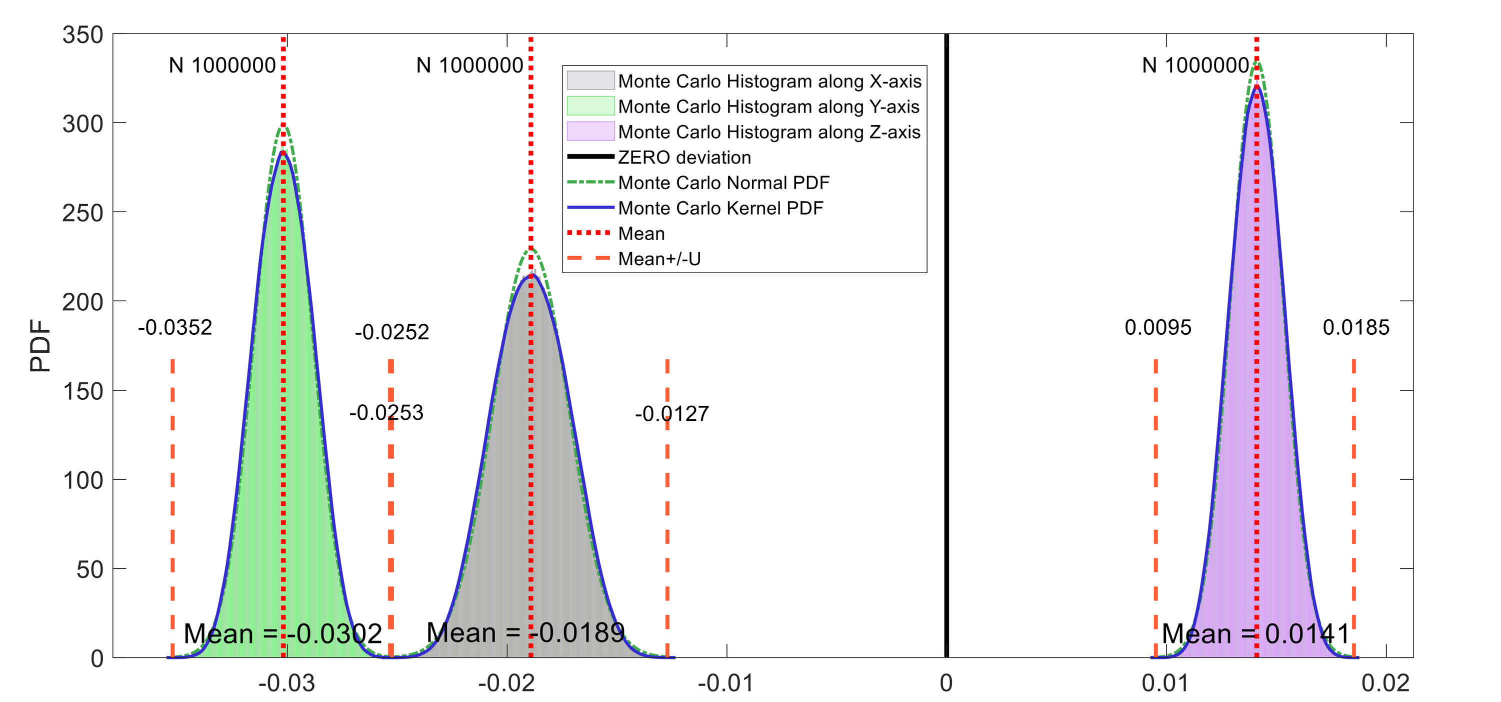
RESULTS



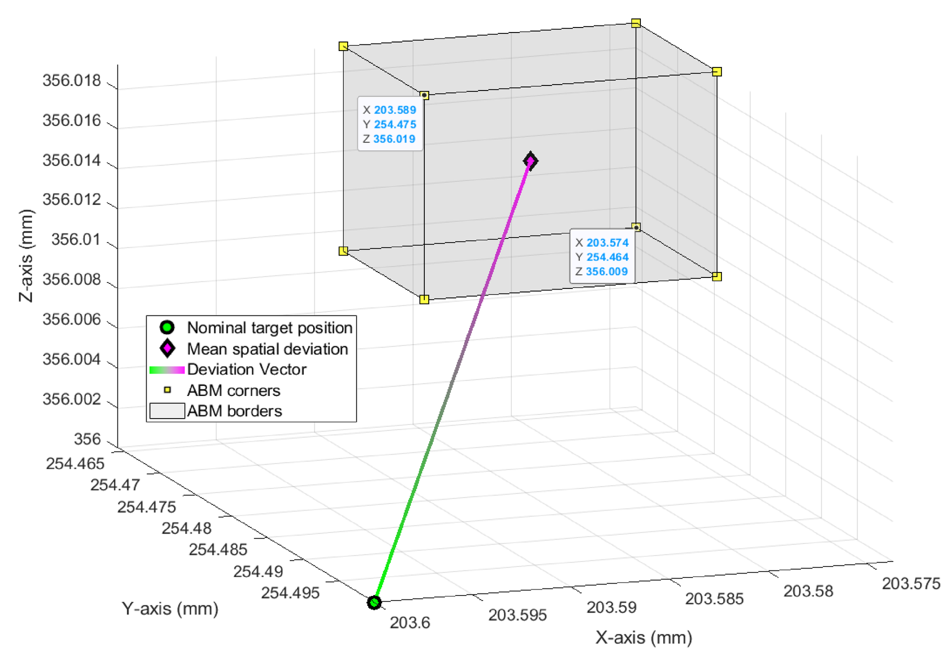
Deviation vectors derived by HTM computations from experimental data for VMC under study



Applying MCM at target position X203.6, Y254.5, Z356.0, N=1000 (Left) N= 10^6 (Right)



Histogram of deviations along linear axes X, Y, and Z (mm) at target position X203.6, Y254.5, Z356.0, N= 10^6 derived by MCM



Applying ABM at target position X203.6, Y254.5, Z356.0

CONCLUSIONS

ABM efficiently estimates the uncertainty boundaries by considering extremes of the input quantities (± 2S of all error motions) while MCM uses all data points between extreme points, as well as extreme points themselves. In other words, ABM is a much faster at finding corners of the cuboidal volume of uncertainty compared to the blind generation of points by Monte Carlo method. Furthermore, MCM provides insight into how the end points of the deviation vector are scattered in 3D space, it primarily demonstrates the more probable shape of uncertainty rather than focusing on the edges (corners) of the volume.

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