TU Delft

Final Presentation

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21 December 2006

Error Parameter Model that made three dimensional tool path measurement in the micron domain possible for a new measuring device

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Contents

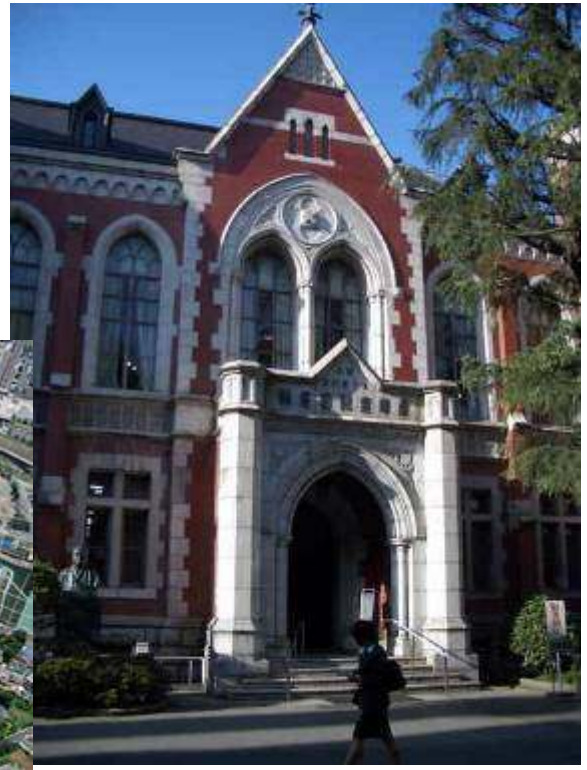
Introduction

Tokyo

- 12 Million People
- 8 Month Research Project
- DeMaMech Exchange Program

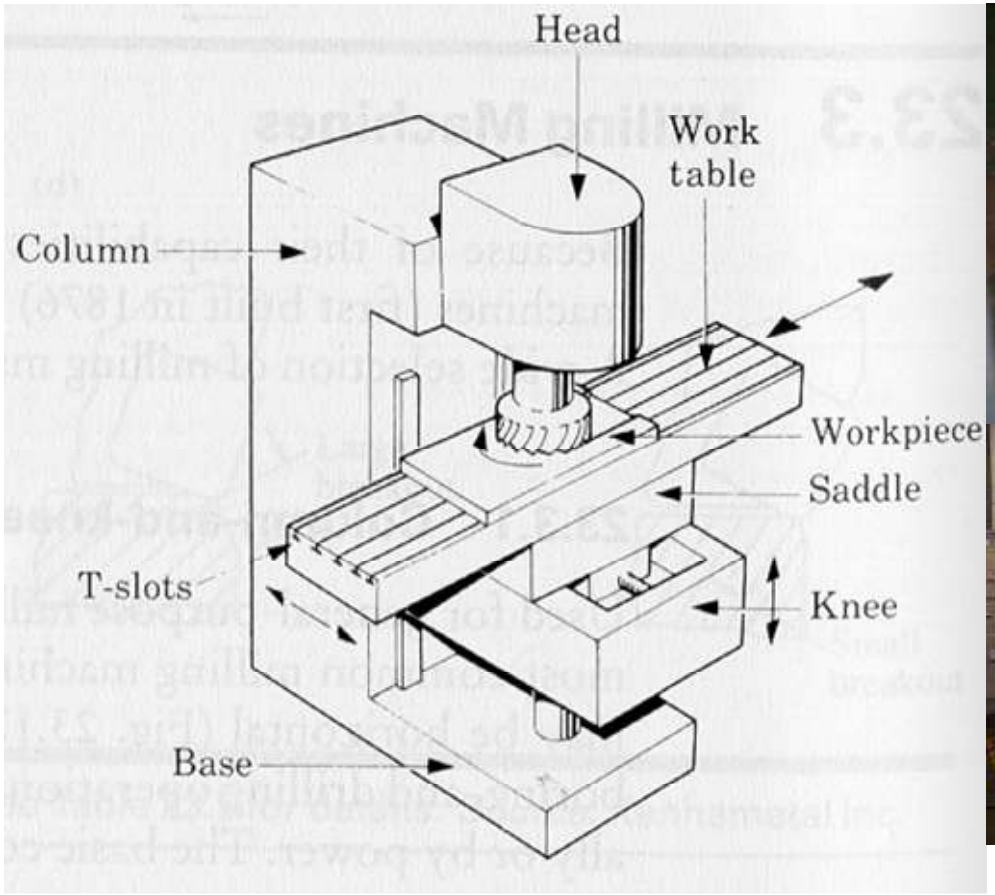
Shibuya

Keio University



Keio University

NC Machine Tools



Problem NC Machine

- **Demand for Machining with Higher Accuracy**
- **Tool Trajectory Errors**
  are copied onto the Workpiece
- **To Achieve Higher Accuracy**
  Measuring of the Tool Path is Necessary

Rotary Encoder Link Mechanism

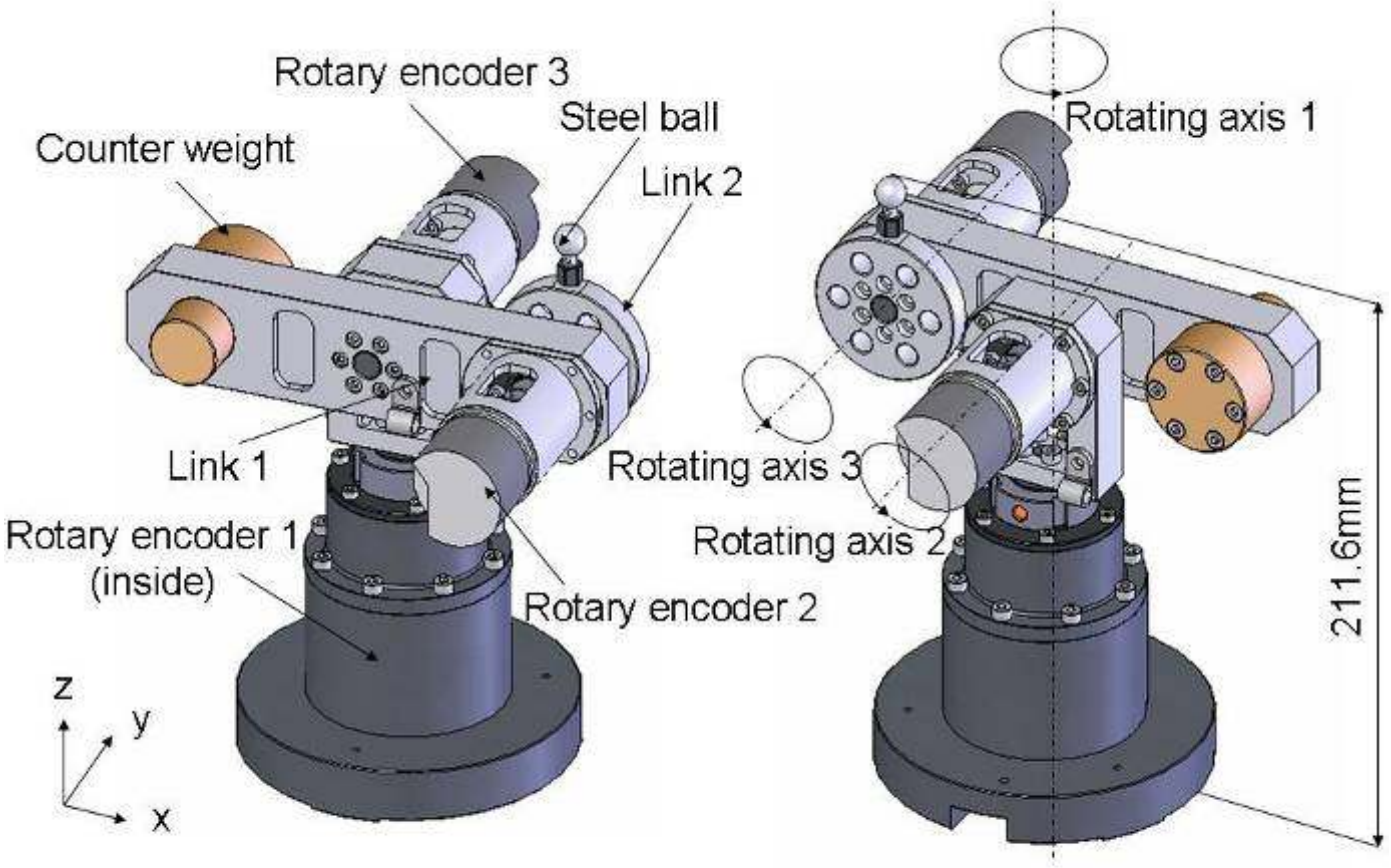
Rotary Encoder

- **Optical Angular Measuring Device**
- **Light pulses are counted that pass through a disk**

Short Movie

Rotary Encoder Link Mechanism

Rotary Encoder Link Mechanism

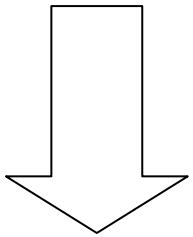


Rotary Encoder Link Mechanism

- **Built up of Links and Rotary Encoders**
- **Measures 3 Dimensional Tool Trajectories**
- **Therefore Able to Measure all Measuring Sequences within its Range**

Problem RELM

- **Errors in the RELM**
  - **Geometrical Errors**
  - **Non-Geometrical Errors**

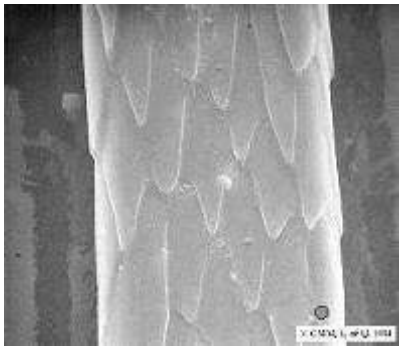


Difference in

Real versus Designed behaviour

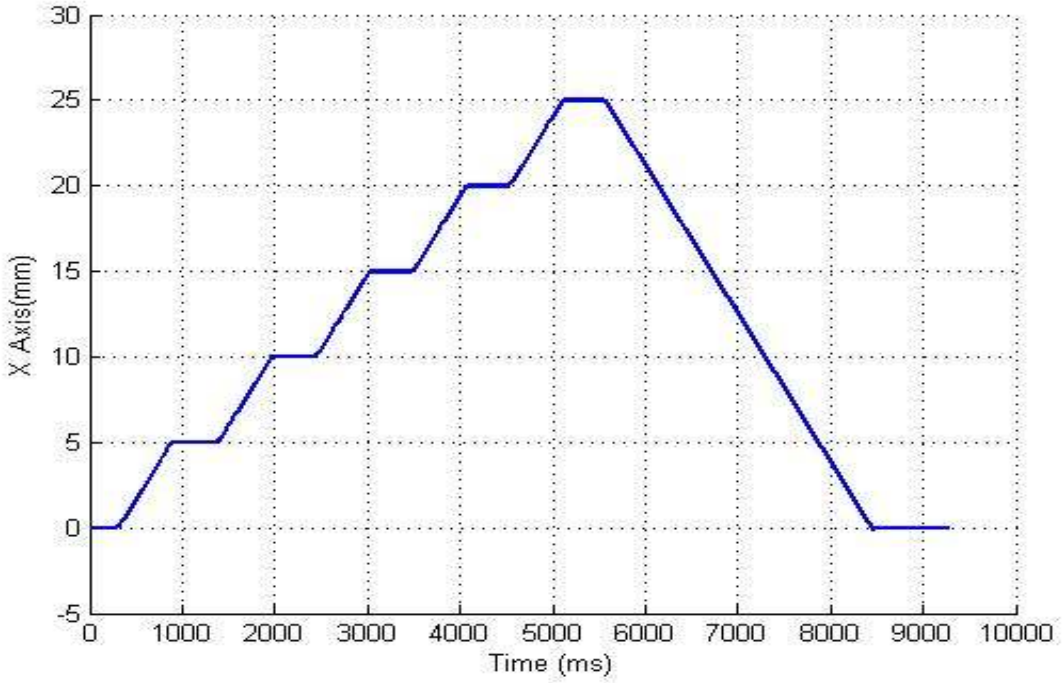
What is a micron?

- 1/1.000.000 m
- 1/1.000 mm



hair = 60 µm

Starting Accuracy

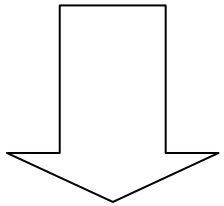


Measuring Accuracy of RELM = ± 349 μm (3D)

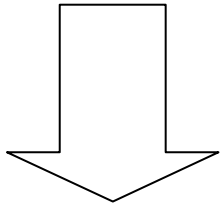
Objective

Objective

- **Find the Errors Parameters of the RELM**



- **Develop a Mathematical Displacement Equation**



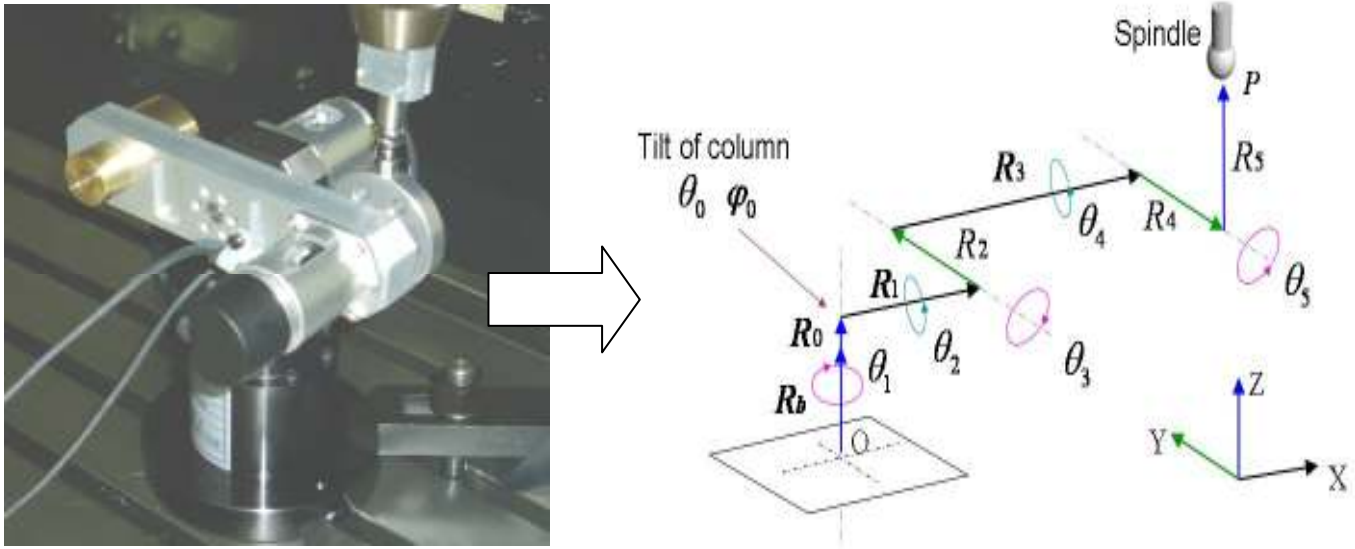
- **Improve the Accuracy of the RELM**

Approach

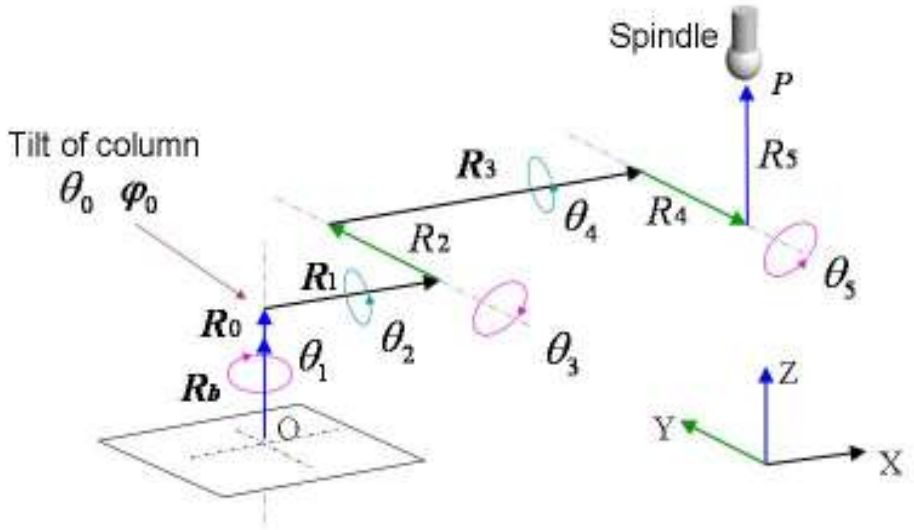
- Make a Mathematical Model of the RELM
- Include Error Parameters
  - Geometrical
  - Bearing Roundness Inaccuracy
- Solve Error Parameters
- Make Measurements Possible in the Whole Measuring Range

Mathematical Model

Mathematical Model



Displacement Equation

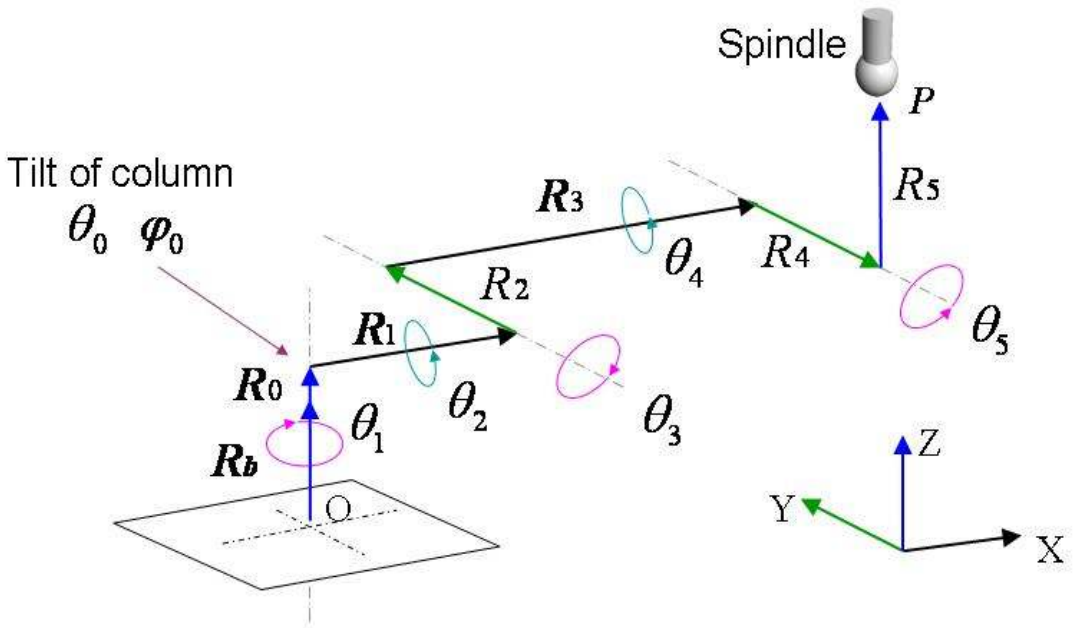


$$P = E_{\theta 0}E_{\varphi 0}(R_0 + (E_{\theta 1}E_{\varphi 1}(R_1 + (E_{\theta 2}E_{\varphi 2}(R_2 + (E_{\theta 3}E_{\varphi 3}(R_3 + (E_{\theta 4}E_{\varphi 4}(R_4 + (E_{\theta 5}E_{\varphi 5}R_5)))))))))$$

$$R_{(q)} = \begin{bmatrix} 0 \\ 0 \\ L_q \end{bmatrix} \qquad E_{\theta(q)} = \begin{bmatrix} \cos\theta_q & -\sin\theta_q & 0 \\ \sin\theta_q & \cos\theta_q & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad E_{\varphi(q)} = \begin{bmatrix} \cos\varphi_q & 0 & \sin\varphi_q \\ 0 & 1 & 0 \\ -\sin\varphi_q & 0 & \cos\varphi_q \end{bmatrix}$$

Geometrical Parameter Model

Geometrical Model

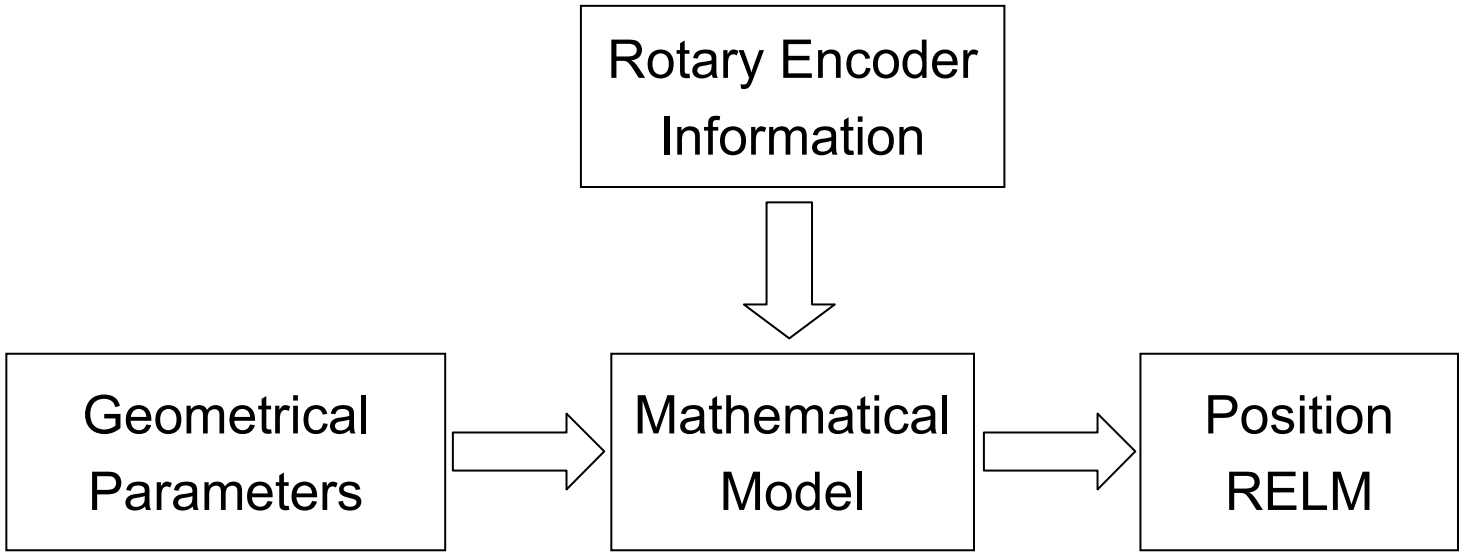


12 Parameters

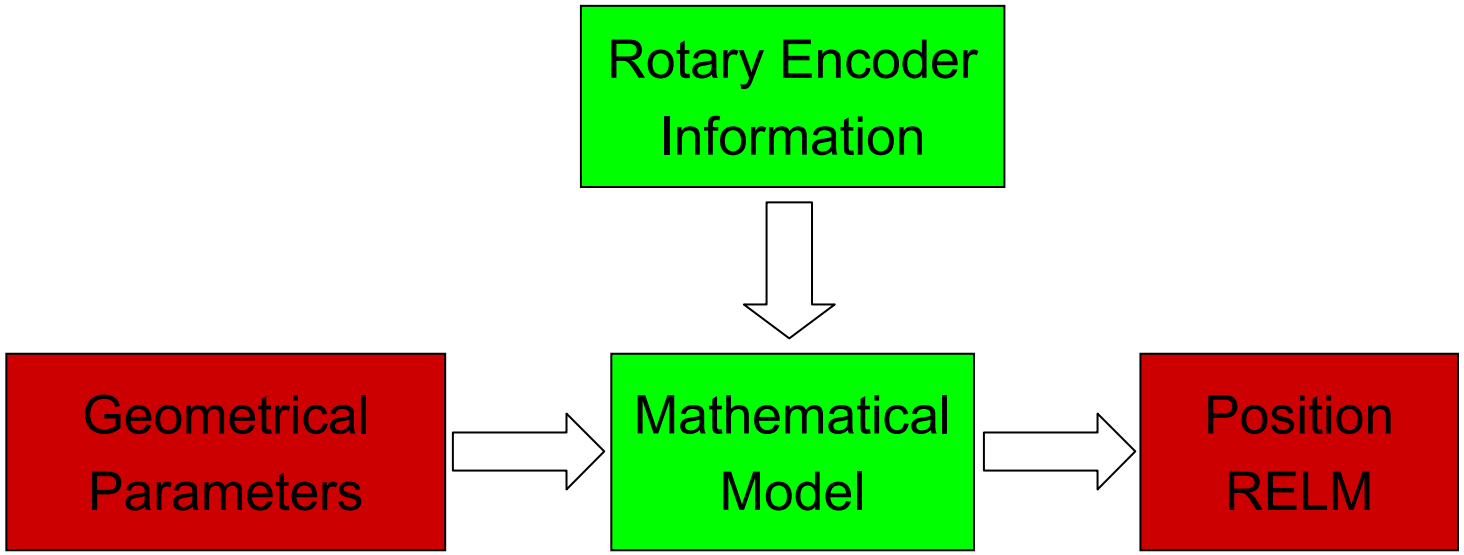
Link Lengths (5x), Relative Radial Angle (5x), Tilt of Head Axis (2x)

Solving the Geometrical Parameters

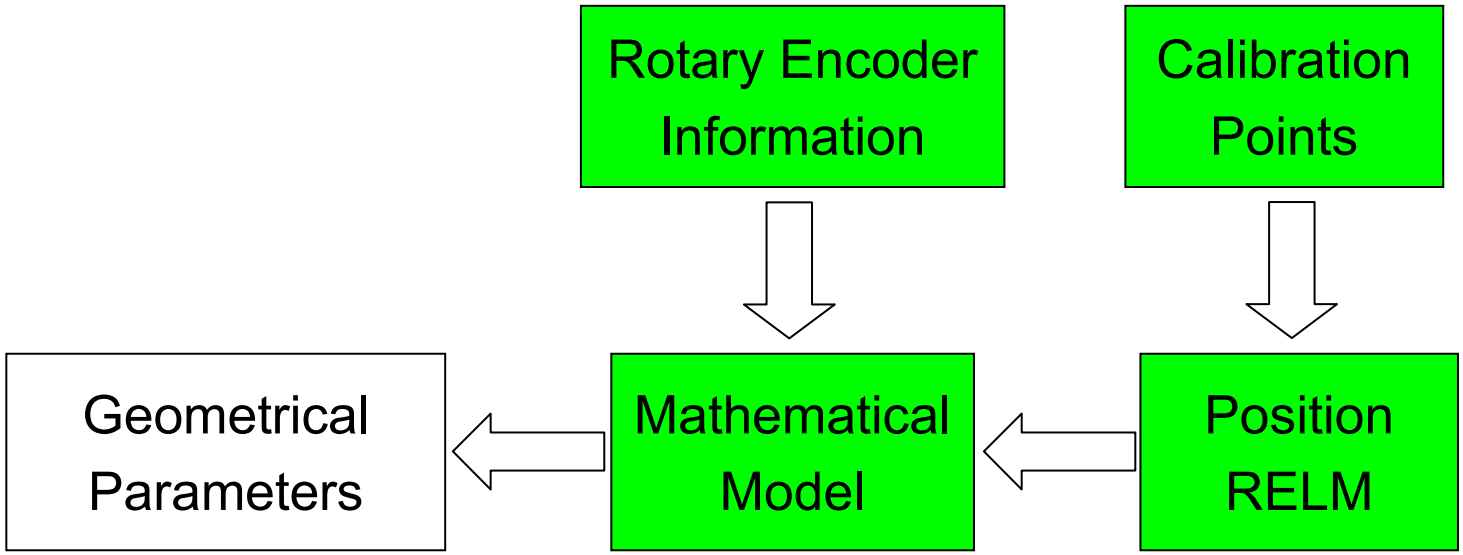
Positional Measurement



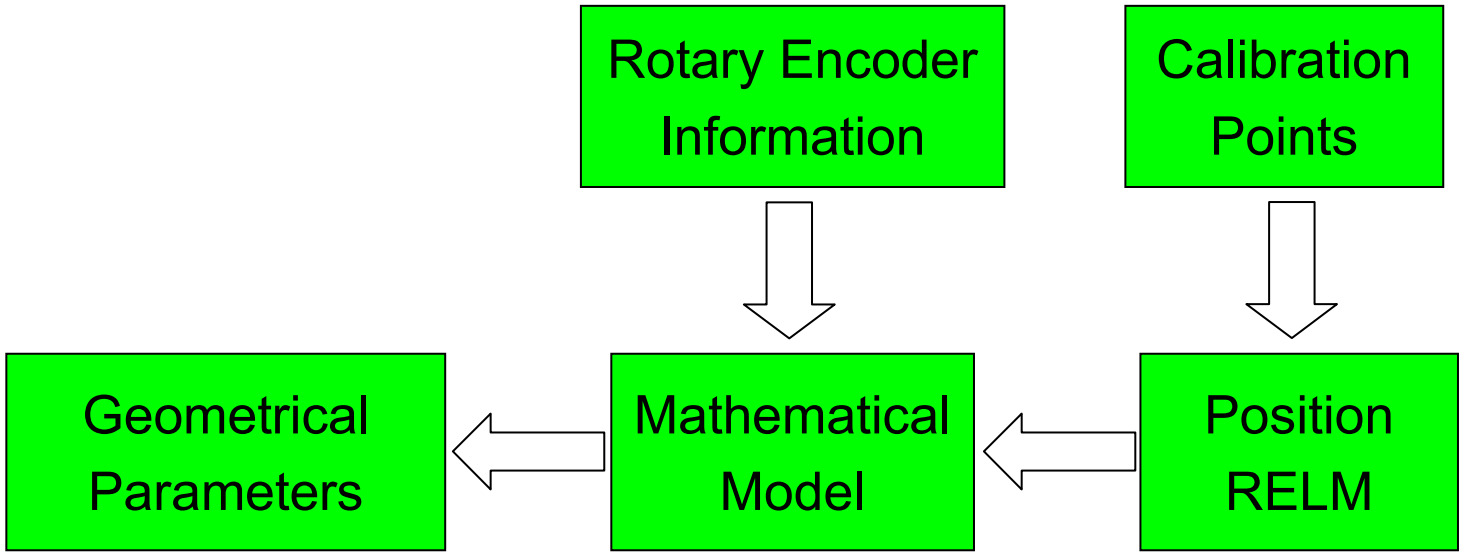
Positional Measurement



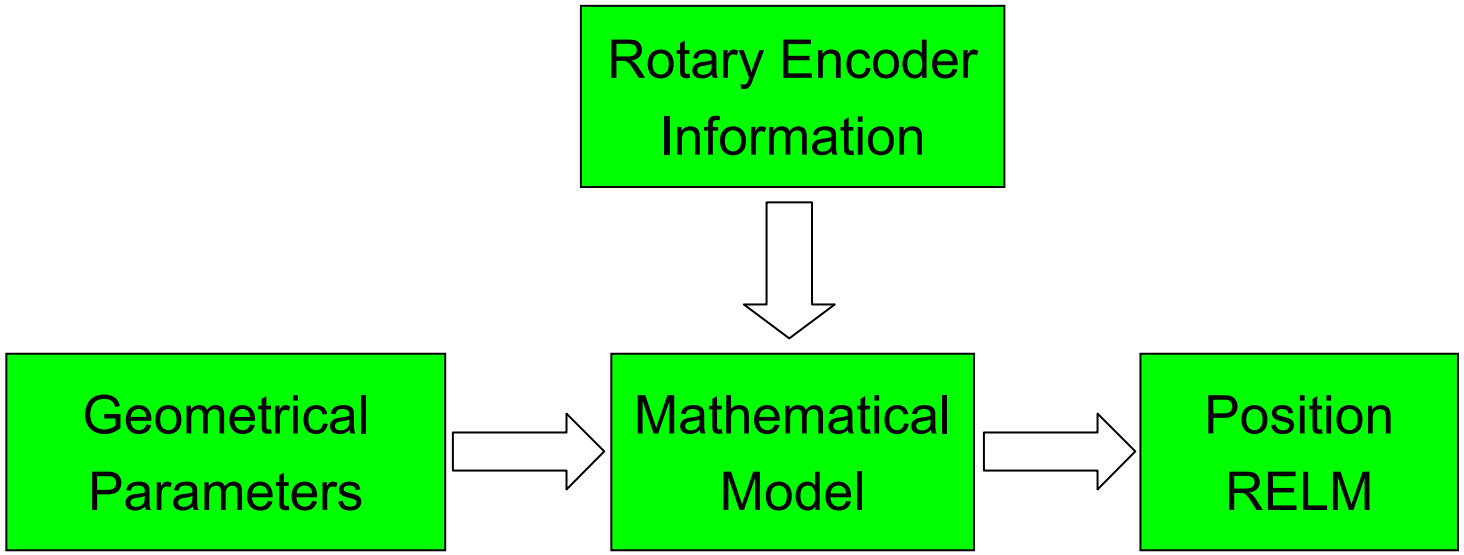
Positional Measurement



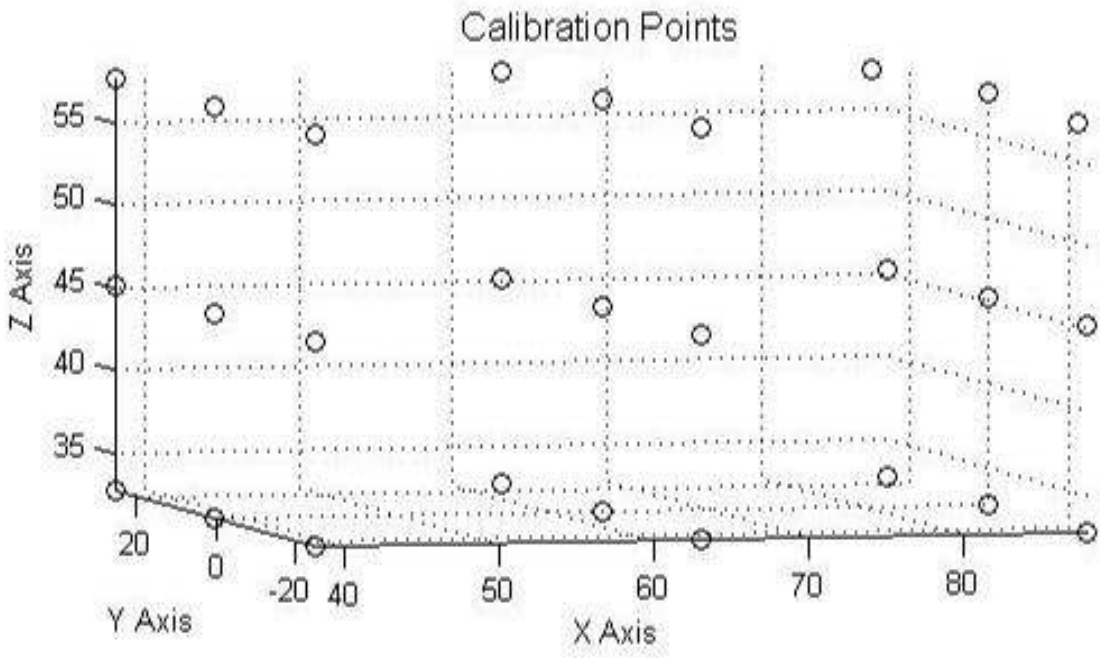
Positional Measurement



Positional Measurement



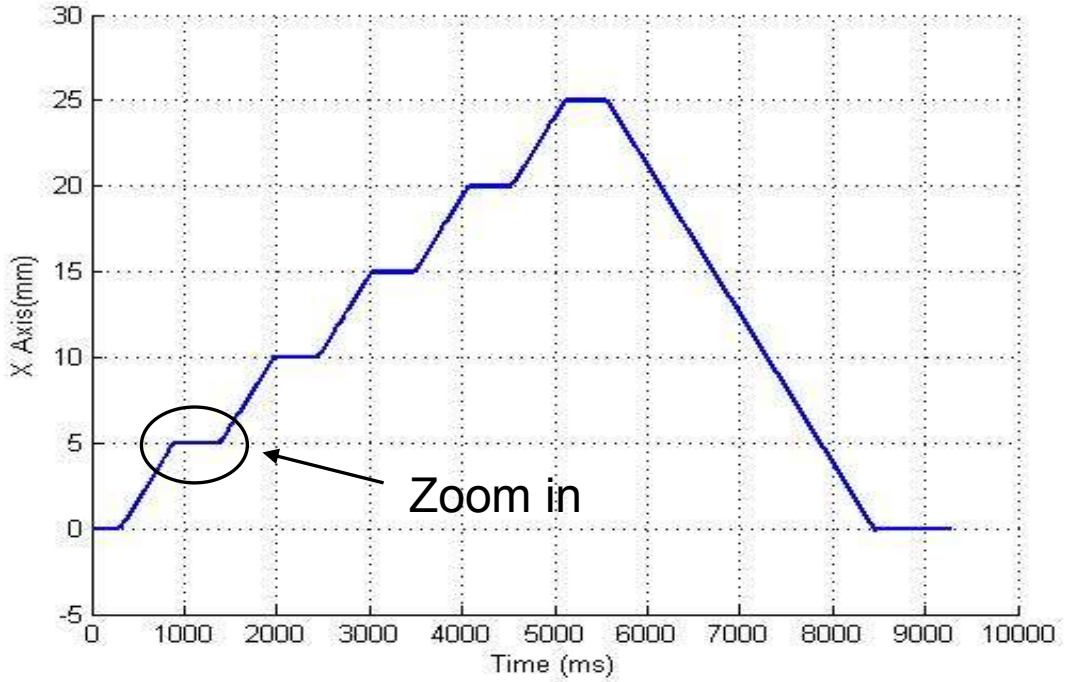
Calibration Points



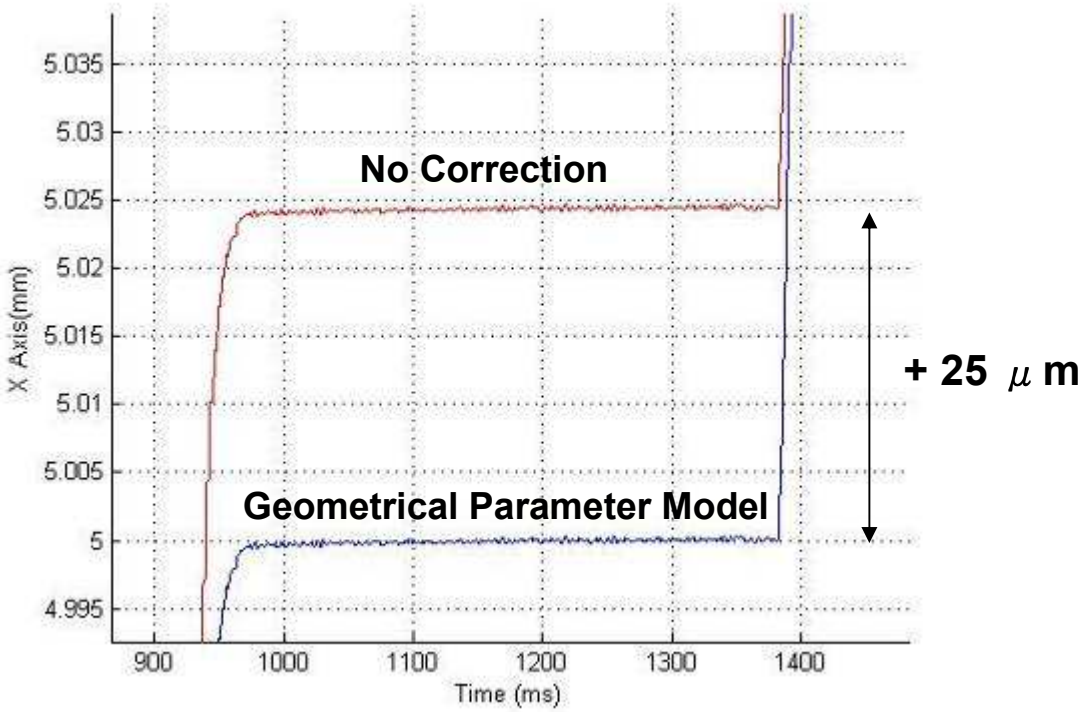
Volume Calibration Cube = 25x25x50mm

Results
Geometrical Parameters

Results Geometrical

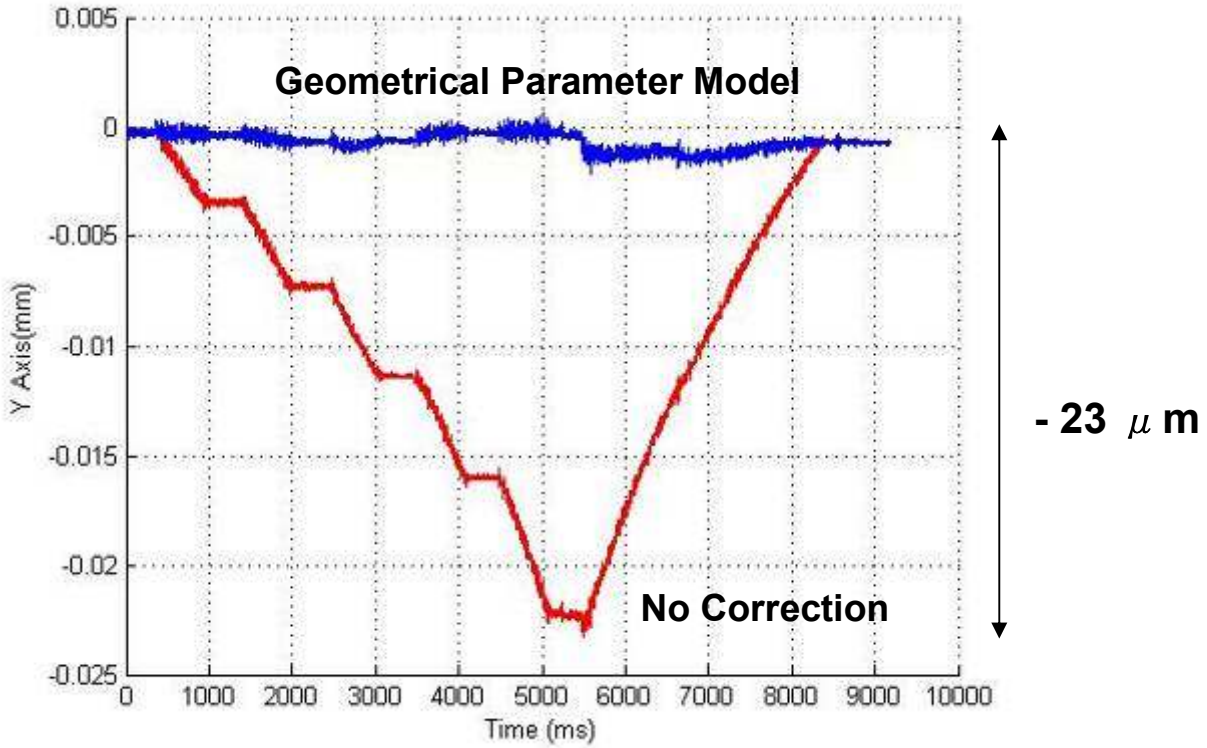


Displacement in X-direction



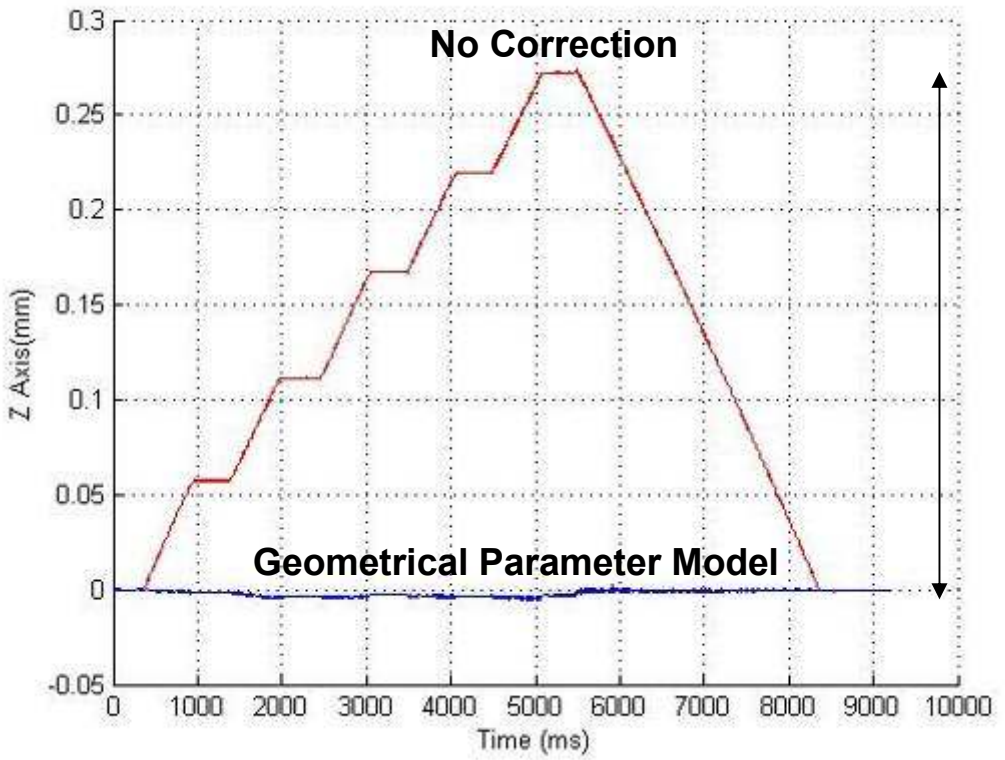
Significant improvement using Parameters

Displacement in Y-direction



Significant improvement using Parameters

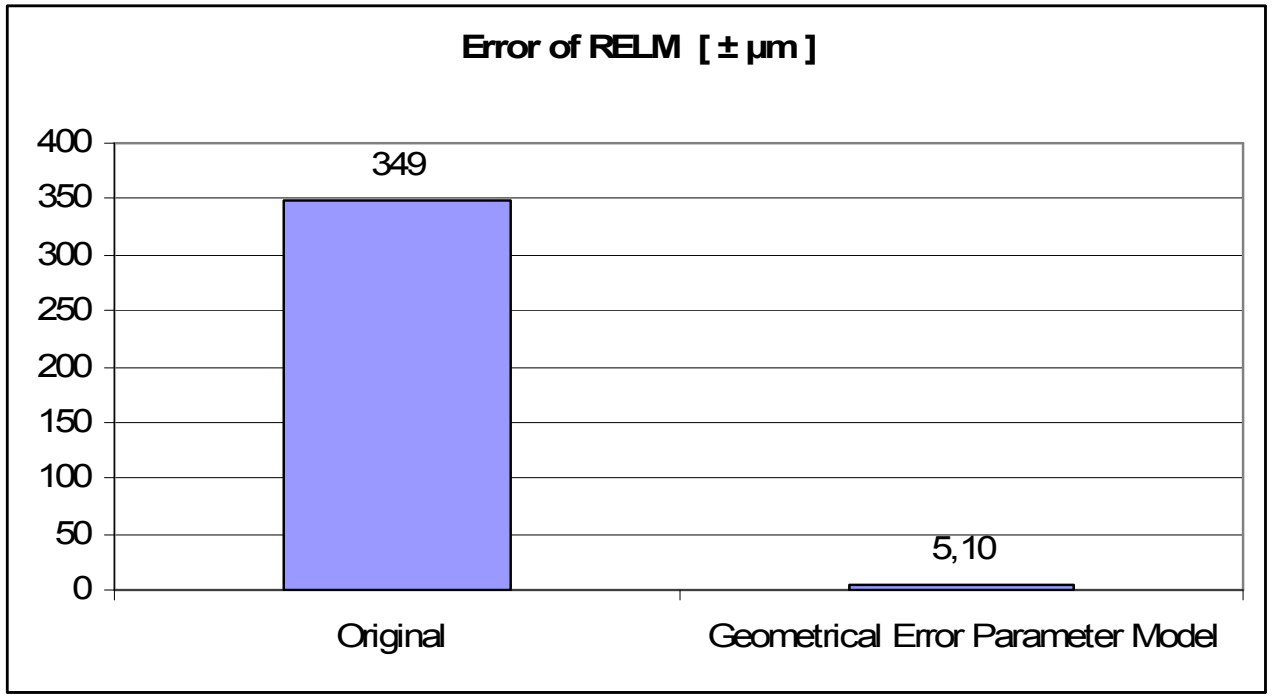
Displacement in Z-direction



+ 270 μ m

Significant improvement using Parameters

First Result



Result: 98.6 % Accuracy Increase

Circular Measurements

Stepping Motion

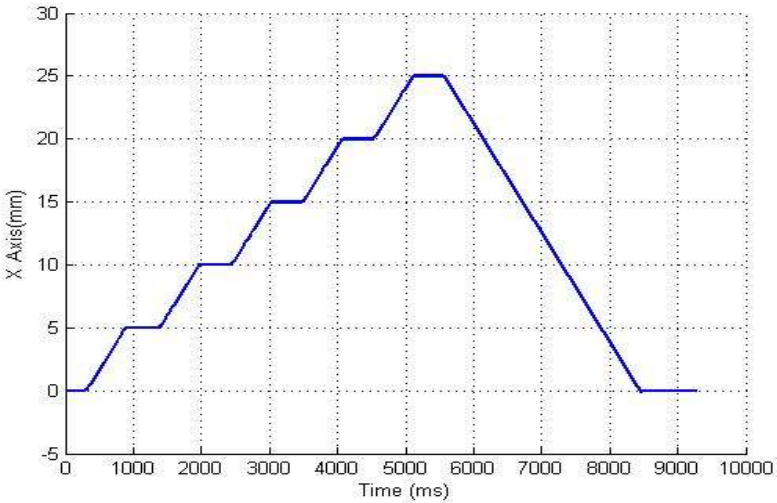
- 6 Stopping Points

  x = 0, 5, 10, 15, 20 and 25 mm

  y = 0

  z = 0

X-axis

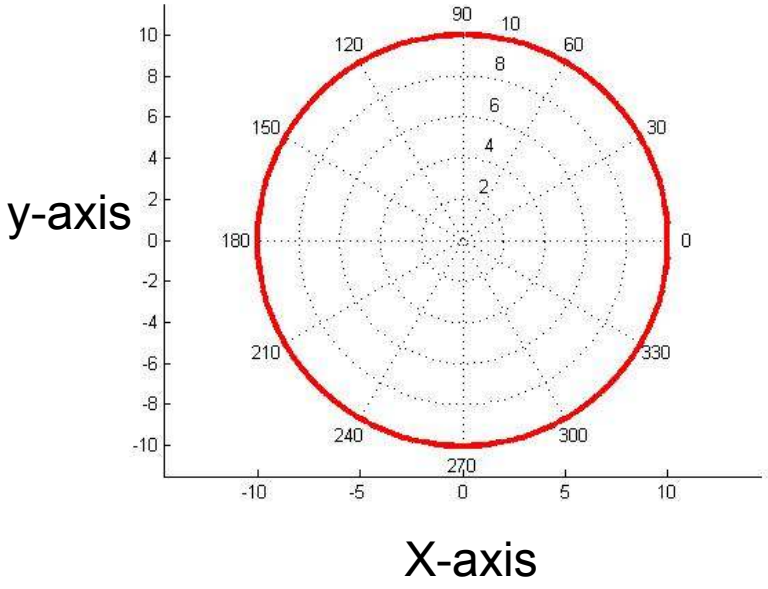


time

Ideal test for Rough Accuracy Comparison

Circular Test

- Continuous Tool Path
  - R = 10 mm
  - F = 100 mm/min
- No Stopping Points



Ideal Test for Precise Accuracy Comparison

Grid Encoder

Grid Encoder

High Precision Two Dimensional Measuring Device

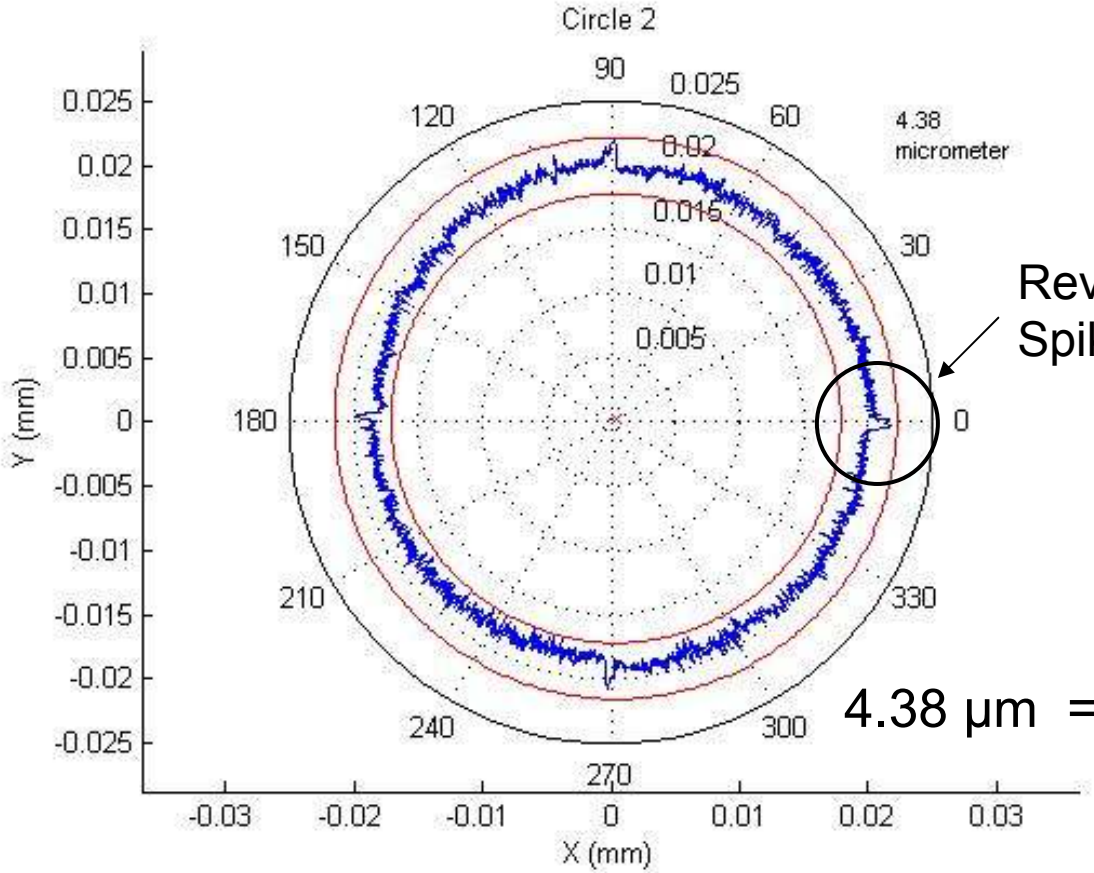
Grid Encoder

- Available on market
- Used for 2D tool path measurement
- Frictionless Measurement
- High Precision accuracy

Used as Reference Measurement

Circular Path Measured With Grid Encoder

Reference Circular Measurement



Reversal Spike

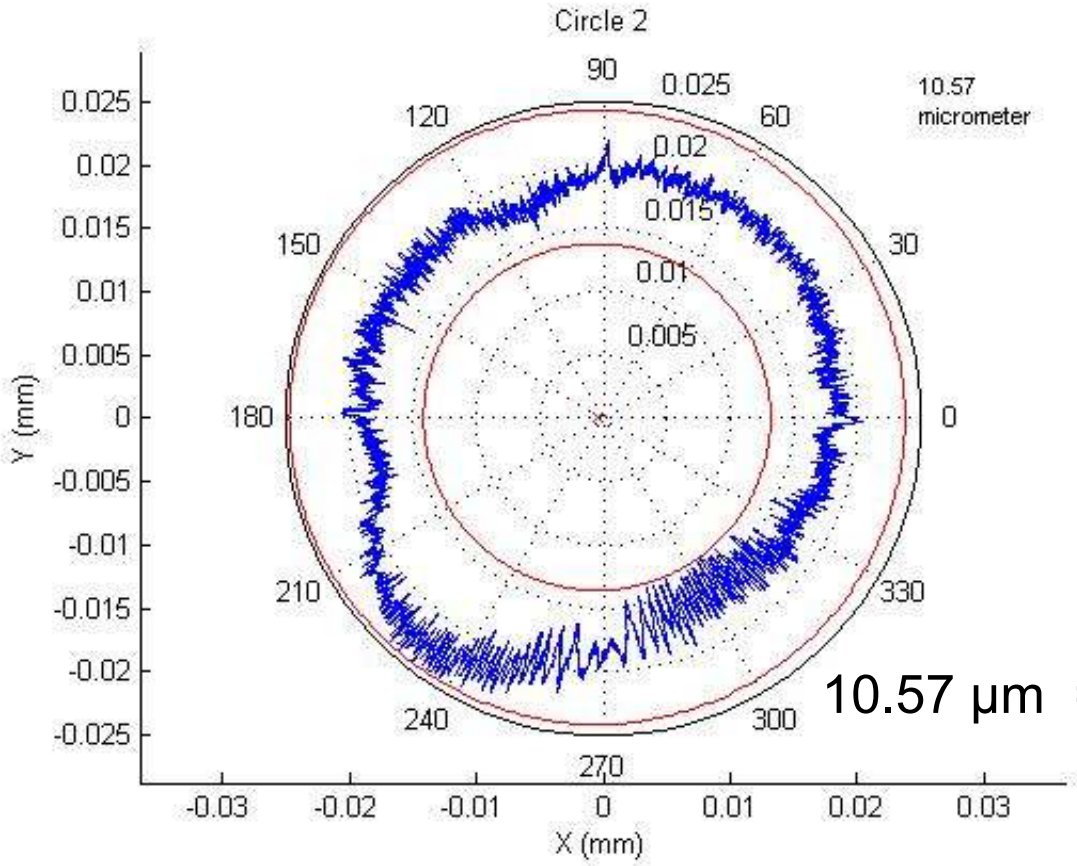
4.38 µm = ± 2.19 µm

Grid Encoder

R = 10 mm F = 100mm/min

Circular Path Measured With RELM (Geometrical Parameters)

Geometrical Parameter



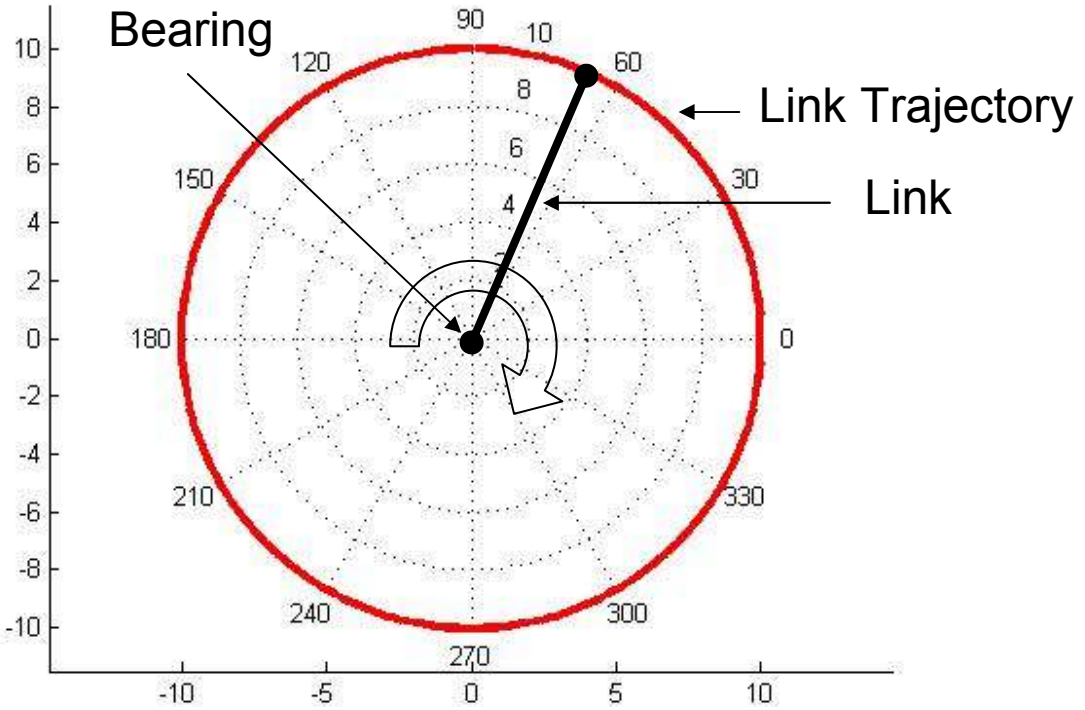
10.57 µm = ± 5.29 µm

RELM

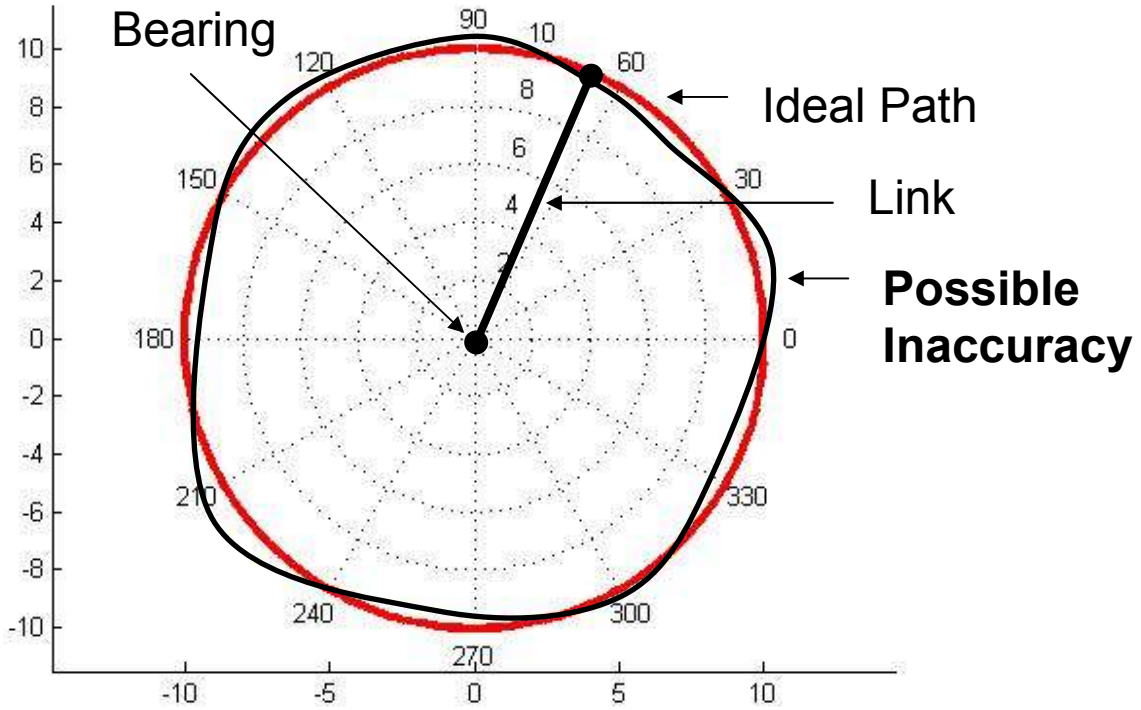
R = 10 mm F = 100mm/min

Bearing Roundness Inaccuracy

Ideal Bearing

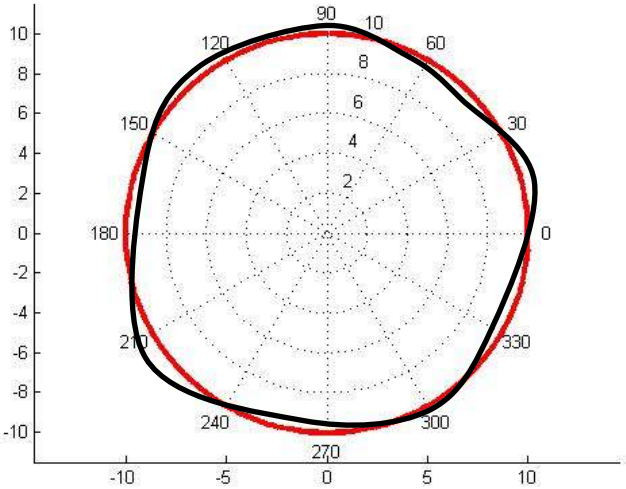


Possible Roundness Inaccuracy



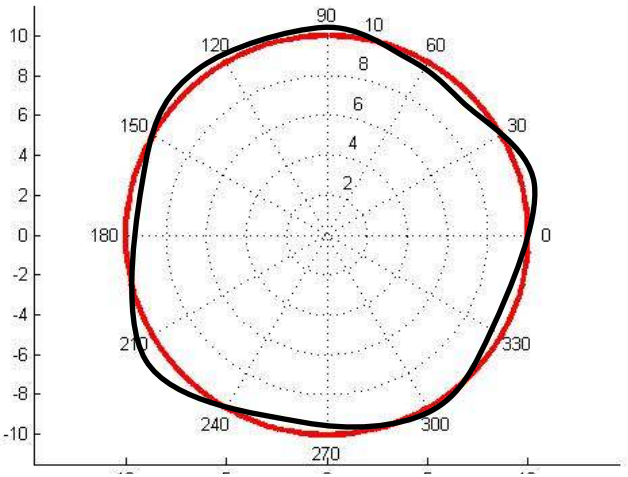
Bearing Roundness Inaccuracy

Ideally Modelled as a Fourier sum of Roundness Inaccuracies



$$L_\theta = L_1 + \sum_{n=1}^{\infty} C_{2n-1} * \sin(n * \theta) + C_{2n} * \cos(n * \theta)$$

Modeling Bearings



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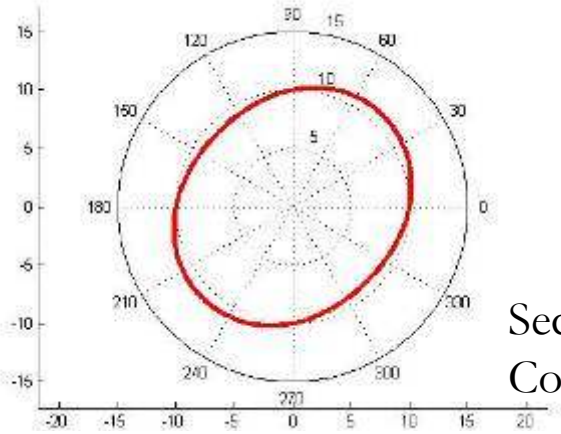
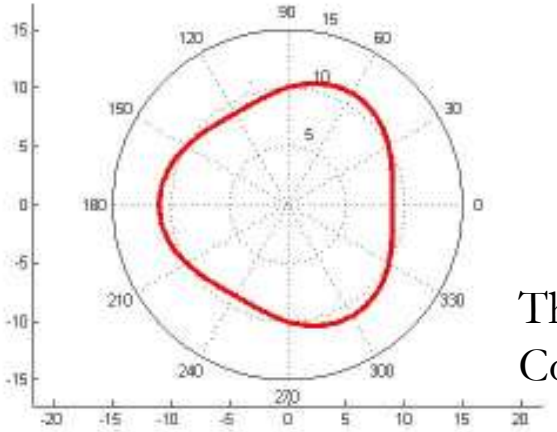


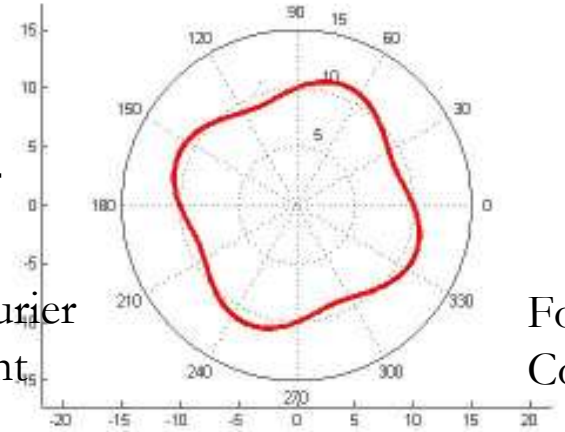
+

Second Fourier Coefficient



+

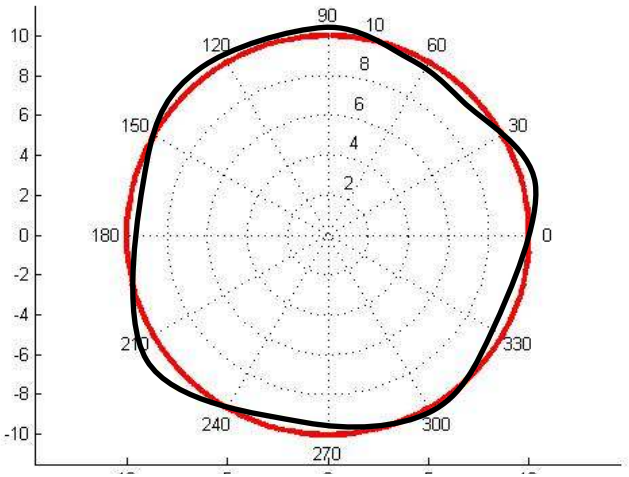
Third Fourier Coefficient



+ etc.

Fourth Fourier Coefficient

Modeling Bearings



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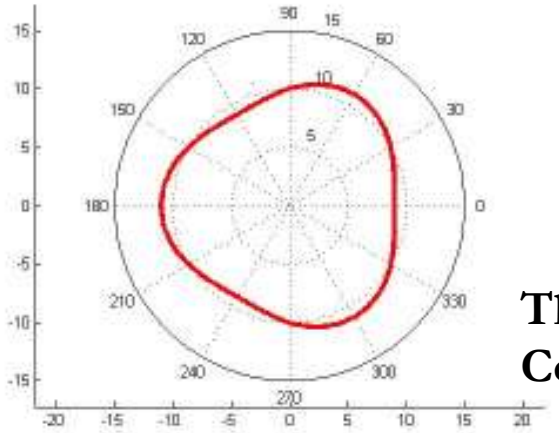
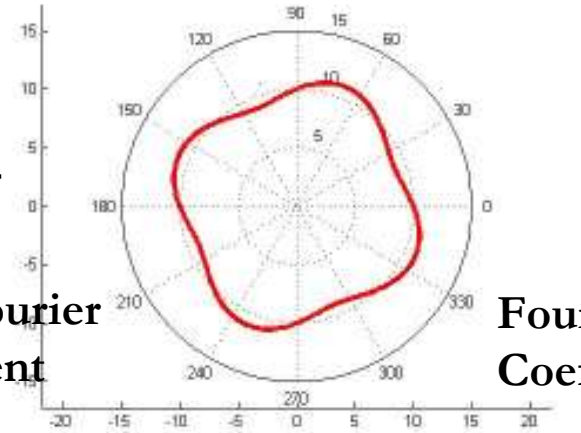


Third Fourier Coefficient

+

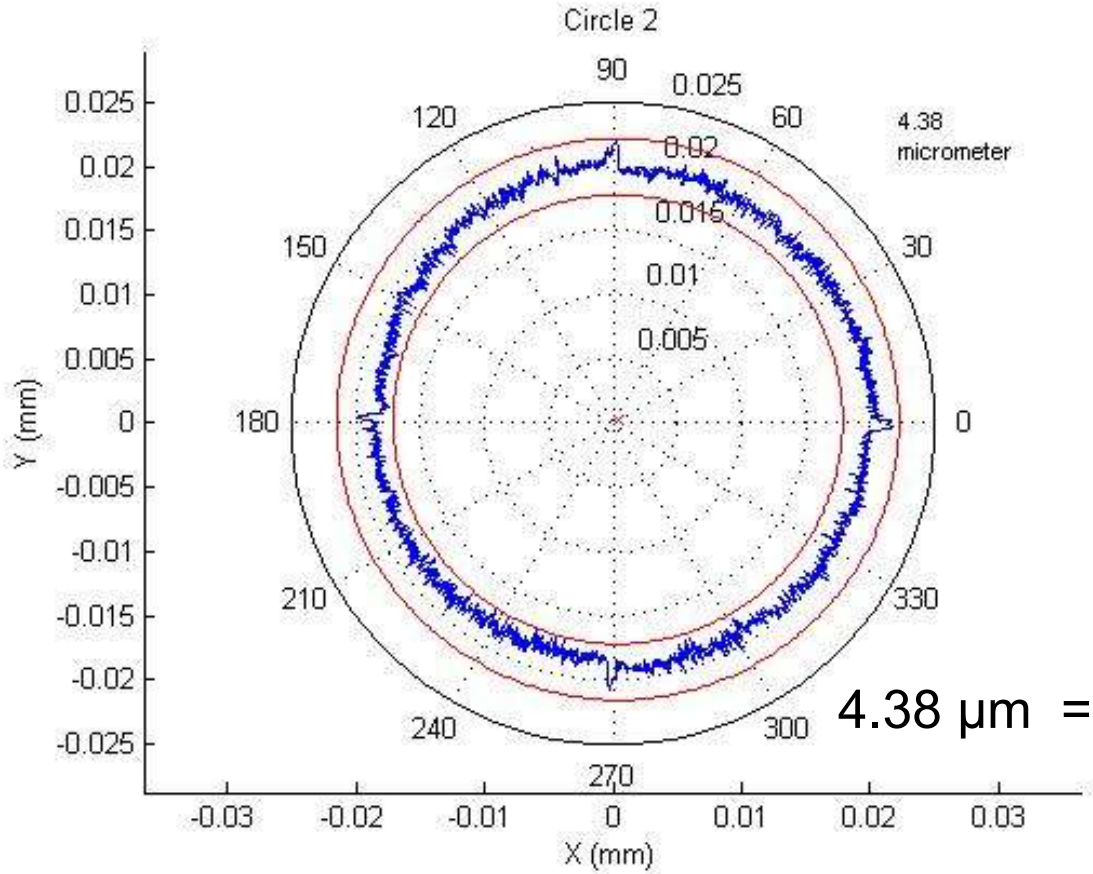


Fourth Fourier Coefficient

Circular Path Measured

(Geometrical & Bearing Parameters)

Reference Circular Measurement

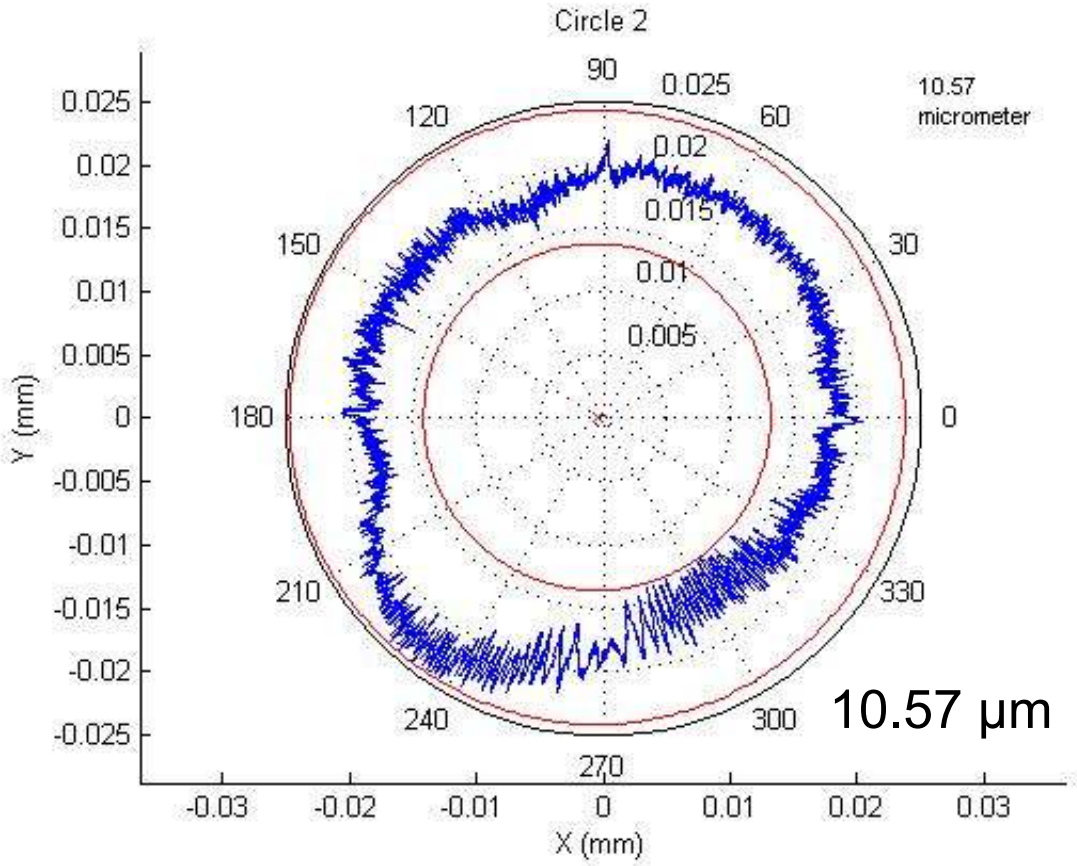


4.38 μm = ± 2.19 μm

Grid Encoder

R = 10 mm F = 100mm/min

Geometrical Parameter

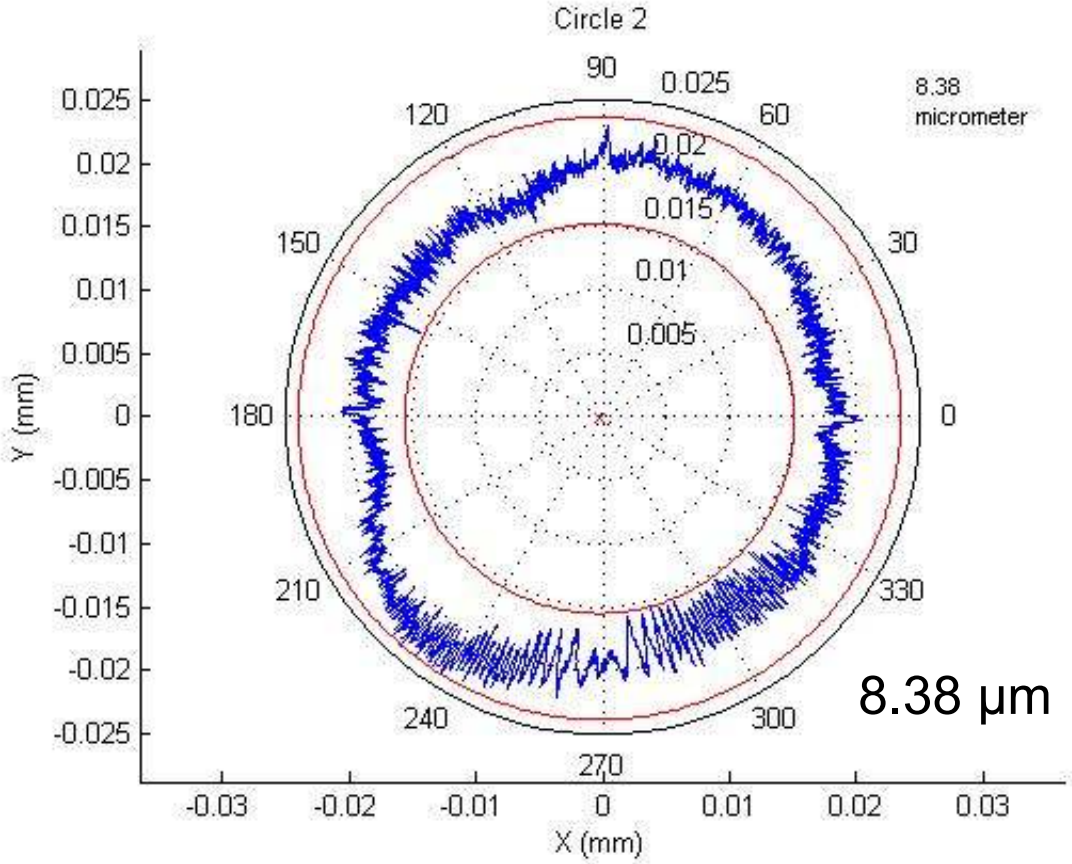


10.57 µm = ± 5.29 µm

RELM

R = 10 mm F = 100mm/min

Geometrical & Bearing Parameters



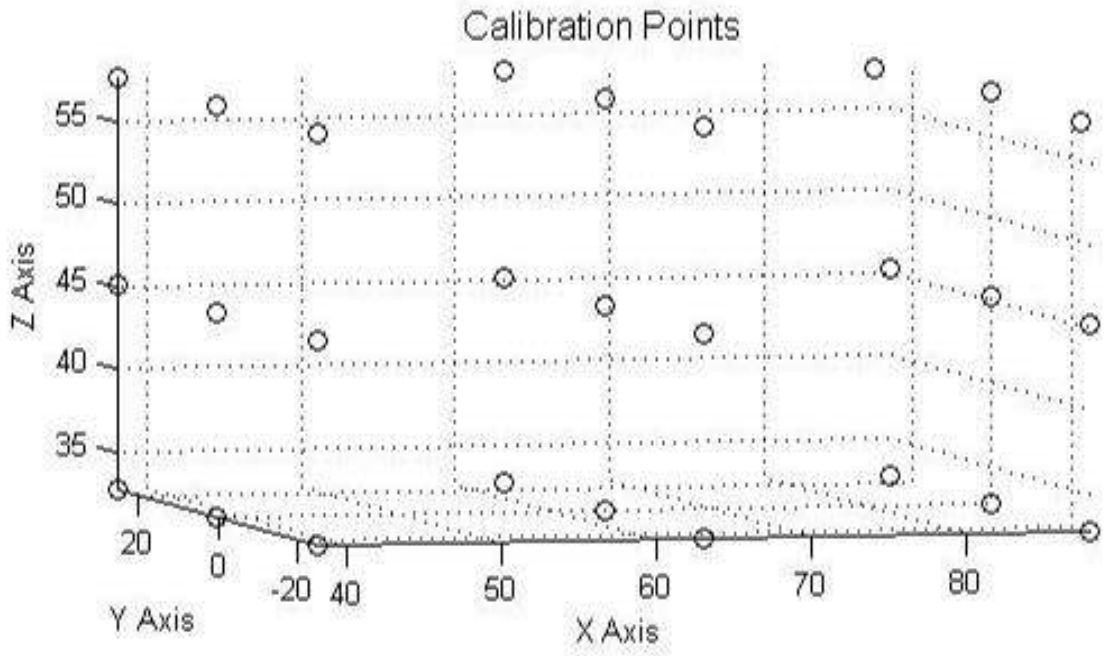
8.38 µm = ± 4.19 µm

RELM

R = 10 mm F = 100mm/min

Mapping of the Parameters

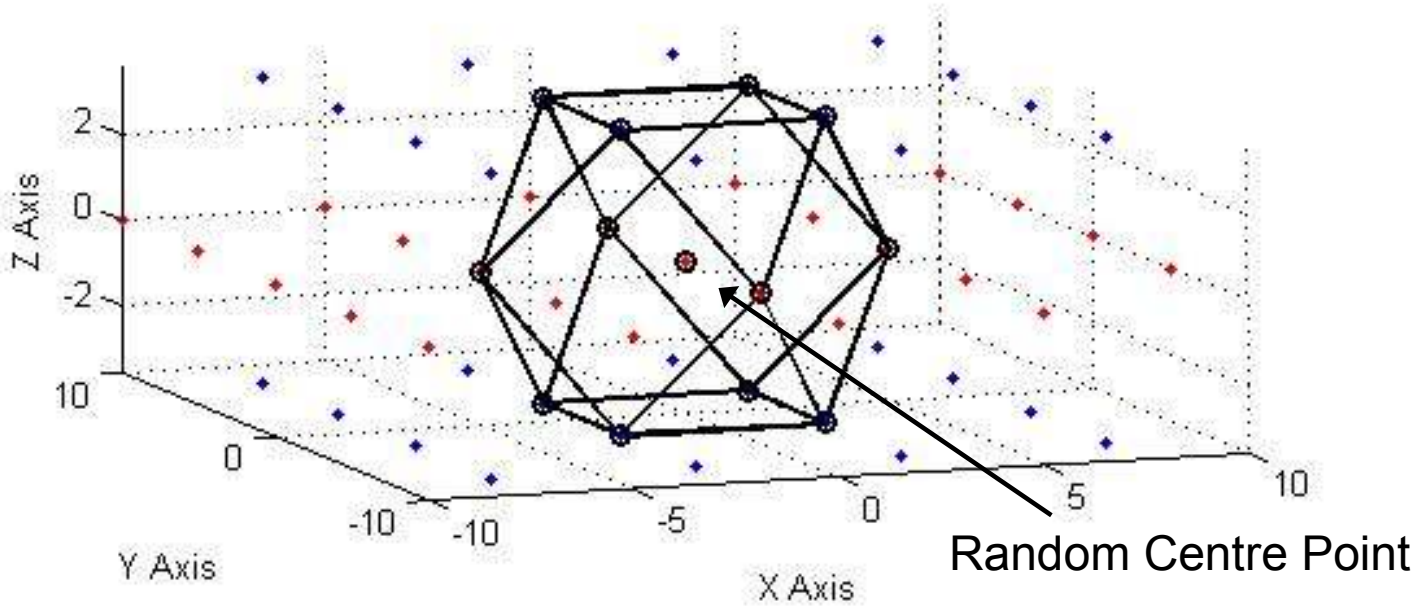
Calibration Points



Volume Calibration Cube = 25x25x50mm = 31250 mm^3

Mapping Calibration Cube

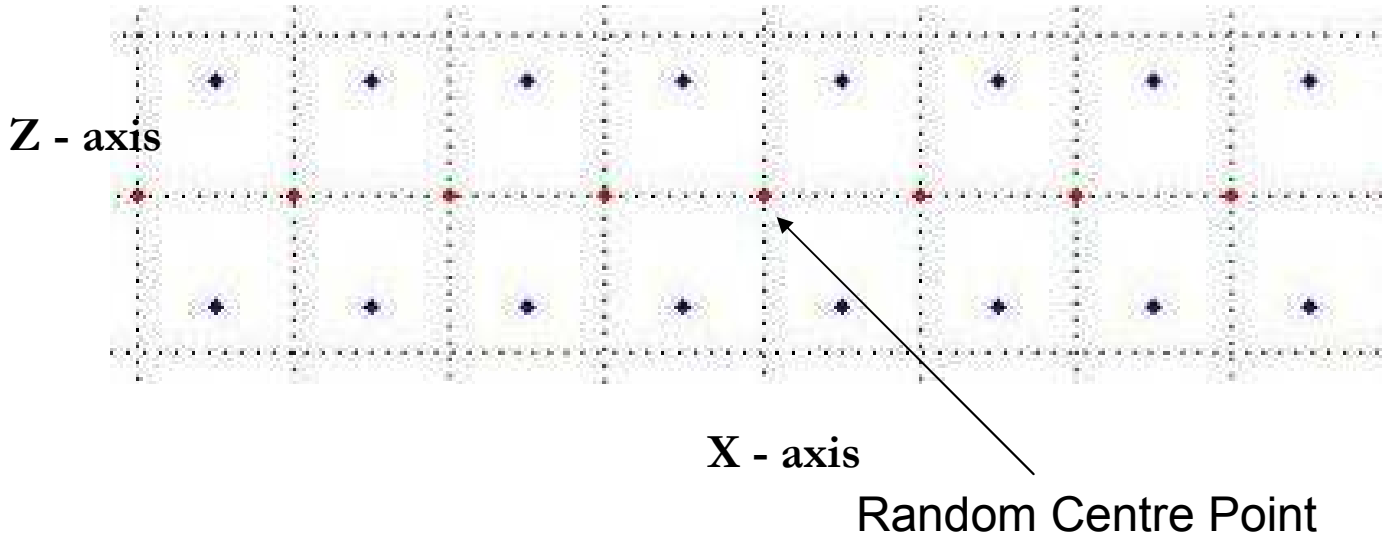
3D Structure Around a Random Centre Calibration Point



Volume Calibration Cube = 530 mm^3

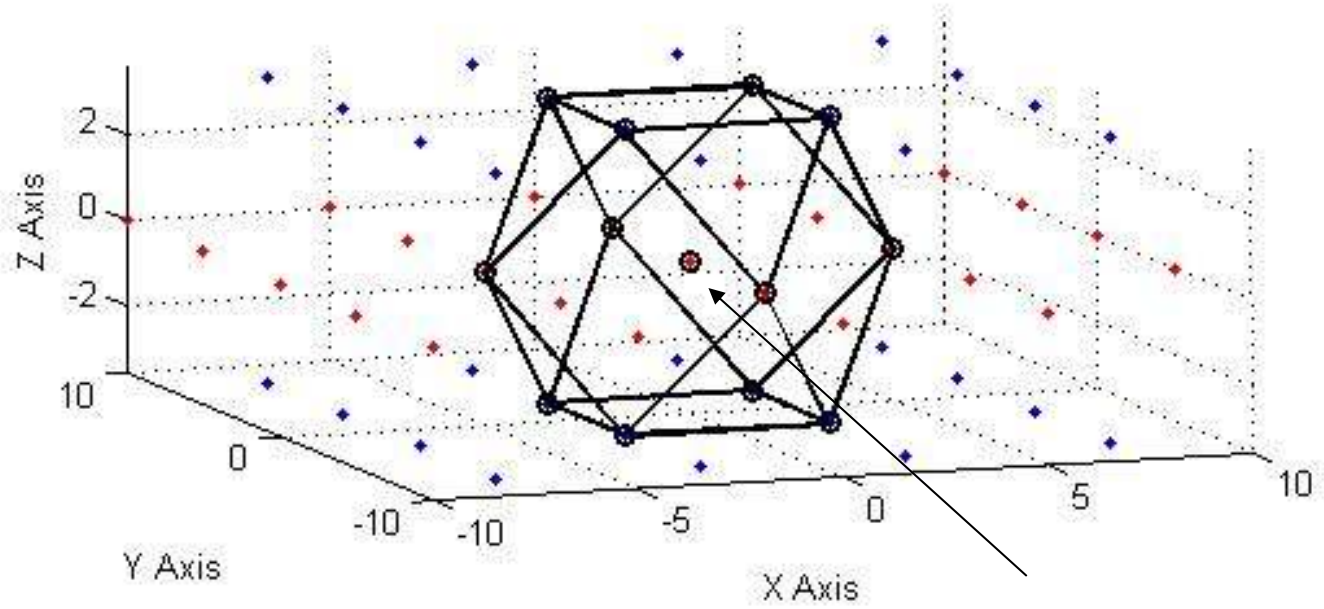
Mapping Calibration Points

Each Centre Point has 12 Calibration Points Surrounding it



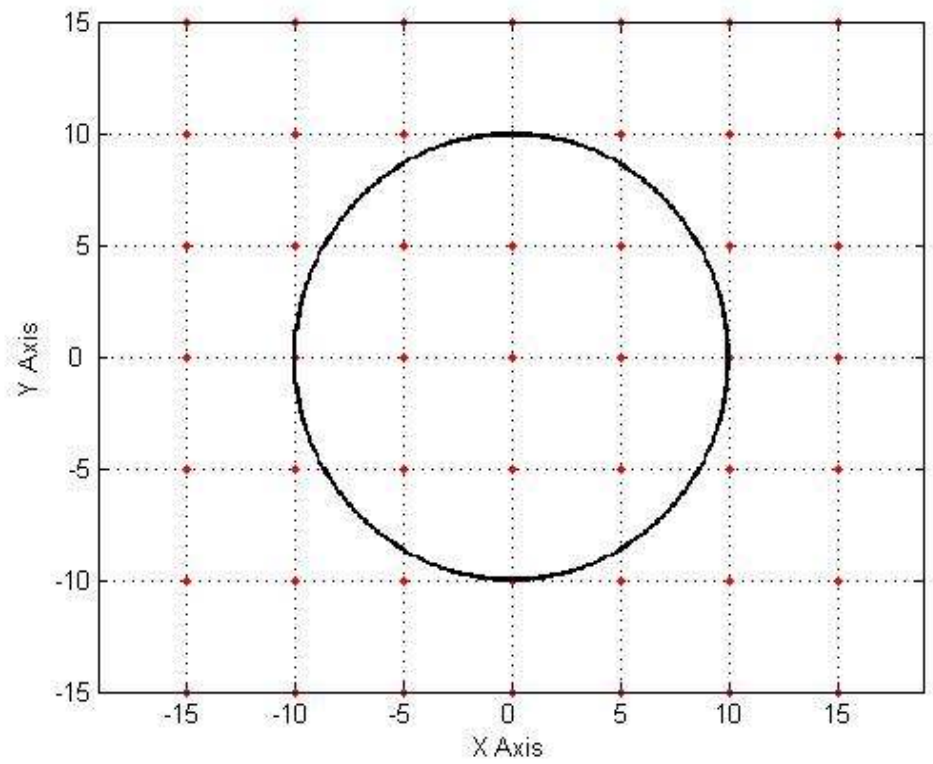
Mapping Calibration Cube

The Parameters are Specific for this Volume

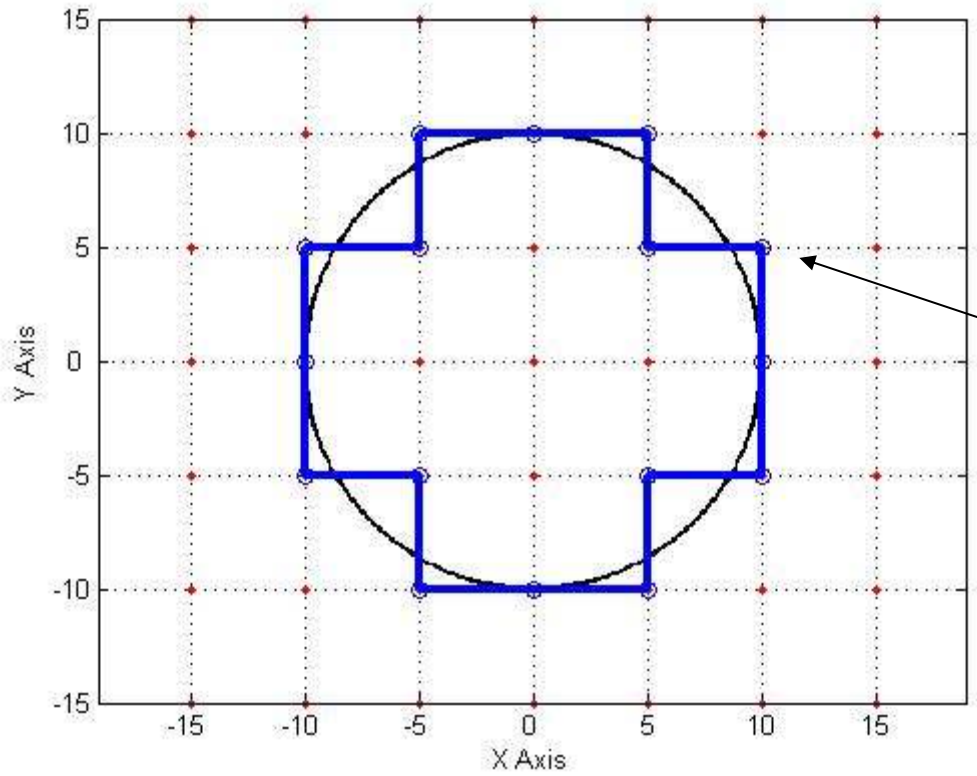


Example of Mapping Principle

Circular Path



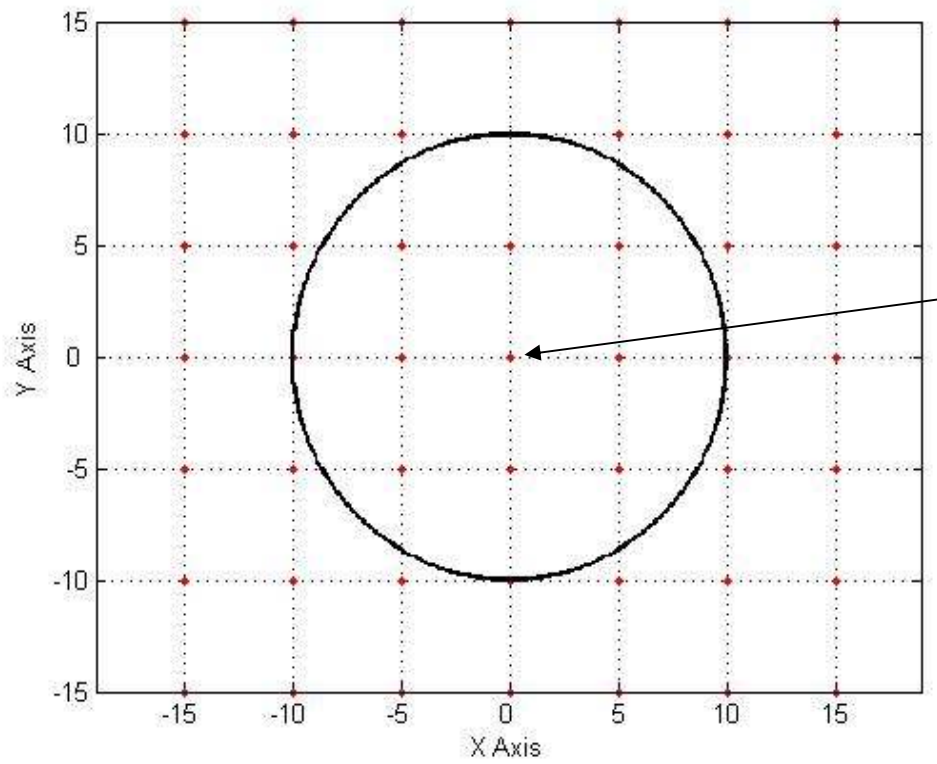
Mapping



Centre Calibration Points used for this specific tool path

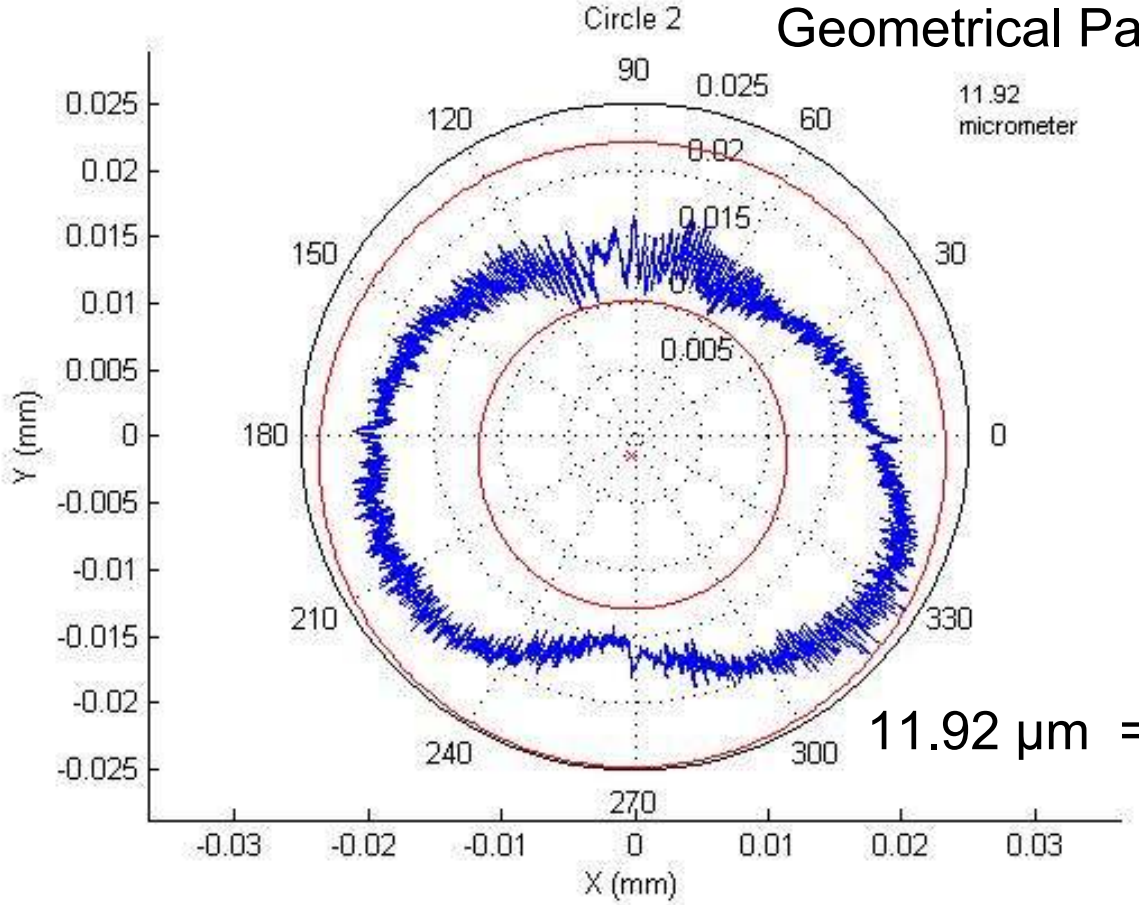
Proving the Mapping Principle

Without Mapping



Only Centre Calibration Point used for next result

Without Mapping



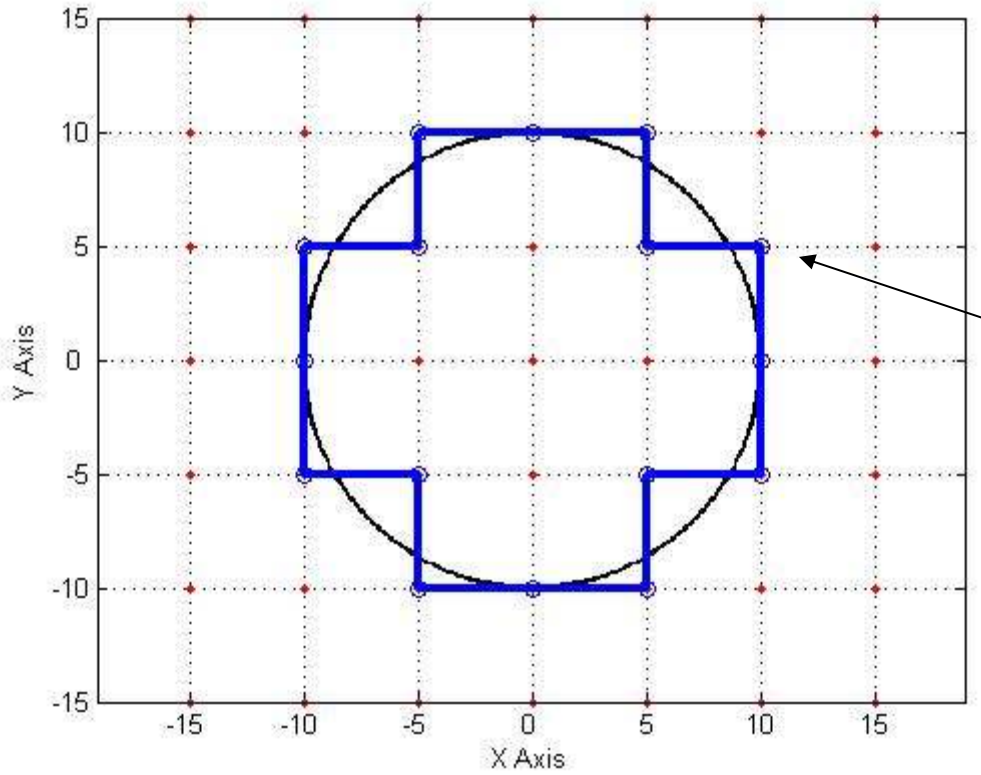
Geometrical Parameters

11.92 µm = ± 5.96 µm

RELM

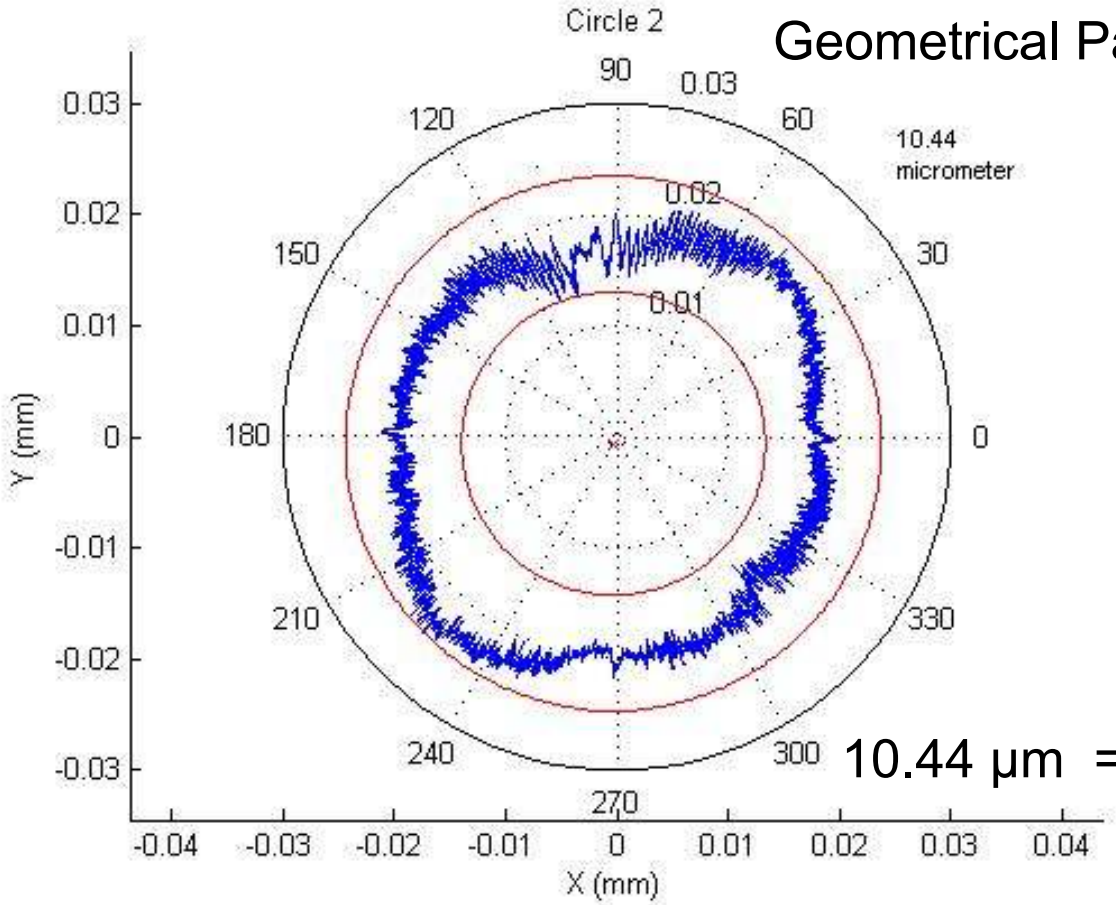
R = 10 mm F = 100mm/min

Mapping



Centre Calibration Points used for this specific tool path

Mapping



Geometrical Parameters

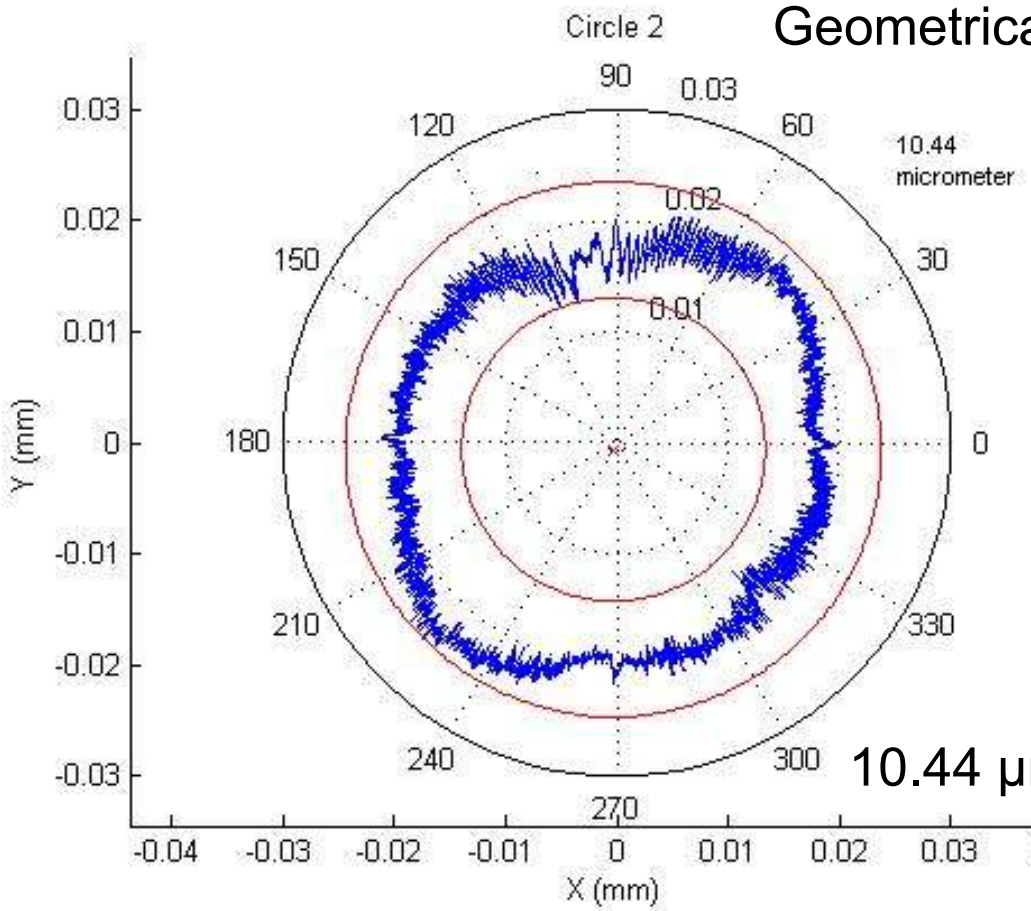
10.44 µm = ± 5.22 µm

RELM

R = 10 mm F = 100mm/min

Mapping Geometrical & Bearing Parameters

Mapping



Geometrical Parameters

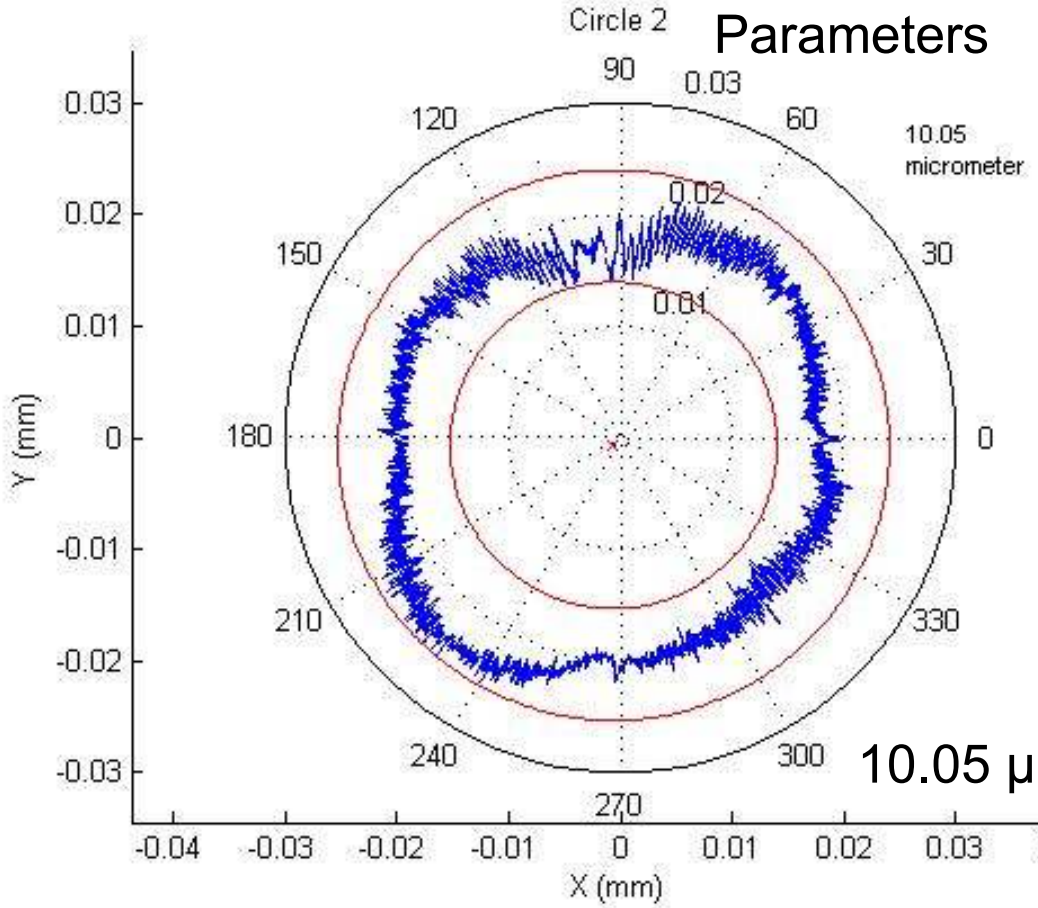
10.44 µm = ± 5.22 µm

RELM

R = 10 mm F = 100mm/min

Mapping

Geometrical & Bearing Parameters



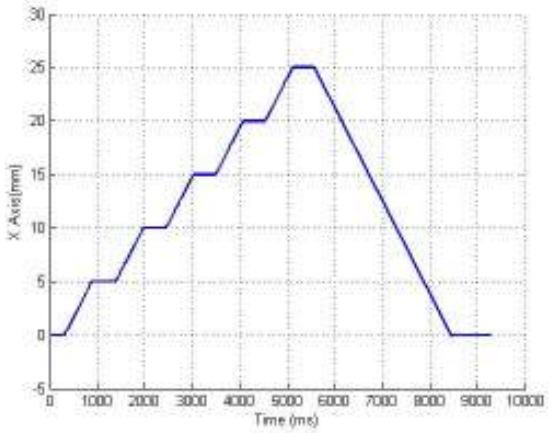
10.05 µm = ± 5.03 µm

RELM

R = 10 mm F = 100mm/min

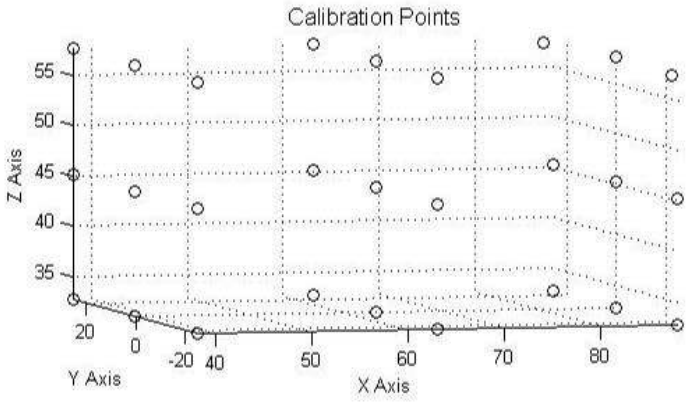
Summary of Results

Proving use of Parameters



Without Parameter Correction

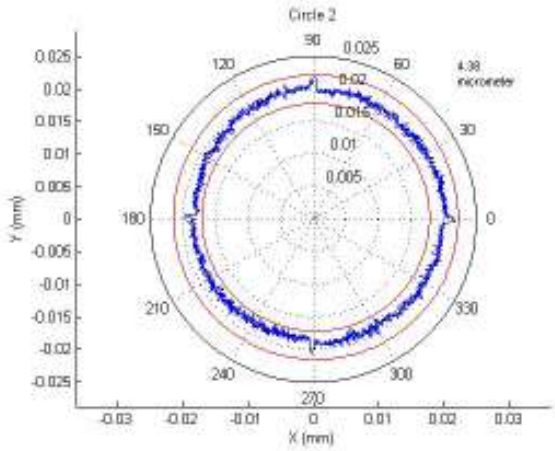
± 349 µm (3D)

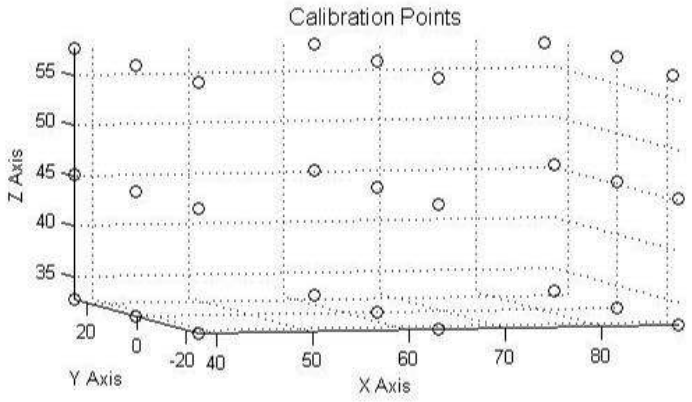


Geometrical Parameter

± 5.10 µm (3D)

Circular Measurements



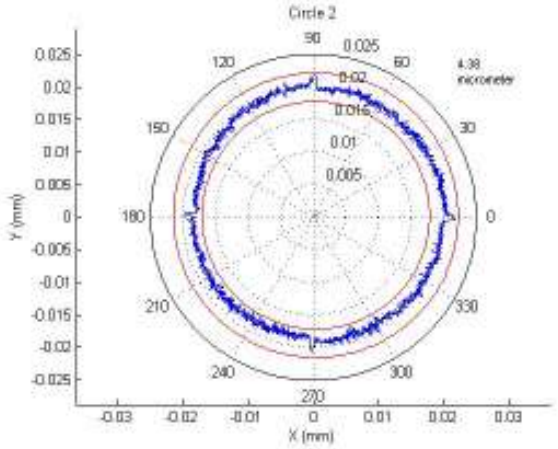


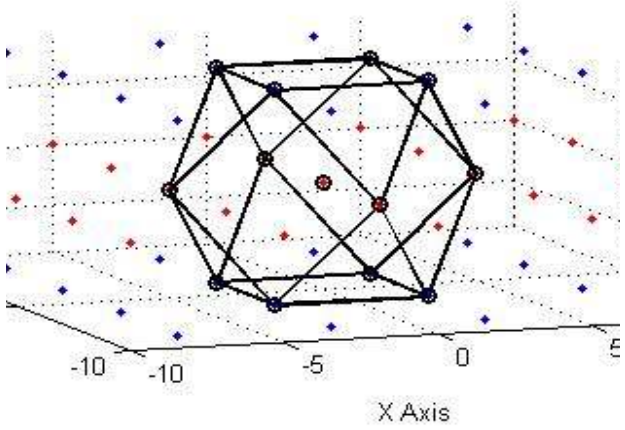
Grid Encoder
± 2.19 µm (2D)

Geometrical Parameter
± 5.29 µm (2D)

Geometrical & Bearing
± 4.19 µm (2D)

Mapping





Grid Encoder
± 2.19 µm (2D)

No Mapping
± 5.96 µm (2D)

Mapping Geometrical Parameter
± 5.22 µm (2D)

Geometrical & Bearing Parameter
± 5.02 µm (2D)

Conclusion & Recommendation

Conclusion

- 24 Parameter Model has been developed
- Model includes Geometrical & Bearing parameters
- Mapping Principle enables measurements in the whole measuring range
- Model shows a dramatic increase in accuracy over the whole measuring range

$\pm$ 349 µm (3D) $\rightarrow$ $\pm$ 5.02 (2D) $\approx \pm$ 6.15 (3D)

Recommendation

- **Generate More Accurate Calibration Points**
- **Research Optimum Calibration Volume**

Questions and Answers