Generalised Test for the Qualification of Distributed Large Volume Metrology Systems for Dynamic Measurement

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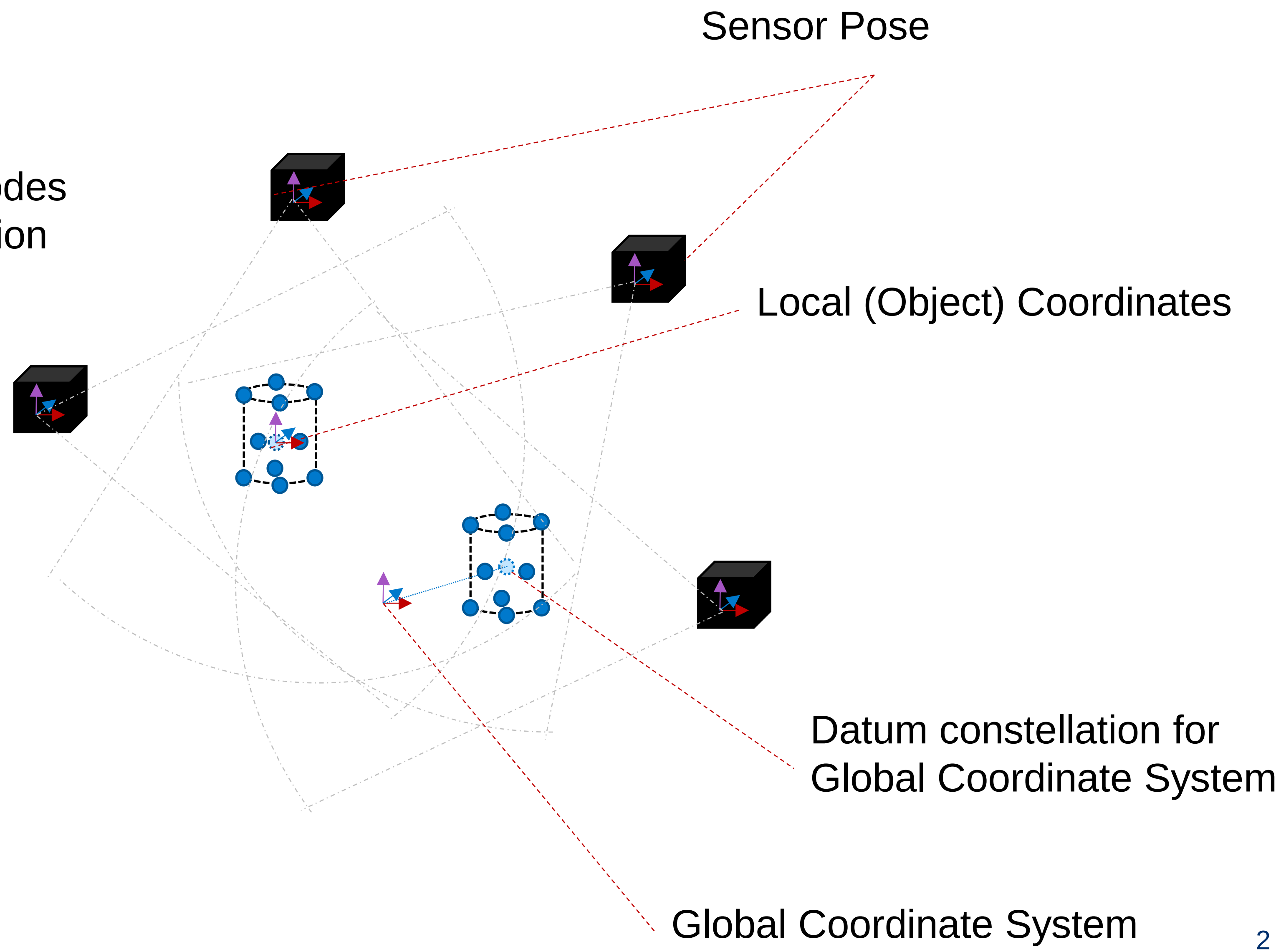
Distributed Large Volume Metrology System

- A distributed LVM system has multiple nodes that work in concert to measure the position and/or orientation of objects

    - are often capable of measuring multiple independent objects simultaneously
    - overcome line of sight limitations
    - can be based on numerous technologies and processing methodologies



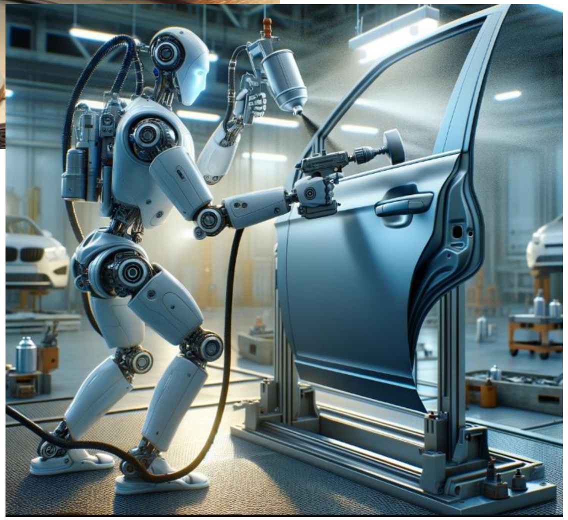
Introduction: The Motivation

Traditional robotic manipulators excel at repeatable tasks in controlled environments but historically do not accommodate high levels of in-task variability.

Improve operational flexibility and autonomy can be achieved via decoupled guidance systems.

A decoupled guidance system can provide a common coordinate system for the workpiece and manipulator, this;

- create control zones allowing compliant and/or generalist robots to perform high precision tasks.
- promotes interoperability between process actuators.
- simplifies new task deployment.
- allows better handling of in-task variability.



Introduction: The Challenge

Many different technologies are, or have the potential to be, used for this application.

Evolving requirements as new technologies promise to automate a broader range of tasks.

Intersection of multiple fields/disciplines

- dimensional metrology, motion capture, positioning systems, and robotics and control.

Complex standards landscape.

Current/Potential Technologies for Robot Guidance
Photogrammetry
Laser Trackers
Structured Light Scanning
Time-of-Flight (ToF) Cameras
Ultra-Wideband (UWB)
Bluetooth Low Energy (BLE)
RFID
Laser Radar (LIDAR)
Inertial Measurement Units (IMU):
Micro-Electro-Mechanical Systems (MEMS)
Acoustic Systems
Magnetic Systems
Kinematic Methods
Hybrid multi-sensor or multi-nodal systems

Contents

Aim

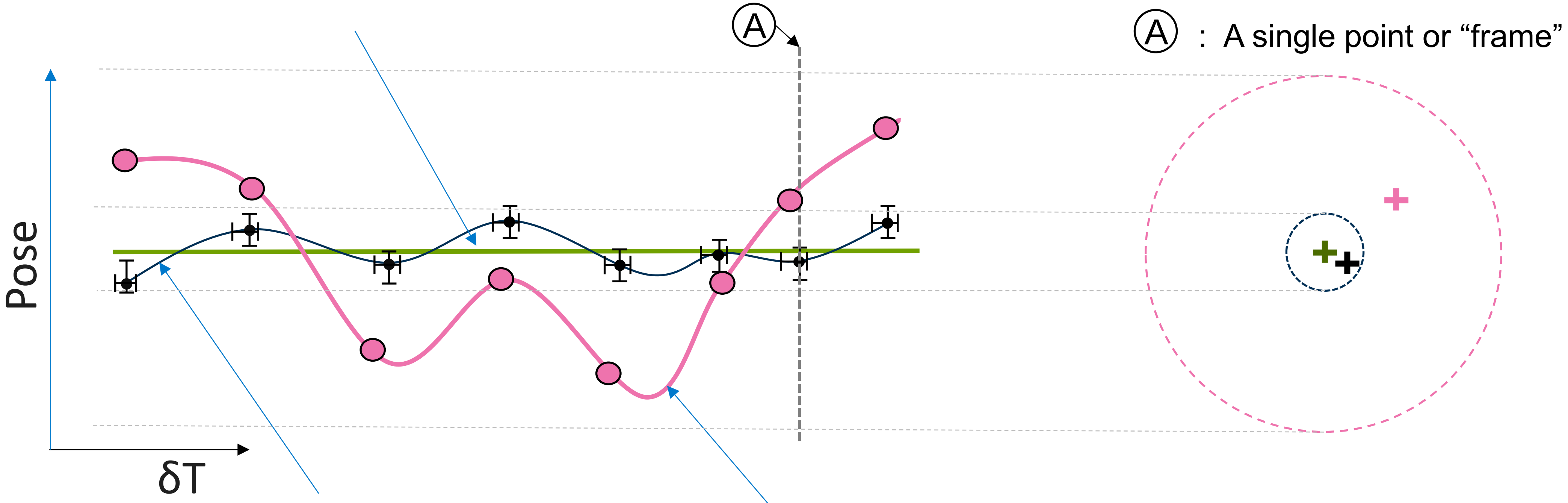
To develop a generalised set of standard tests to quantify the performance of a distributed six degrees of freedom, single or multi- target, large volume metrology (LVM) system for *dynamic* (moving) applications

Contents

Method : Principle

Nominal / Control / Requested Path: The path requested of the actuator

- Determined through calibration.
- May be quantified relatively opposed to absolute.



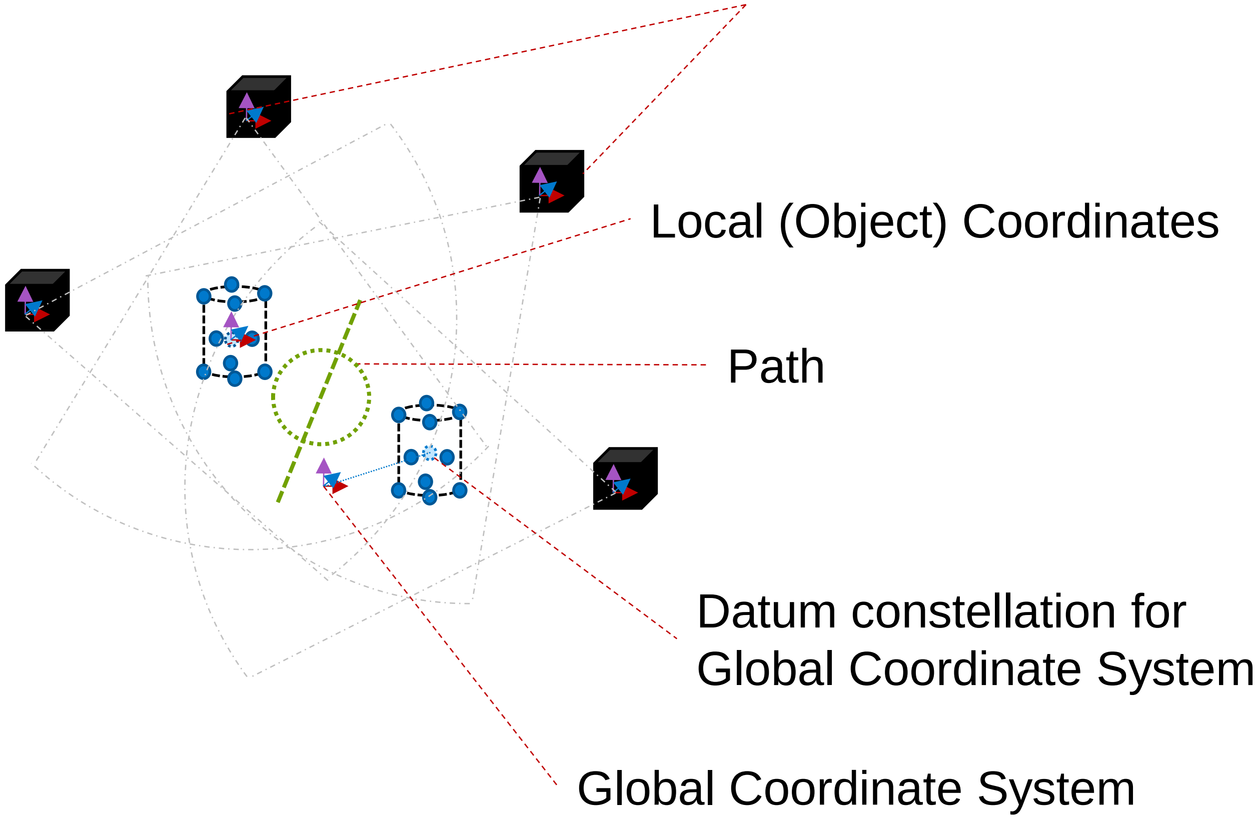
Actual Path: in real space

- Dynamic errors,
- Steady state errors,
- Temporal error,
- Kinematic error,
- Environmental error.

Measured Path: in measurement space

Method : Path Selection

A distributed measurement system may not have a convenient set of intrinsic coordinates. The mapping of real space, $\mathbb{R}^3$, into measurement space is complex. A linear path in $\mathbb{R}^3$ is not a linear path through measurement space.



Pros/Cons of Linear vs Circular Path	
Linear Path	Circular Path
Absolute distance can be measured (with calibration).	Absolute distance is fixed around a point.
Additional length is needed for acceleration and damping/decay of oscillation –> limits maximum speed.	Can set up continuous rotatory motion - high achievable speed.
Orientation in $\mathbb{R}^3$ is nominally fixed.	Orientation in $\mathbb{R}^3$ is constantly changing.
Large lengths can be impractical and are susceptible to mechanical and thermal effects.	Large radii are impractical and likely less than can be achieved using a linear path.
Calibration of orientation perpendicular to the path can be challenging.	Calibration of circular path should be easier than a linear path.
Gravity is constancy direction.	Gravity is continuously changing direction.

Reference Artifact Design

*Please, join us at our poster on artefact design for further discussion

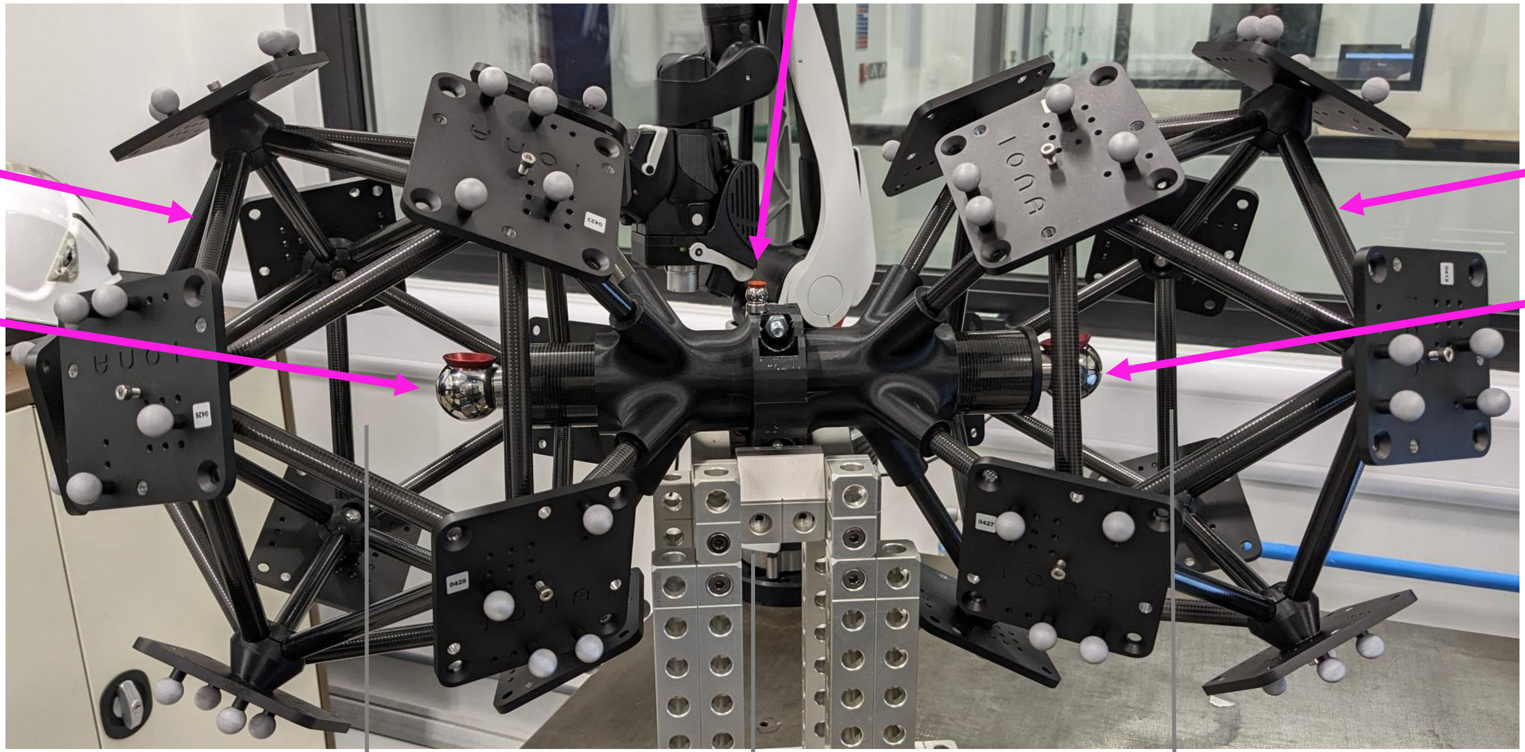
SMR. C

Constellation A

Constellation B

SMR. A

SMR. B



Reference Value:
length = $|\overrightarrow{AAxis}|$

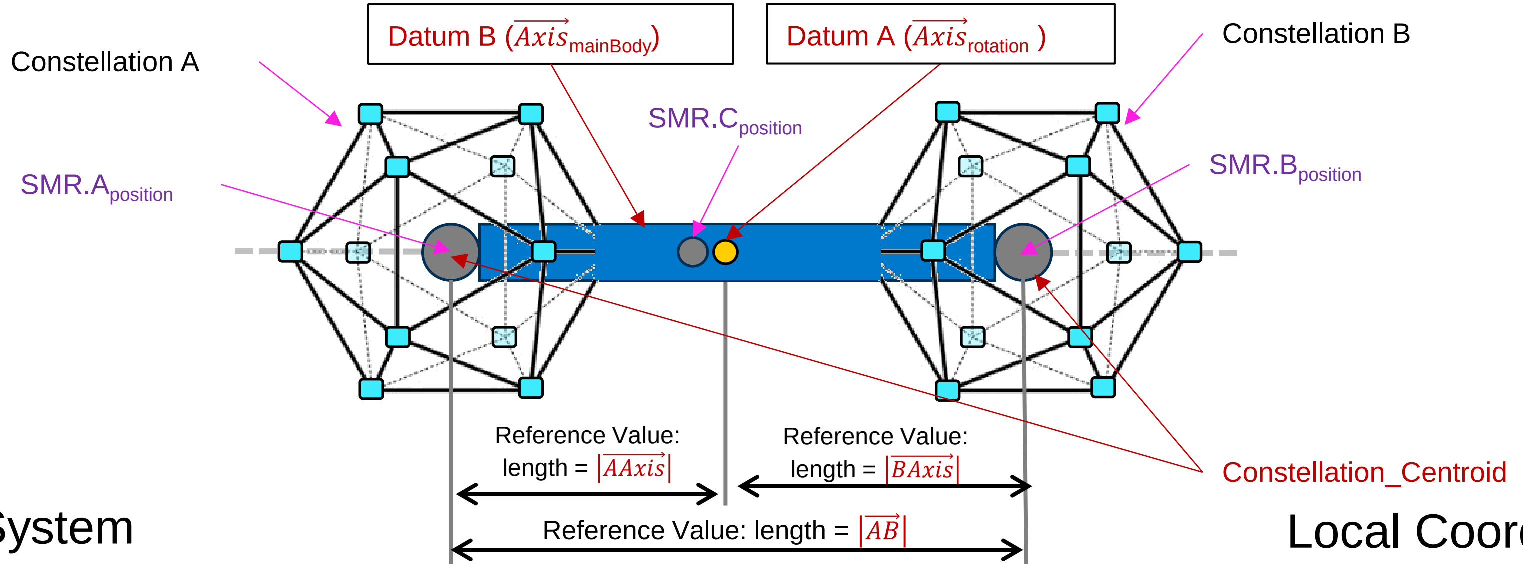
Reference Value:
length = $|\overrightarrow{BAxis}|$

Reference Value: length = $|\overrightarrow{AB}|$

❖ Outer targets will be moving faster than inner targets
❖ It may be difficult to accurately measure a sensor/constellation centroid for traceable measurement

Reference Artifact Design

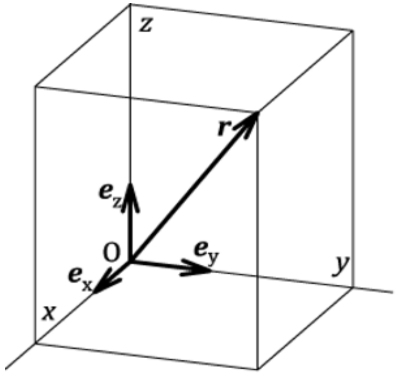
Conversion Between Local coordinate System and Global Coordinate System



Global Coordinate System

Cartesian Coordinates

ISO/IEC 80000



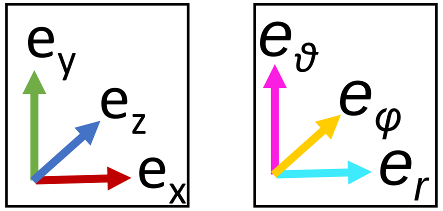
Coordinate: x, y, z

Positional Vector: $r = xe_x + ye_y + ze_z$

Differential of Pos. Vector: $dr = dx\, e_x + dy\, e_y + dz\, e_z$

$$\overrightarrow{Axis}_{rotation} = P_{AxisGlobal}(x,y,z),\ \overrightarrow{Axis}(xe_x, ye_y, ze_z)$$

$$\overrightarrow{Axis}_{rotation} = P_{AxisLocal}(r,\ \theta,\ \varphi),\ \overrightarrow{Axis}(e_\theta)$$

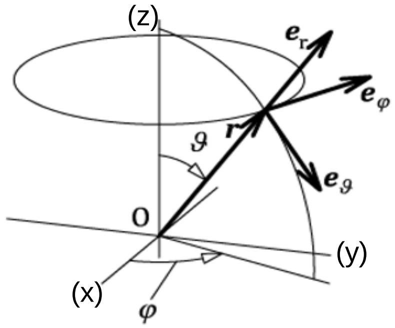


Local Coordinate System

Spherical Polar Coordinates

ISO/IEC 80000

radial distance: $r \geq 0$,
polar angle: $0° \leq \vartheta \leq 180°$
azimuth : $0° \leq \varphi < 360°$



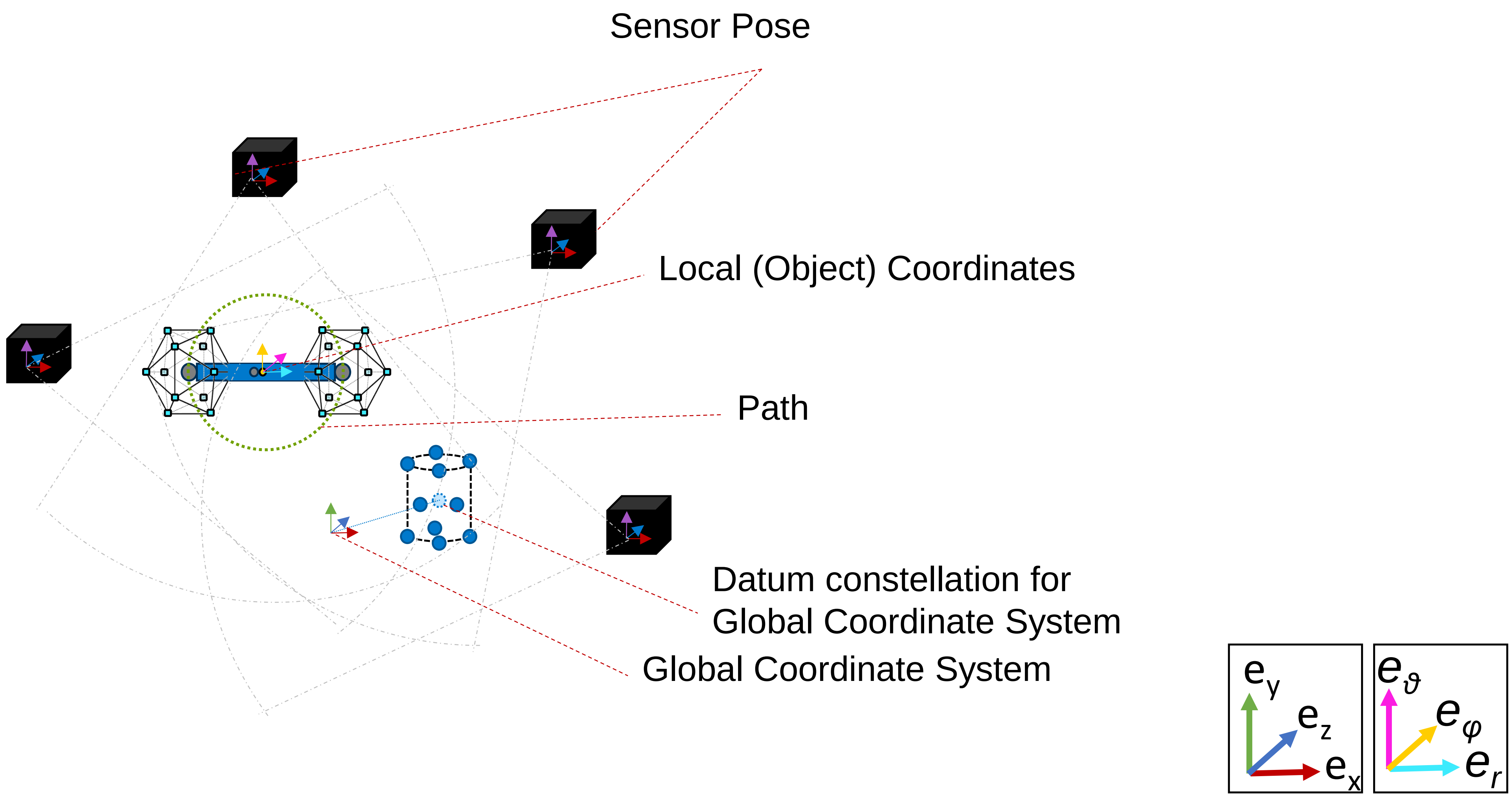
Coordinate: r, ϑ, φ

Positional Vector: $r = re_r$

Differential of Pos. Vector: $dr = dr\, e_r + r\, d\vartheta\, e_\vartheta + r \sin\vartheta\, d\varphi\, e_\varphi$

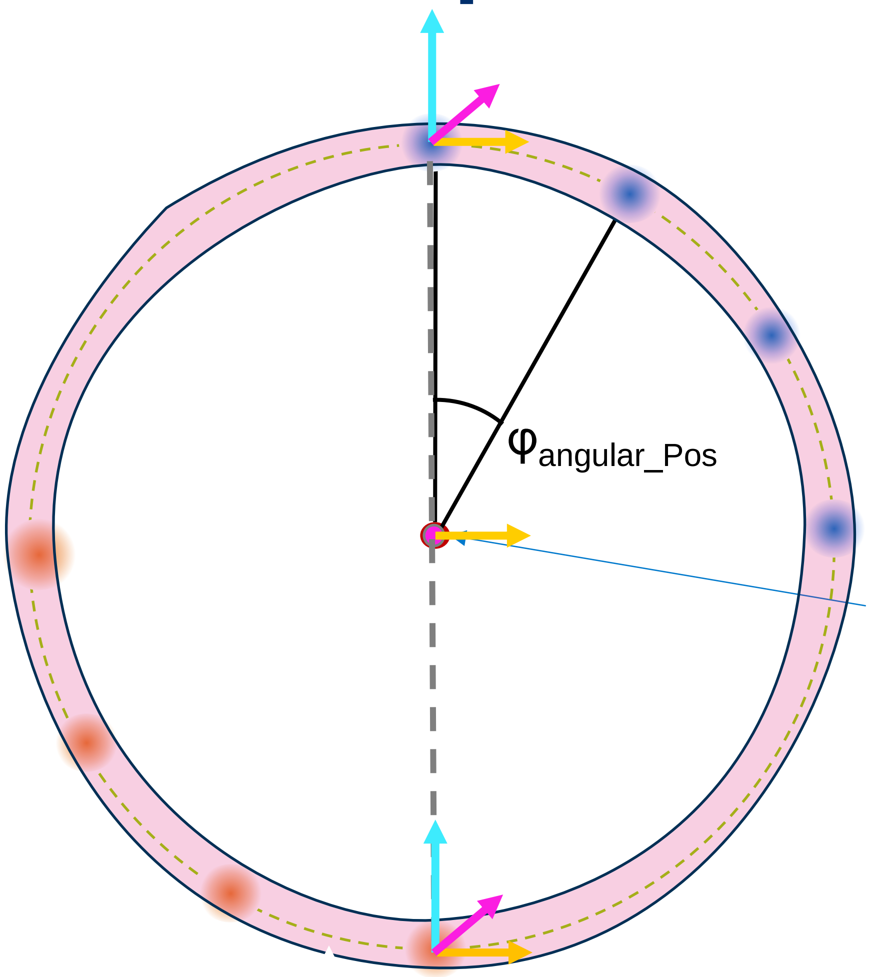
Reference Artifact Design

Conversion Between Local coordinate System and Global Coordinate System

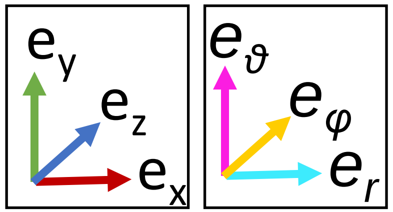


Data Collection Protocol: Stop/Start

- Actuator provides nominal value for angular position, $\varphi_{\text{angularPos}}$
- Zero point of $\varphi_{\text{angularPos}}$, i.e. when $x_{\text{const.A}} = x_{\text{Const.B}}$
- $\overrightarrow{Axis}$ must be determined in the Global coordinate system to represent results in (x, y, z)
  - Can be derived from the measurement data.
  - Can be determined independently using a registered reference measurement system.
- Path can be determined using;
  - Circle fitting: incorporates *a priori* information on the path in $\mathbb{R}^3$.

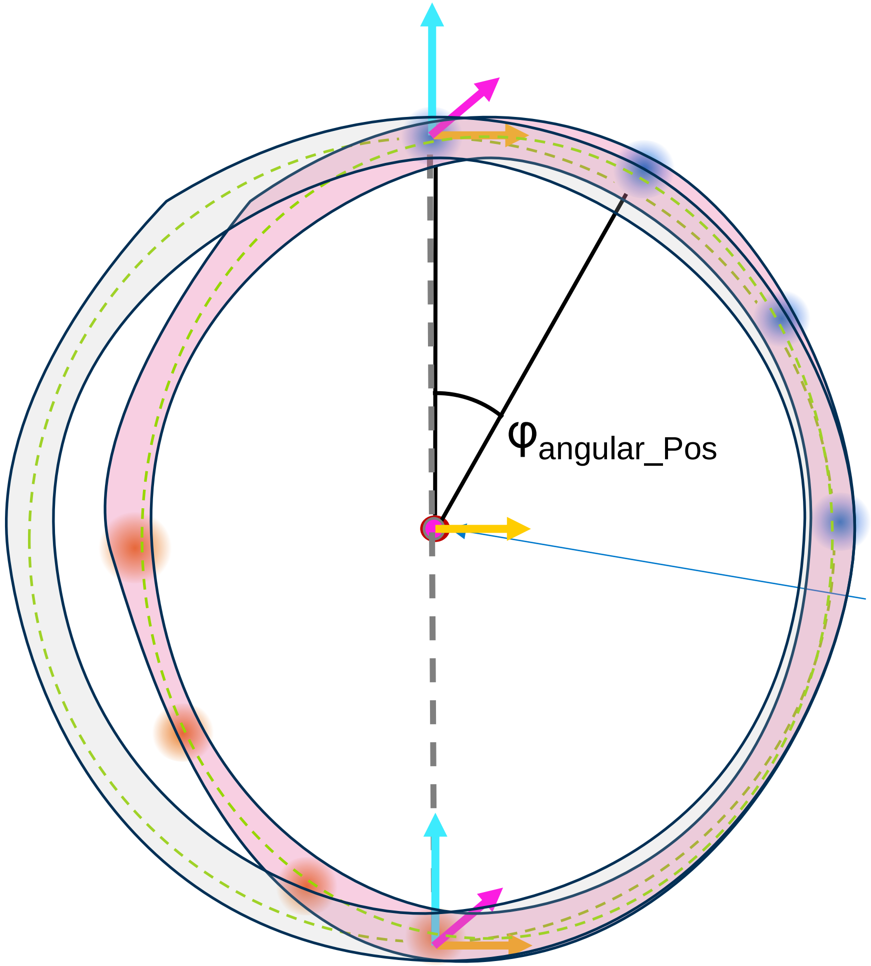


Axis of Rotation
$= P_{\text{AxisGlobal}}(x,y,z),\ \overrightarrow{Axis}(xe_x, ye_y, ze_z)$
$= P_{\text{AxisLocal}}(r,\ \theta,\ \varphi),\ \overrightarrow{Axis}(e_\theta)$



Data Collection Protocol: Stop/Start

- Path can be determined using;
  - Circle fitting: incorporates *a priori* information on the path in $\mathbb{R}^{3}$.
  - Interpolation: working purely in measurement space.



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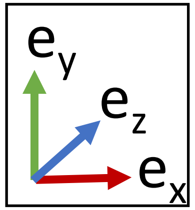
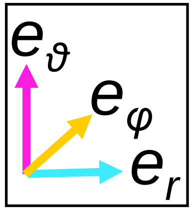
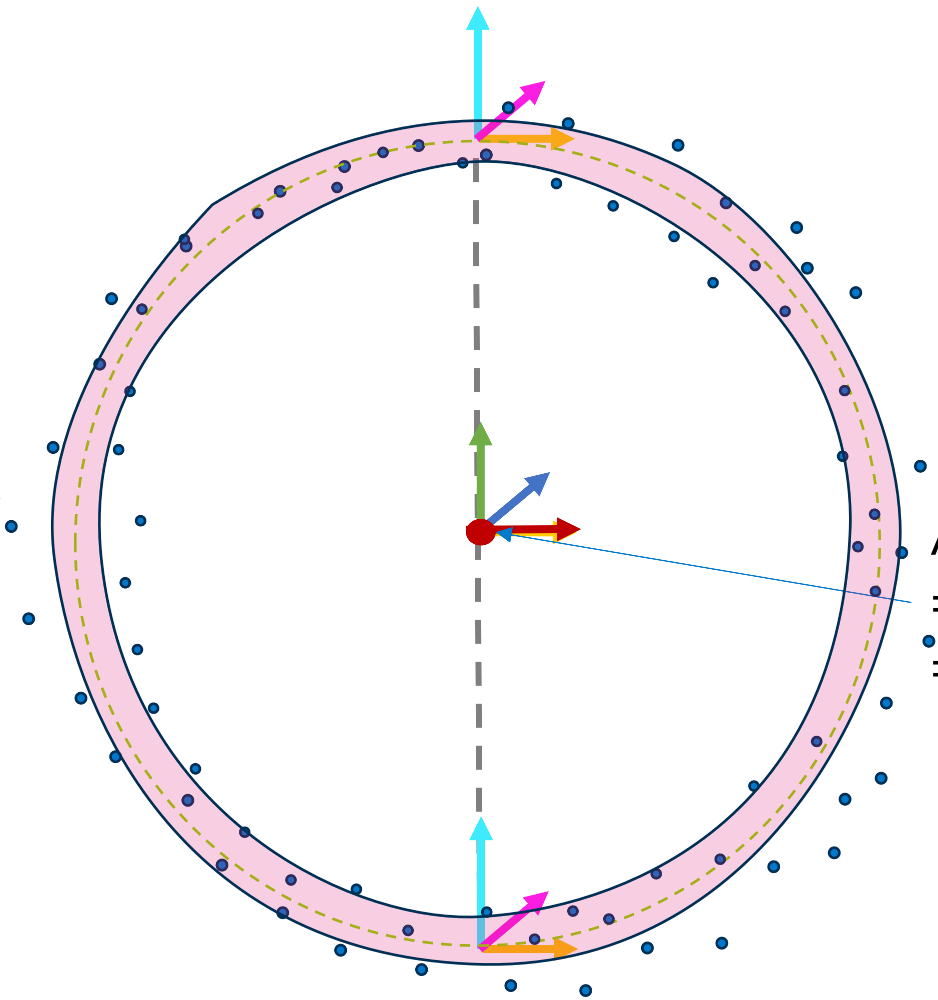




Data Collection Protocol: Continuous

- Continuous measurement requires temporal synchronisation with the system under test.

- Errors are parameterised as deviation from path,
  - *e_r, e_ϑ, e_φ, are orthonormal basis vectors representing the intrinsic coordinates of the path.*
  - *Velocity is a scalar multiplied by e_φ.*



Axis of Rotation

$= P_{AxisGlobal}(x,y,z), \overrightarrow{Axis}(xe_x, ye_y, ze_z)$

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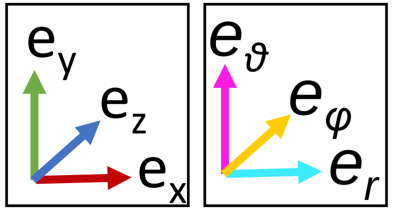
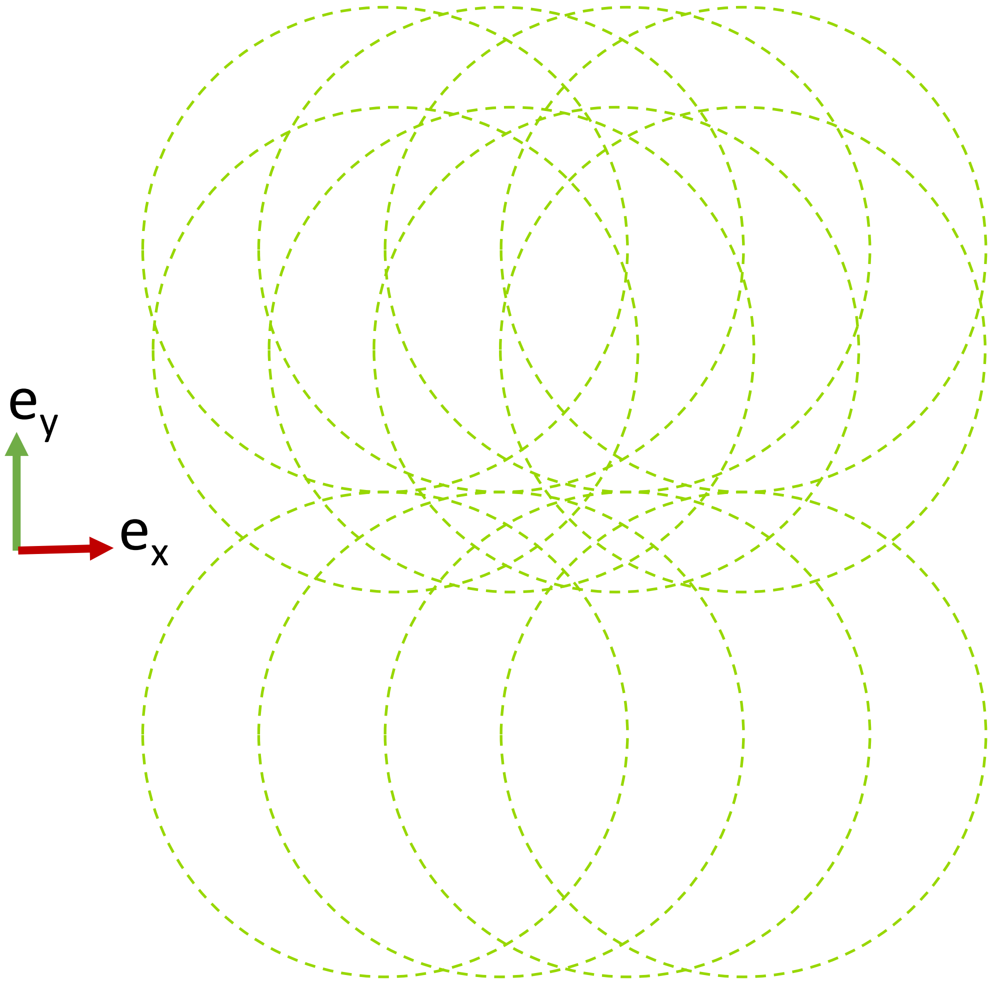
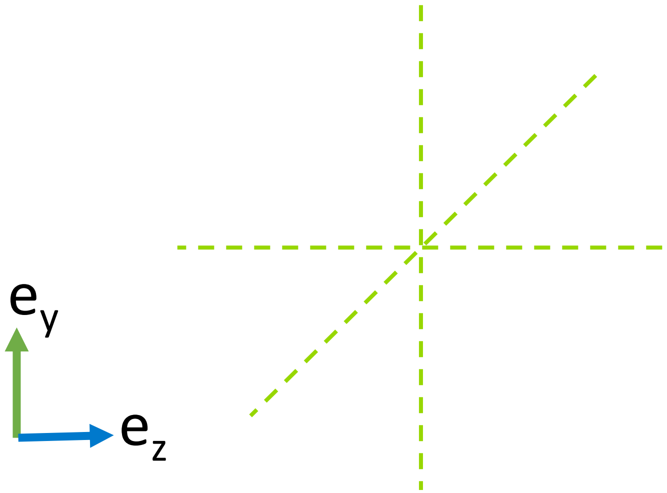
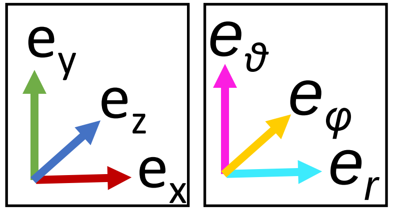


❖ Method requires an in-situ comparator system to measure absolute position
❖ Circular motion may not replicate the intended use case for manufacturing processes
❖ The measured performance of a system is not localised as test takes up space.

Data Collection Protocol: Mapping







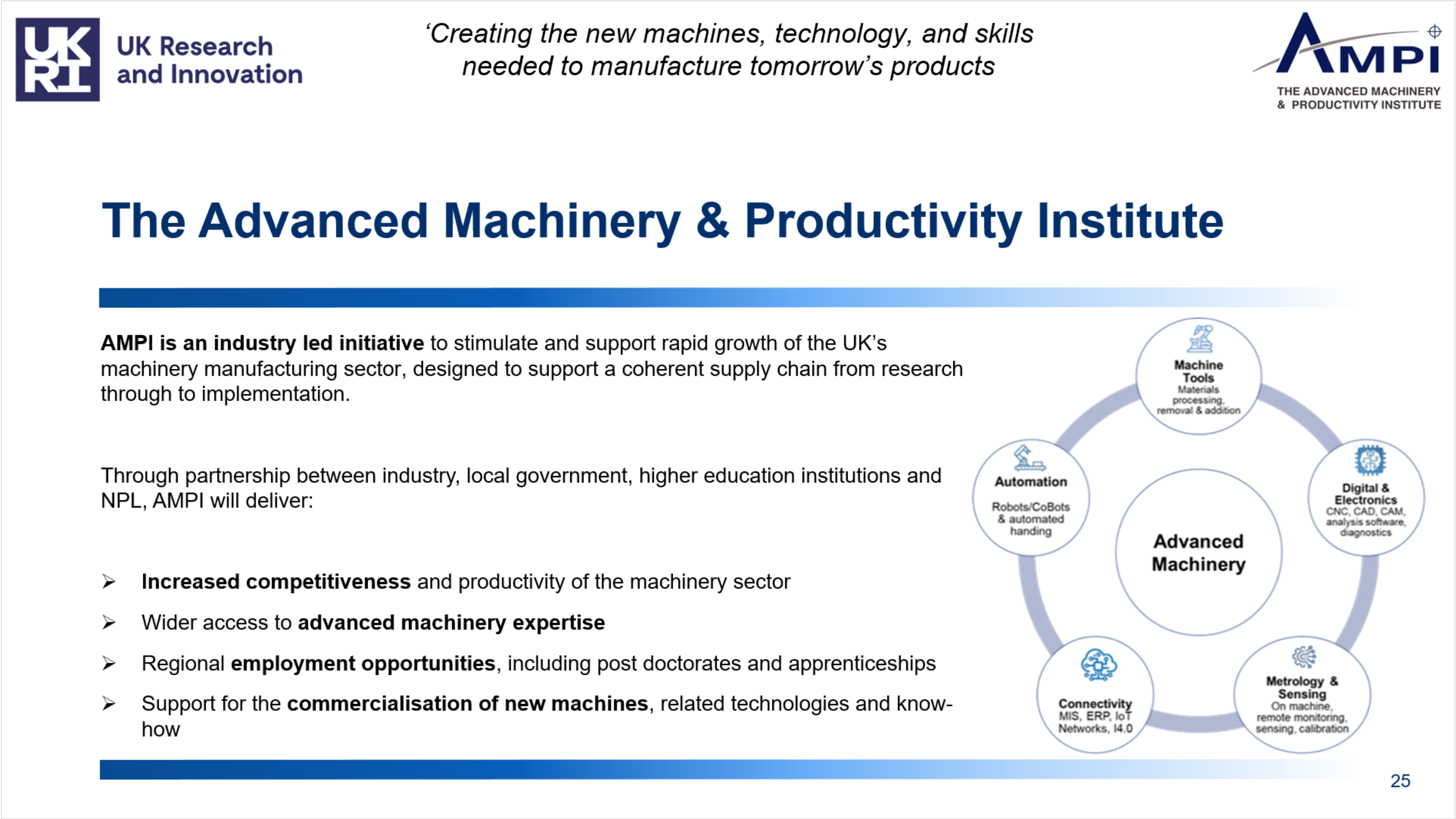
Contents

Aim

To develop a generalised set of standard tests to quantify the performance of a distributed six degrees of freedom, single or multi- target, large volume metrology (LVM) system for *dynamic* (moving) applications

Contents

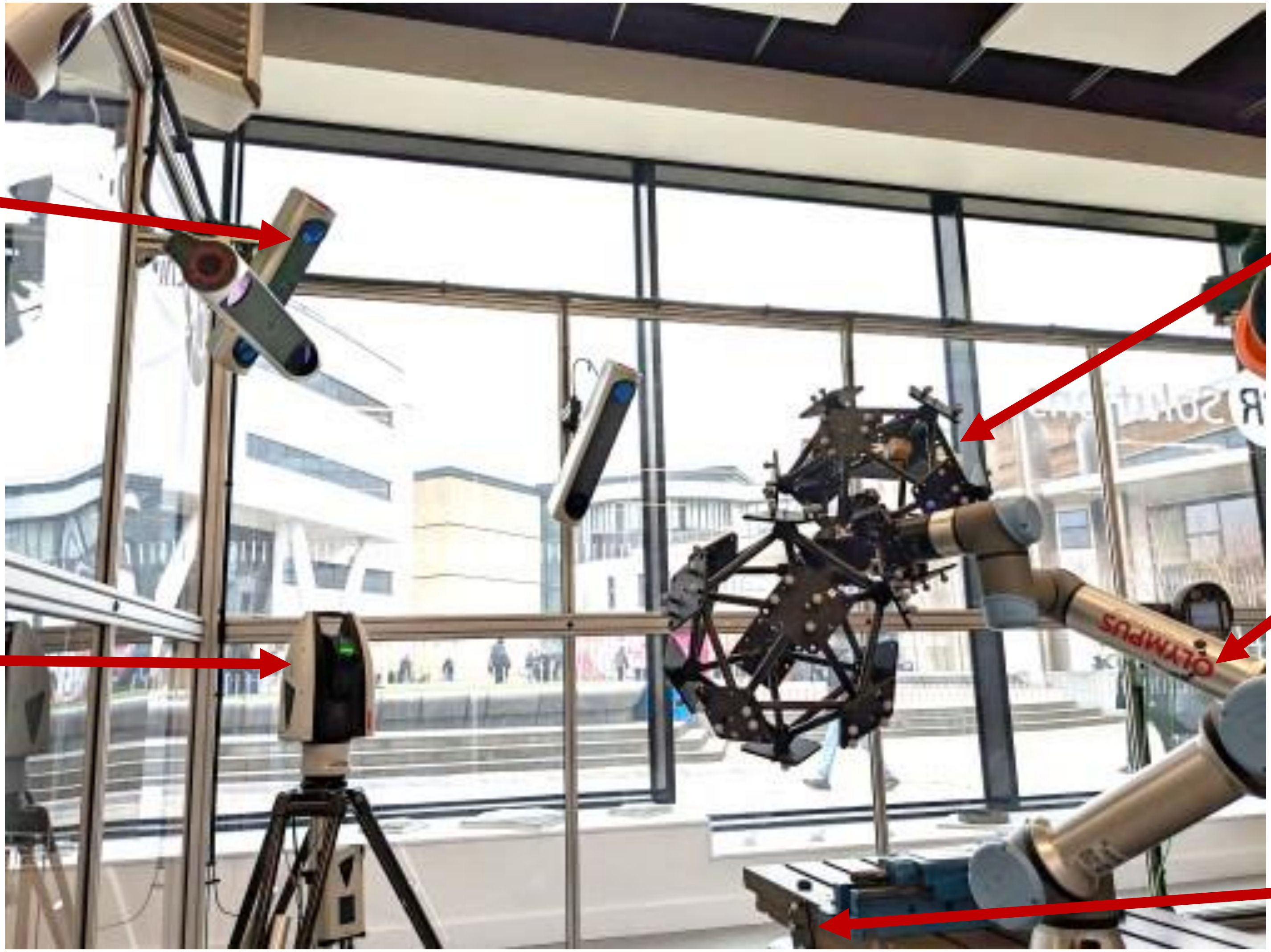
- Introduction
  - Motivation, Challenge
- Method
  - Overview of a distributed large volume metrology system
  - Methodology Development
- Preliminary Results
  - Data collection
  - Illustrative results
- Summary and Further work



Data Collection

Iona Detector Node

Laser Tracker



Test Artifact

Universal Robot: UR5e

Datum constellation
(most is out of shot)

Data collected in collaboration with Huddersfield University, Centre for Precision Technologies

Data Collection Protocol

Time →

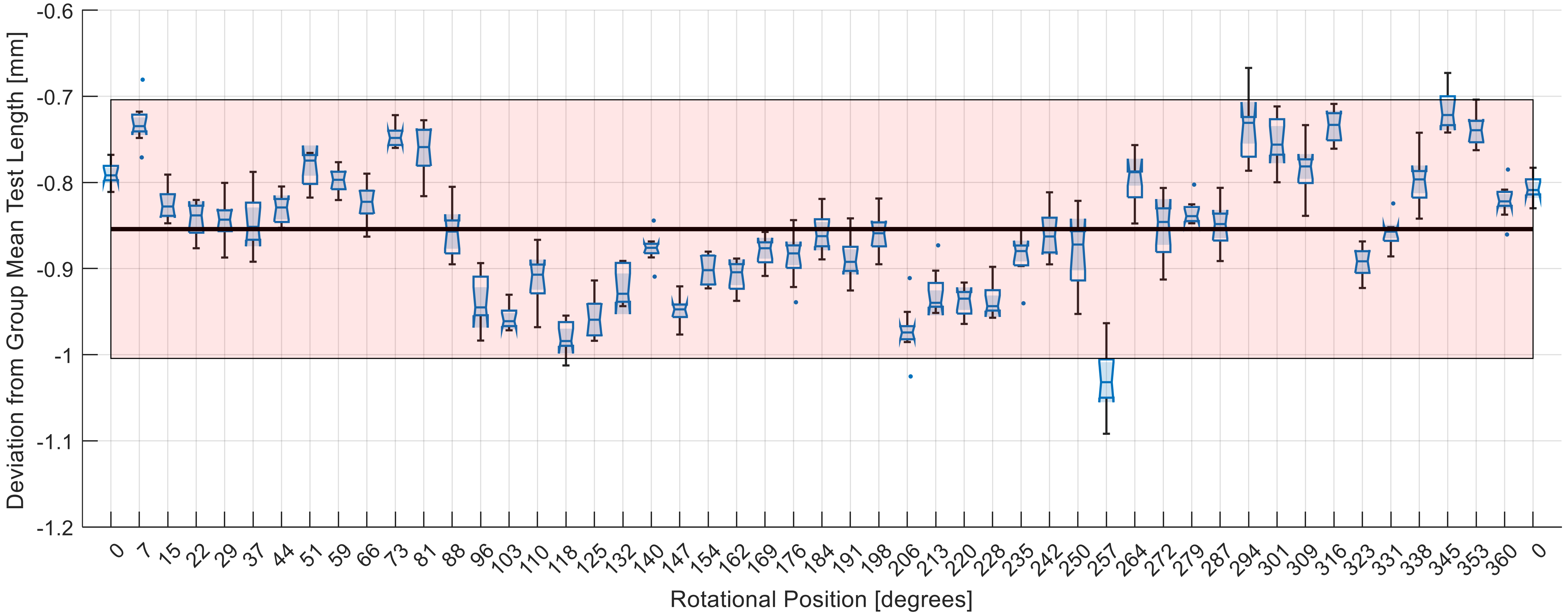
Stop/Start Protocol	Dynamic Protocol
• 51 positions (1 and 51 were nominally identical) • Repeat protocol (9 repeats)	• Data collected over a range of angular speeds.

- 9 repeat tests using the stop/start protocol
  - The laser tracker measures 3 different target locations.
- 9 continuous motion tests using the same angular speed
  - These interleaved with the Stop/Start tests as they are taken as the actuator return to its start position.

Test Matrix

Protocol	n	Laser Tracker	Angular Speed (rads s^{-1})	Positions	Samples Per Position
Stop/Start	3	A (Constellation A)	0.0	51	60
Stop/Start	3	B (Constellation B)	0.0	51	60
Stop/Start	3	C	0.0	51	60
Dynamic	5	C	0.2, 0.4, 0.6, 0.8, 1.0	-	1
Return	3	A (Constellation A)	0.4	20	1
Return	3	B (Constellation B)	0.4	20	1
Return	3	C	0.4	20	1

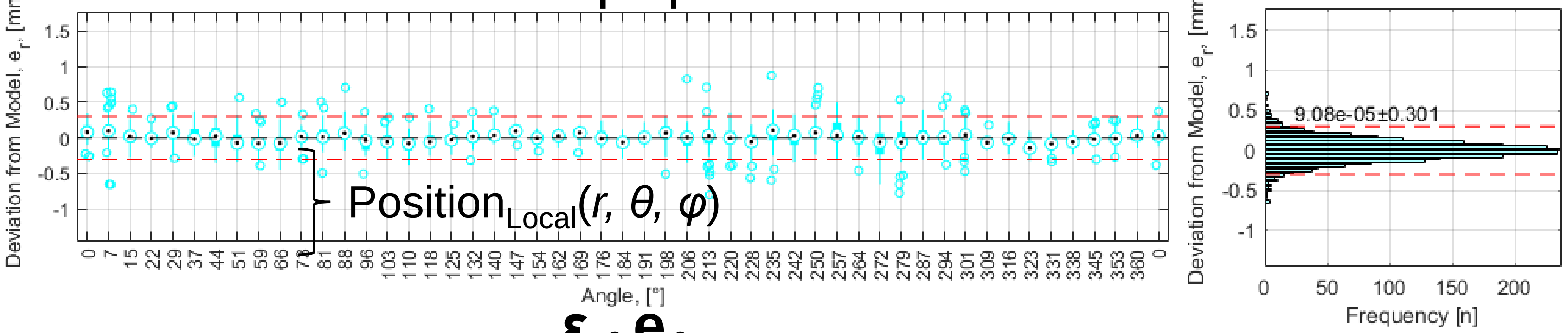
Comparison to Reference Value: length = $|\overrightarrow{AB}|$



Reference Value: length = $|\overrightarrow{AB}|$

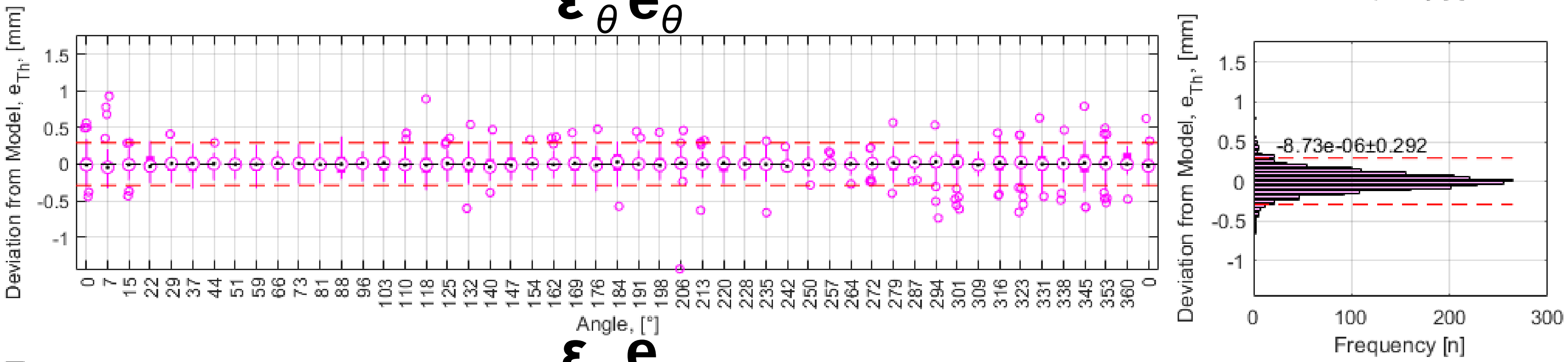
$Position_{Local}(r, \theta, \varphi)$

ε_r e_r



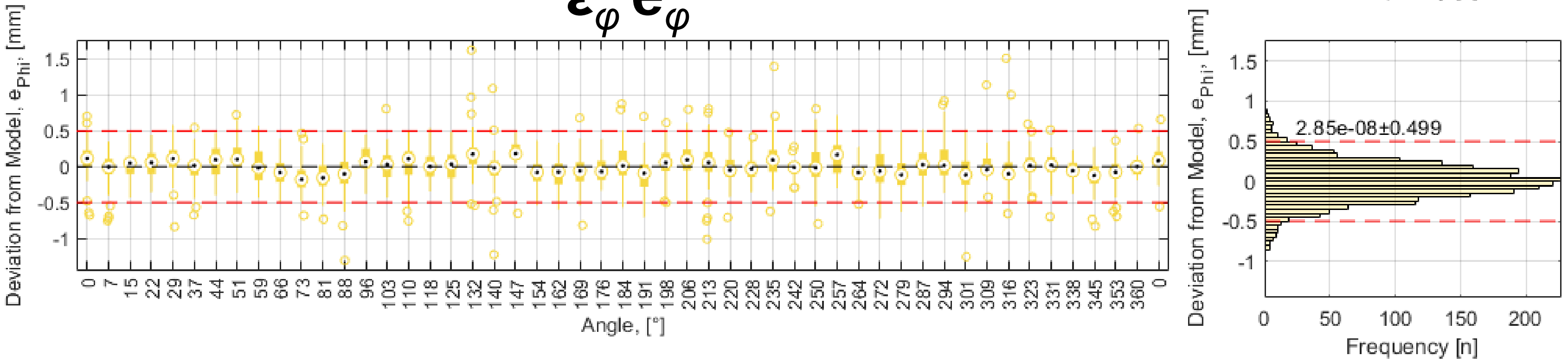
$\varepsilon_r = e^{-4} \pm 0.30$ mm, k=2, norm

ε_θ e_θ



$\varepsilon_\theta = e^{-4} \pm 0.29$ mm, k=2, norm

ε_φ e_φ

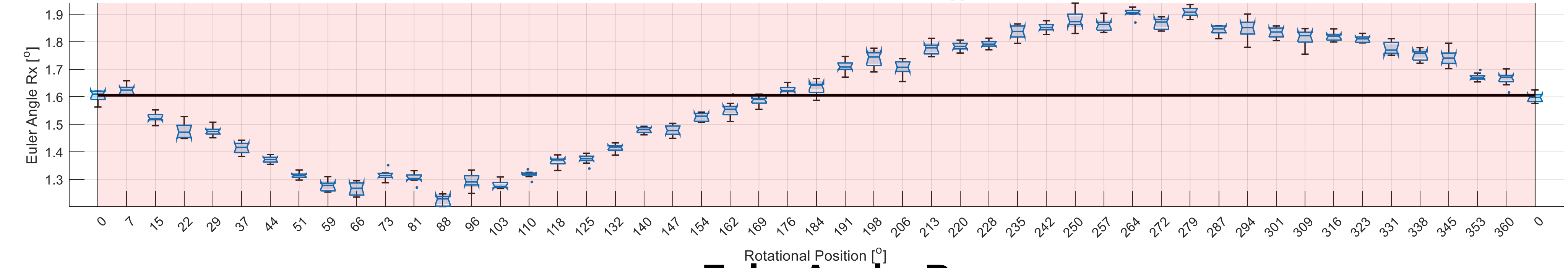


$\varepsilon_\varphi = e^{-8} \pm 0.50$ mm, k=2, norm

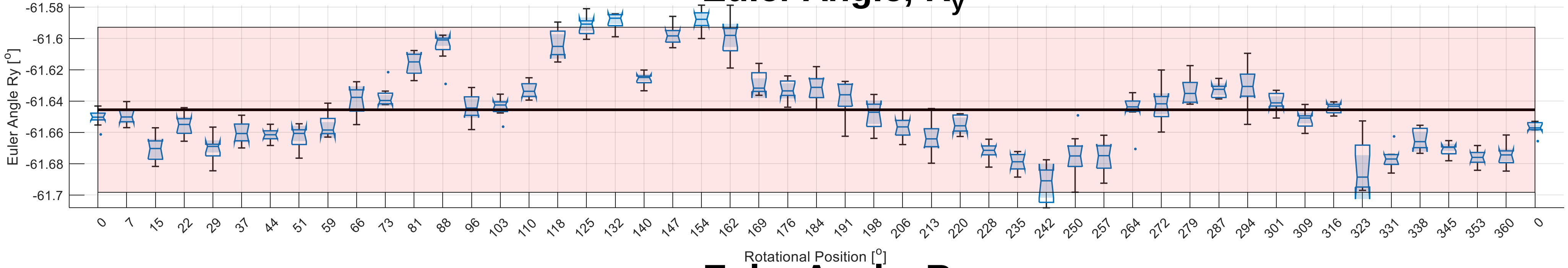
Orientation$_{Global}$ [Rx, Ry, Rz]

ε, standard error on the mean

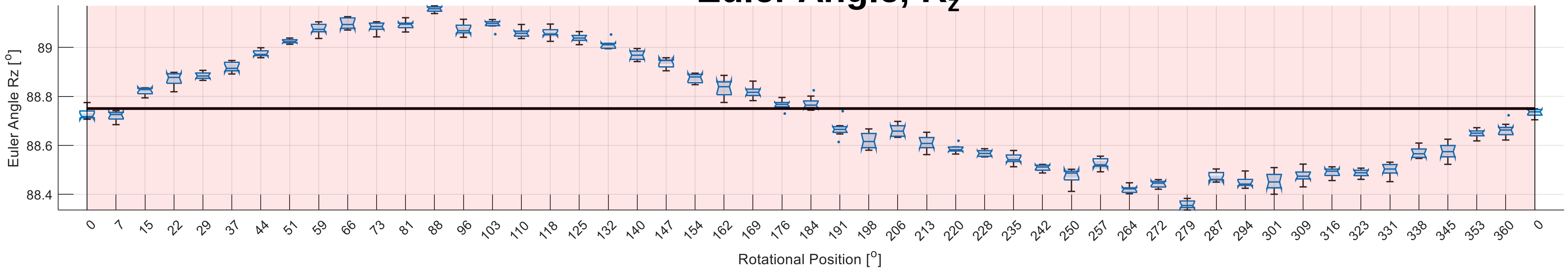
Euler Angle, R_x



Euler Angle, R_y



Euler Angle, R_z



Summary and Ongoing Work

- A method of quantifying the dynamic performance of a distributed large volume metrology system has been presented aimed at addressing metrological challenges on the horizon of automation.

- The method accommodates multiple levels of comparison;
  - comparison of a systems' static performance against its dynamic performance.
  - comparison against a calibrated length.
  - comparison against an alternative 3 DOF(or more) system.

- Controlled test variables include; position, orientation, velocity, and time

- A prototype artefact has been built for proof of concept with promising results, however;
  - rigidity must be improved.
  - greater velocities need to be achieved (at least 3 ms^{-1}).

Work is ongoing

- Iterate the artefact design : increased rigidity, incorporate precision rotational actuator.
- Show system performance as a function of angular velocity.
- Creation of a kinematic model to quantify and potentially correct for errors.
- Robust test uncertainty estimation.
- Sensitisation of the artefact

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National Physical Laboratory

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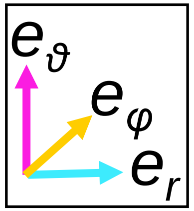
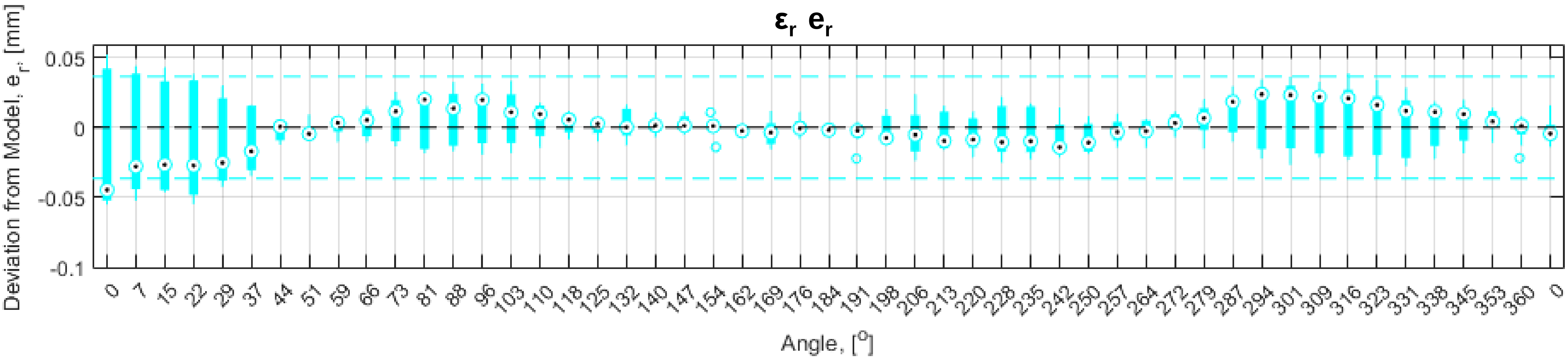
Deviation from Path: Comparator System

Path : Fit circle





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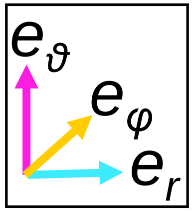
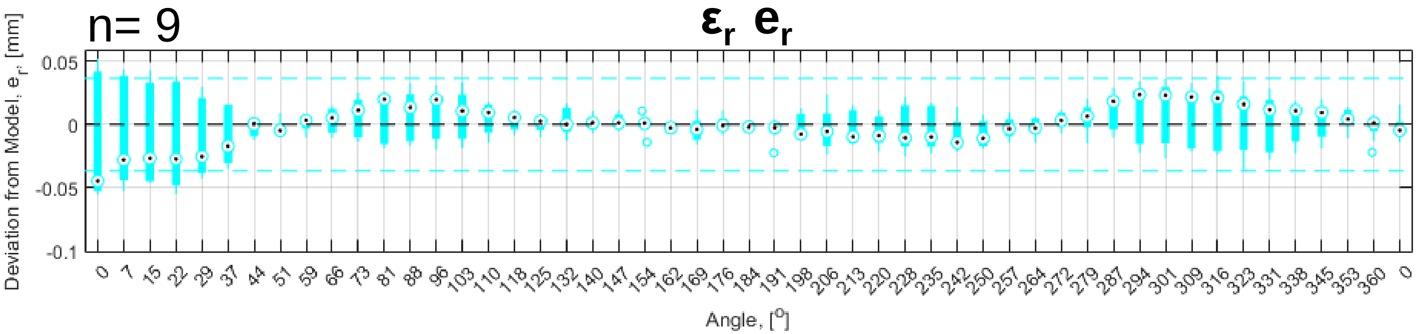
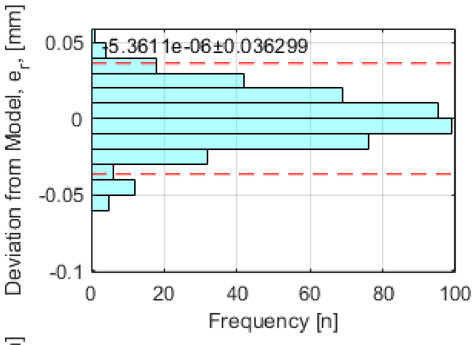
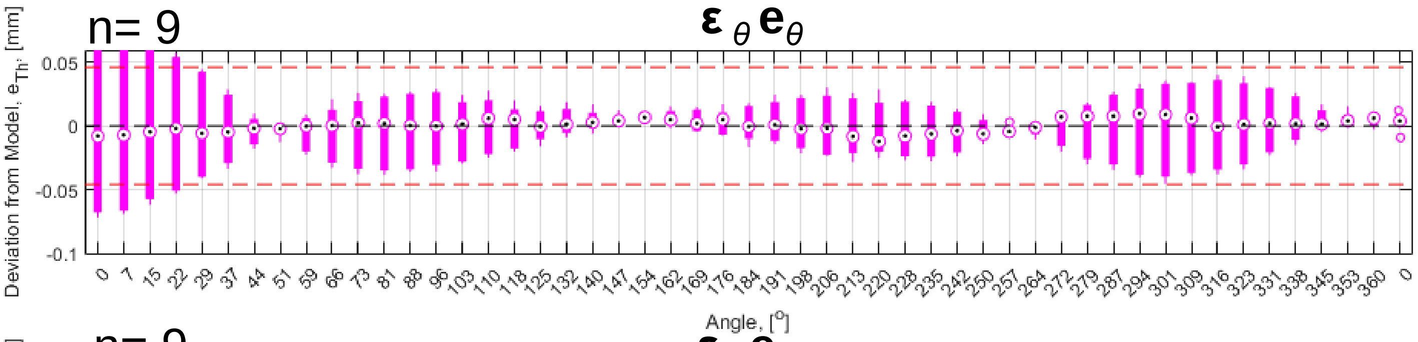
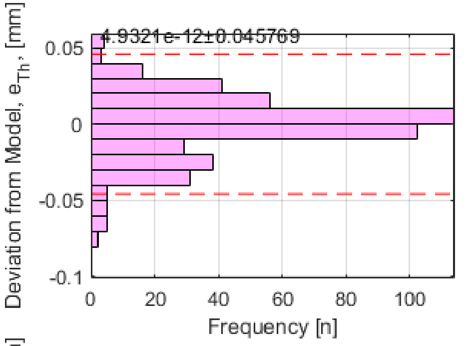




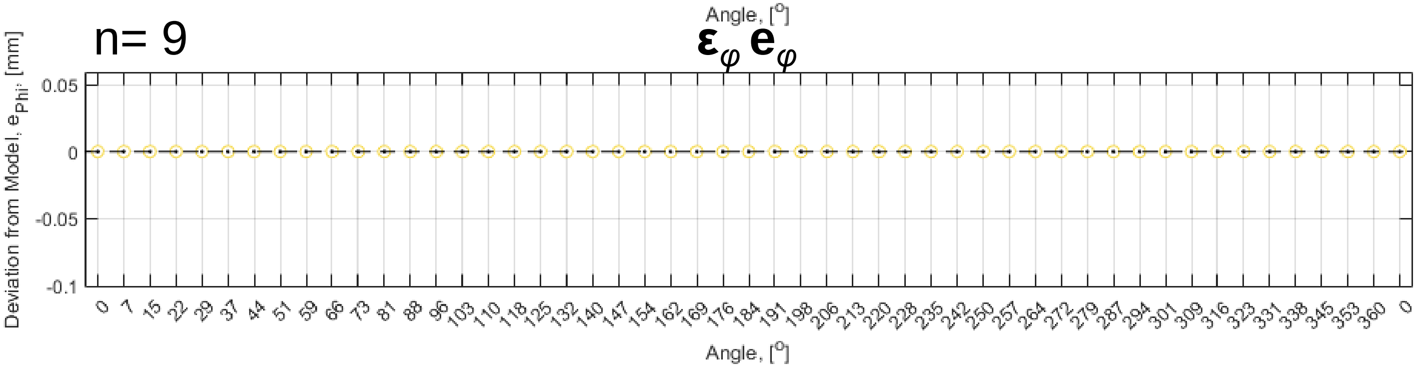


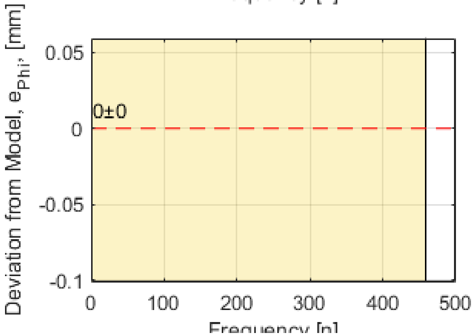
e-6 ± 0.036, k=2, norm





e-12 ± 0.046, k=2, norm





~~0 ± 0.0, k=2, norm~~

Data from the SMR placed ~coincident with the centroid of Constellation A

Data collection method used: “stable point”, hence no distribution for φ. *Method should not require repeat runs of the stop/start protocol*

The Advanced Machinery & Productivity Institute

AMPI is an industry led initiative to stimulate and support rapid growth of the UK's machinery manufacturing sector, designed to support a coherent supply chain from research through to implementation.

Through partnership between industry, local government, higher education institutions and NPL, AMPI will deliver:

- **Increased competitiveness** and productivity of the machinery sector
- Wider access to **advanced machinery expertise**
- Regional **employment opportunities**, including post doctorates and apprenticeships
- Support for the **commercialisation of new machines**, related technologies and know-how