Generalised Test for Evaluation of Large Volume Metrology Systems for Dynamic Measurement

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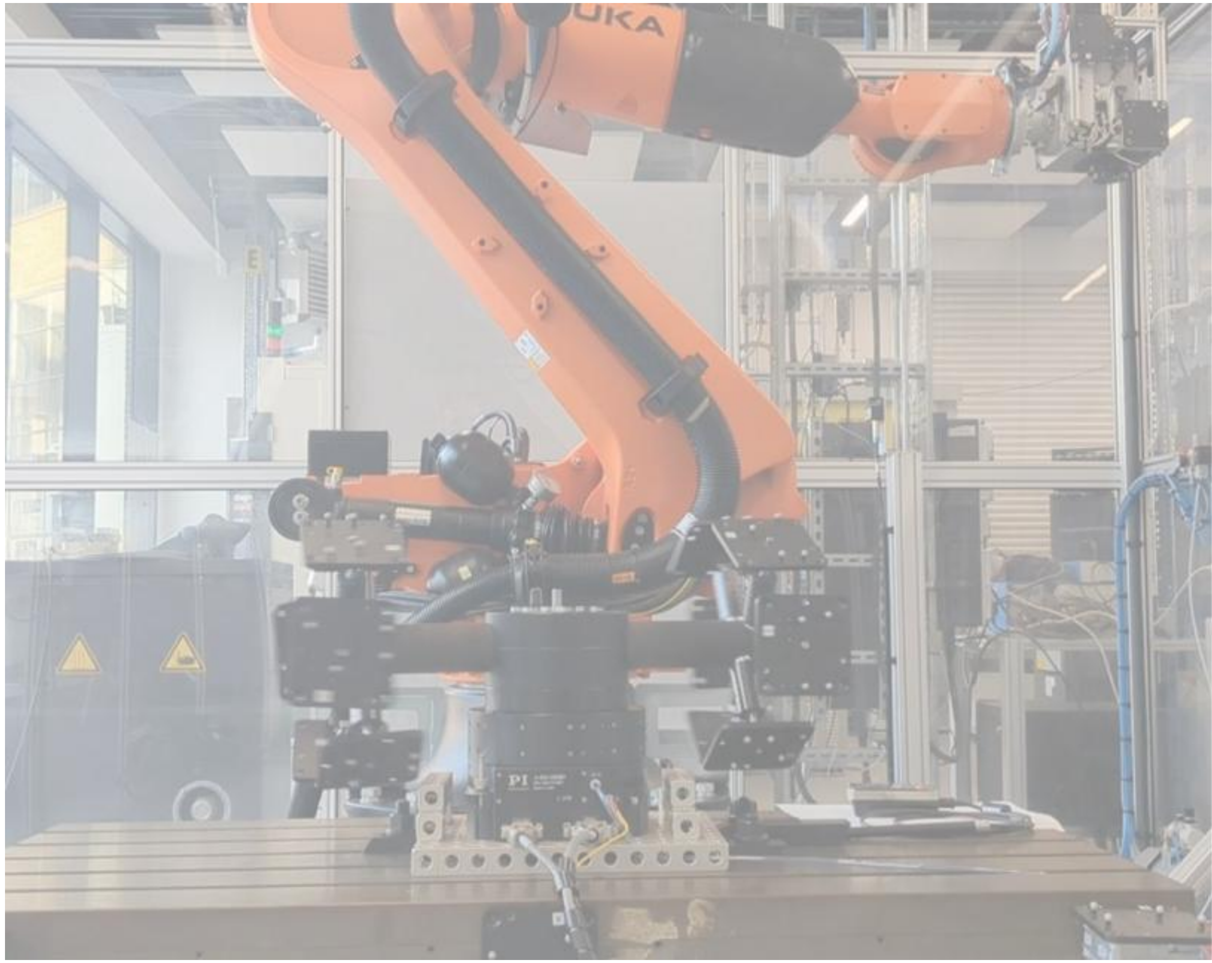

Motivation

Robots are used in industry:

- Repeat tasks.
- Robust.
- Versatile.

But they have limitations associated with traditional automation approaches:

- Rigid architectures.
- Task reprogramming.
- Need for complex validation and calibration.

→ Pursuit of more flexible and intelligent robot guidance methods

Distributed Large Volume Metrology systems

NPL

DLVM systems can **track multiple objects simultaneously over large volume** (e.g. 3 m x 2 m x 2 m to 12 m x 8 m x 2 m).

Advantages:

- Overcomes occlusions issues.
- Implementation of dynamic control zones.
- Enhance human-robot interoperability and collaboration.

Based on wide range of carrier signals, processing methods and metrological principals, such as:

- Photogrammetry.
- Interferometry.
- Structured light projection.

Are current standards adequate to bring confidence in the use of these systems?

Limitation in the current standards

NPL

- **Technology Agnosticism**:
  The absence of a technology-agnostic test method suitable for different sensor types and metrological approaches.
- **Coherent Static and Dynamic Performance Characterisation**:
  The lack of test procedures that adequately evaluate both static and dynamic measurement capabilities within a single, coherent framework.
- **Complex System or Process Variables**:
  The inability to accommodate unique DLVM test variables when considered for the application of robot guidance in a manufacturing process.
- **Industrial Relevance**:
  The lack of tests that replicate industrially relevant environmental conditions, addressing real-world factors like temperature gradients, ambient lighting conditions, humidity, and vibration.

Develop a generalized set of standardized tests designed specifically for evaluating the performance of DLVM systems for dynamic applications

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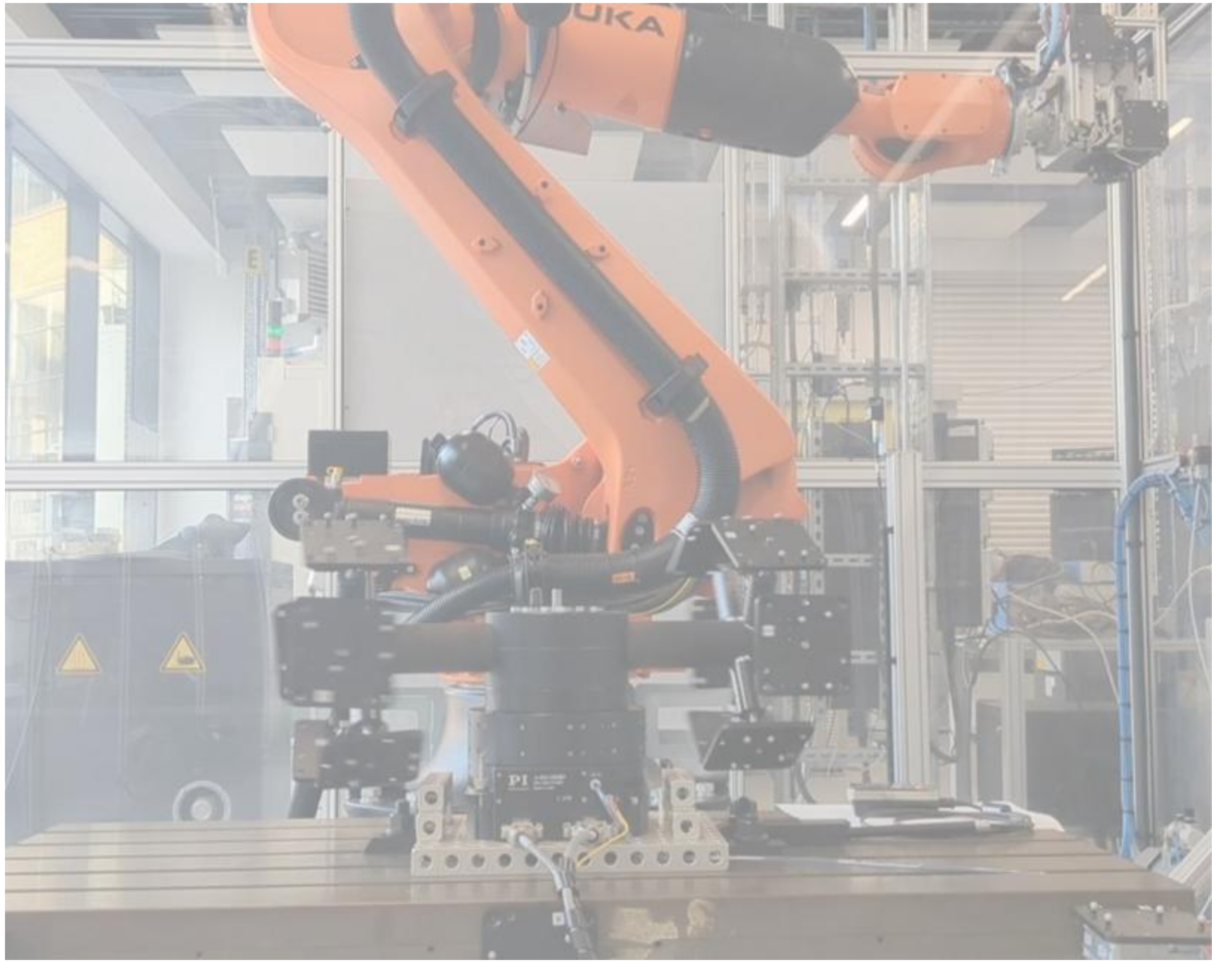
2. Data collection and artefact
3. Results
4. Conclusion
5. Ongoing work



Method : Principle

Nominal / Control Path: The path requested of the actuator

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

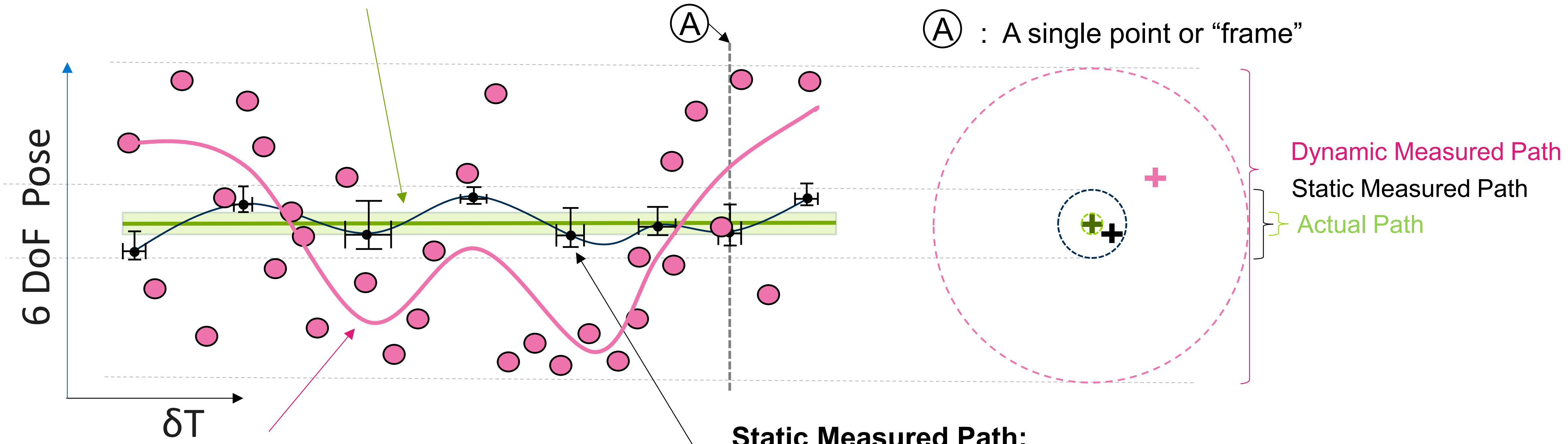
Actual Path:

- Uncertainty relate to the error model
- Some error can be compensated for to refine the nominal, e.g. flexure of the cantilever supporting the constellation

Nominal + Uncertainty = Actual Path

Static Measurement Path (standard error on the mean)

Dynamic Measurement Path

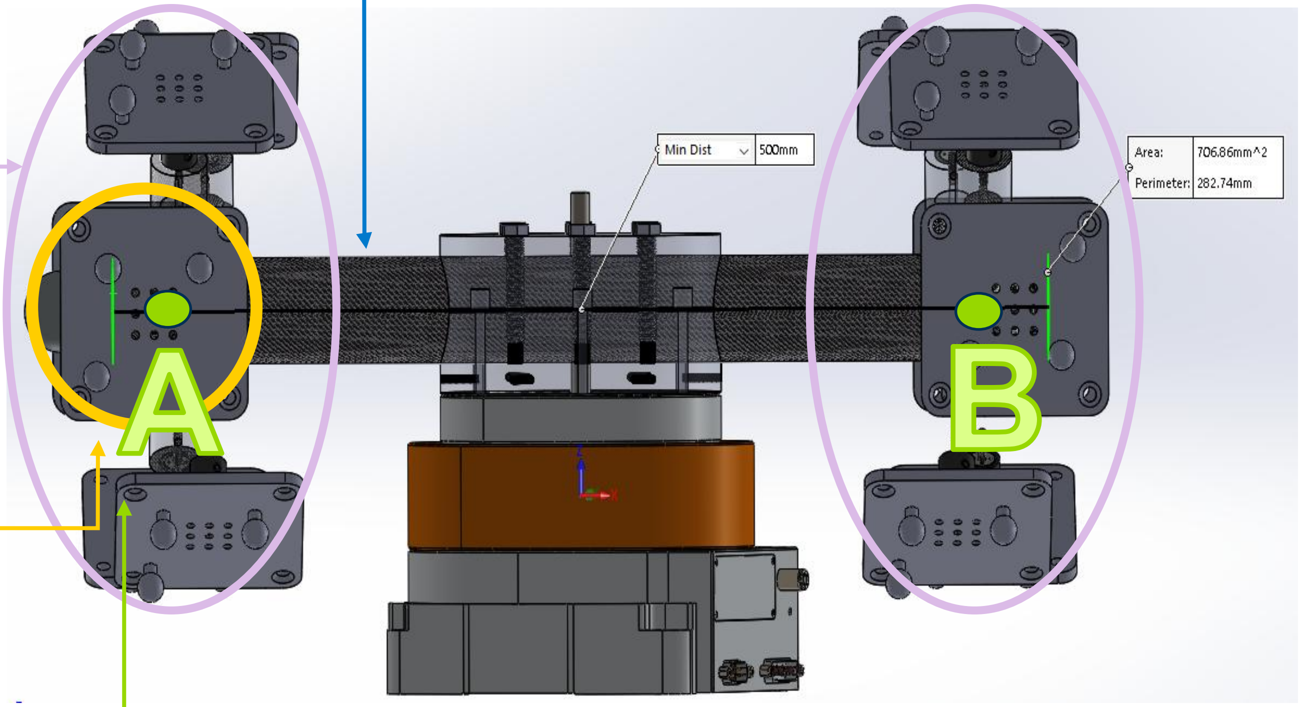


Dynamic Measured Path:
The path as measured dynamically by the system under test with additional errors: temporal error, dynamic forces.

Static Measured Path:
The path measured statically in measurement space and interpolated
N > 100 per sample

Artefact

- **Carbon fibre tube** attached to a rotational actuator with an aluminium split clamp.
- **Two reconfigurable constellations** are connected to each end of the carbon fibre tube.
- **Each constellation consists of 6 aluminium tiles** each mounting 4 retroreflective spheres.
- **Two virtual points** are defined, called centroids, and are **nominally coincident with the axis of the carbon fibre tube**.



Artefact dimensions (mm):
L x W x H : 580 x 300 x 340.

Protocols

- ***Oscillation protocol***:

The actuator slowly oscillates between two locations, **e.g. +/- 5°,** over a set period following a sinusoidal pattern.

- ***Stop/Start protocol:***

The actuator performs one complete rotation waiting at several discrete locations to allow the system under test to capture multiple measurement frames of the static constellation(s).

- ***Continuous Motion protocol:***

The actuator rotates at constant angular velocity whilst the system under test captures multiple measurement frames.

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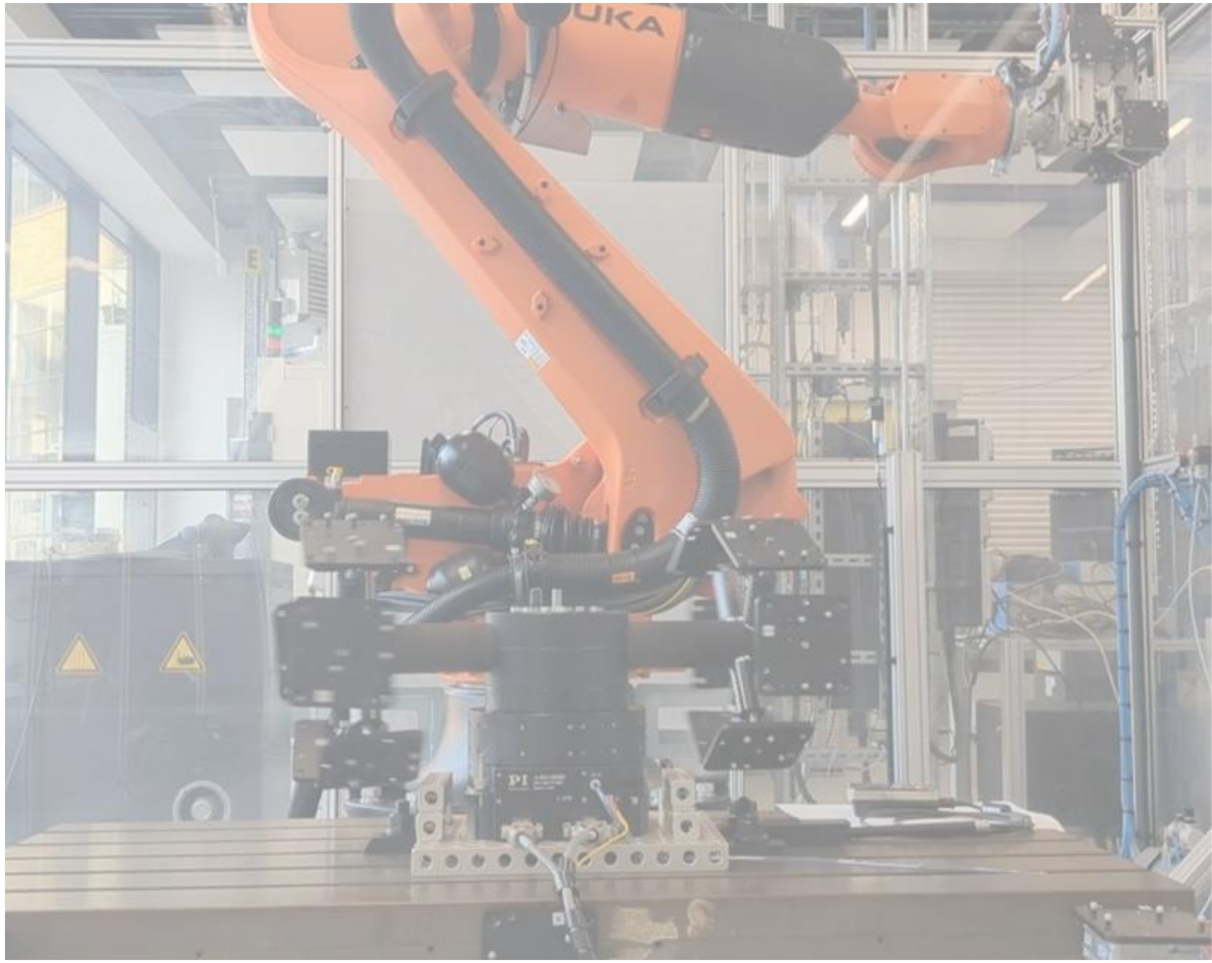


Test details

- Test carried at Huddersfield University using the IONA system (multi-nodal distance camera system).

- All data collected horizontally

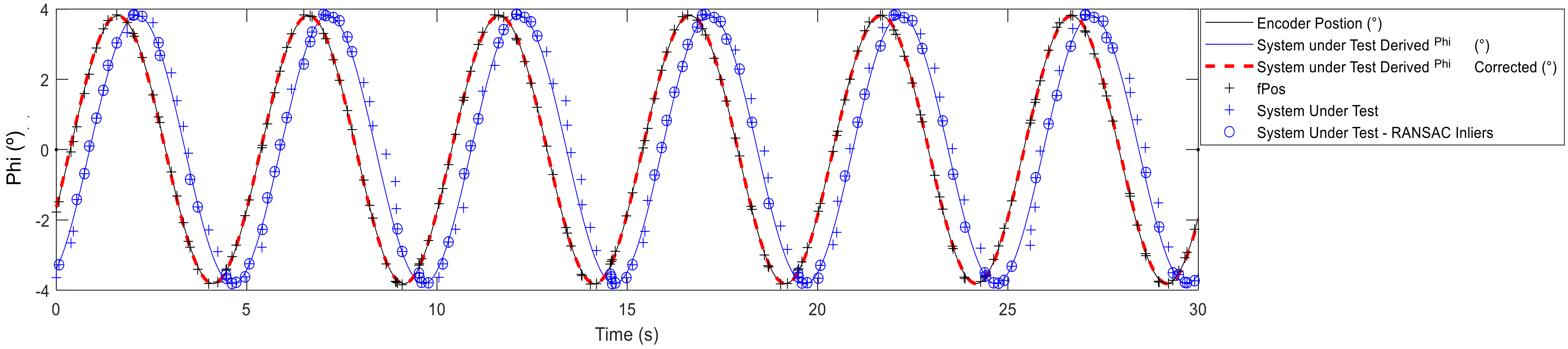
- Data is streamed off the actuator encoder via EtherCAT.

- Data is steamed off the IONA system via MQTT.

- Data is time stamped on receipt by the data acquisition computer. This is used to temporally align the clocks of the actuator and Iona system.

The specific Iona system used and therefore the performance values presented are not representative of general Iona systems' performance.

Oscillating Protocol: Temporal Alignment

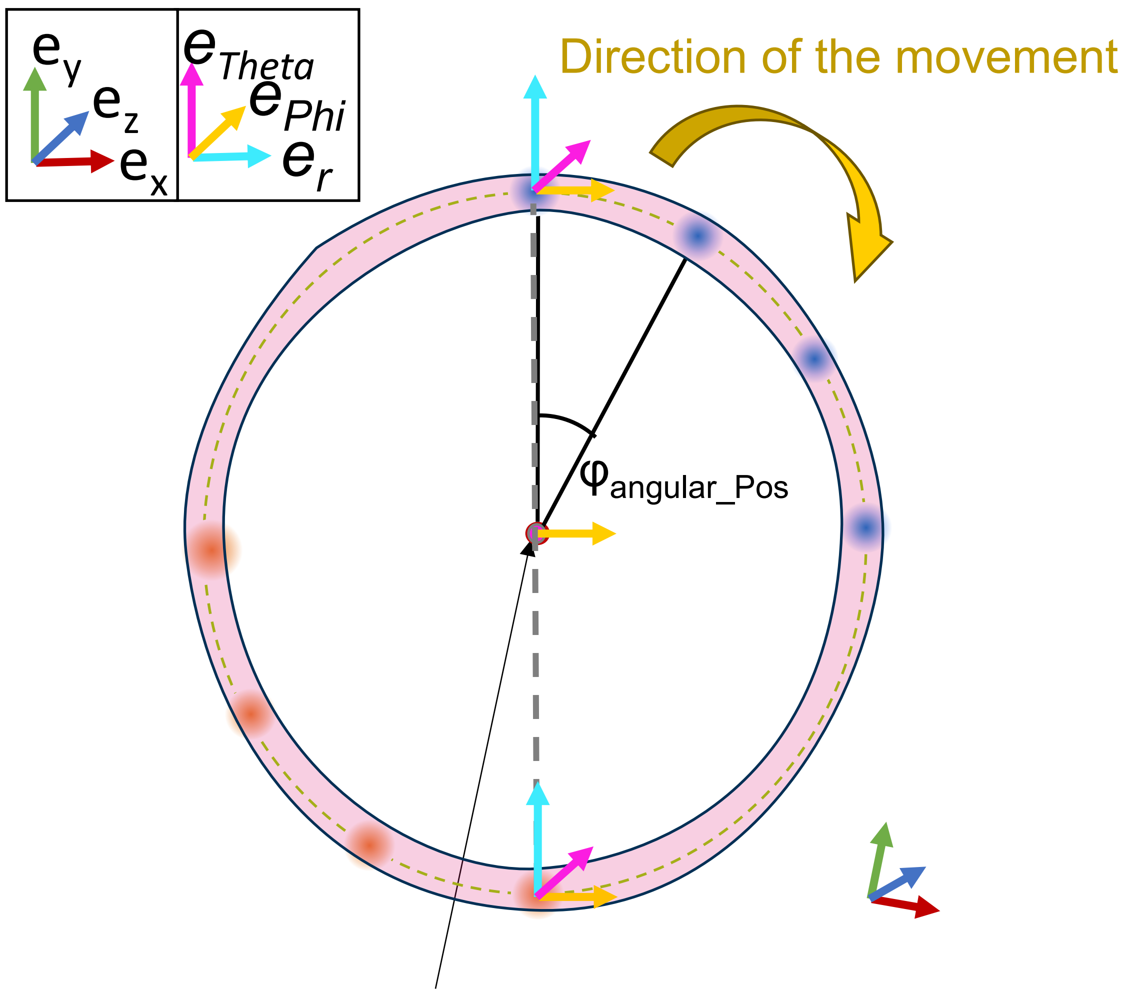


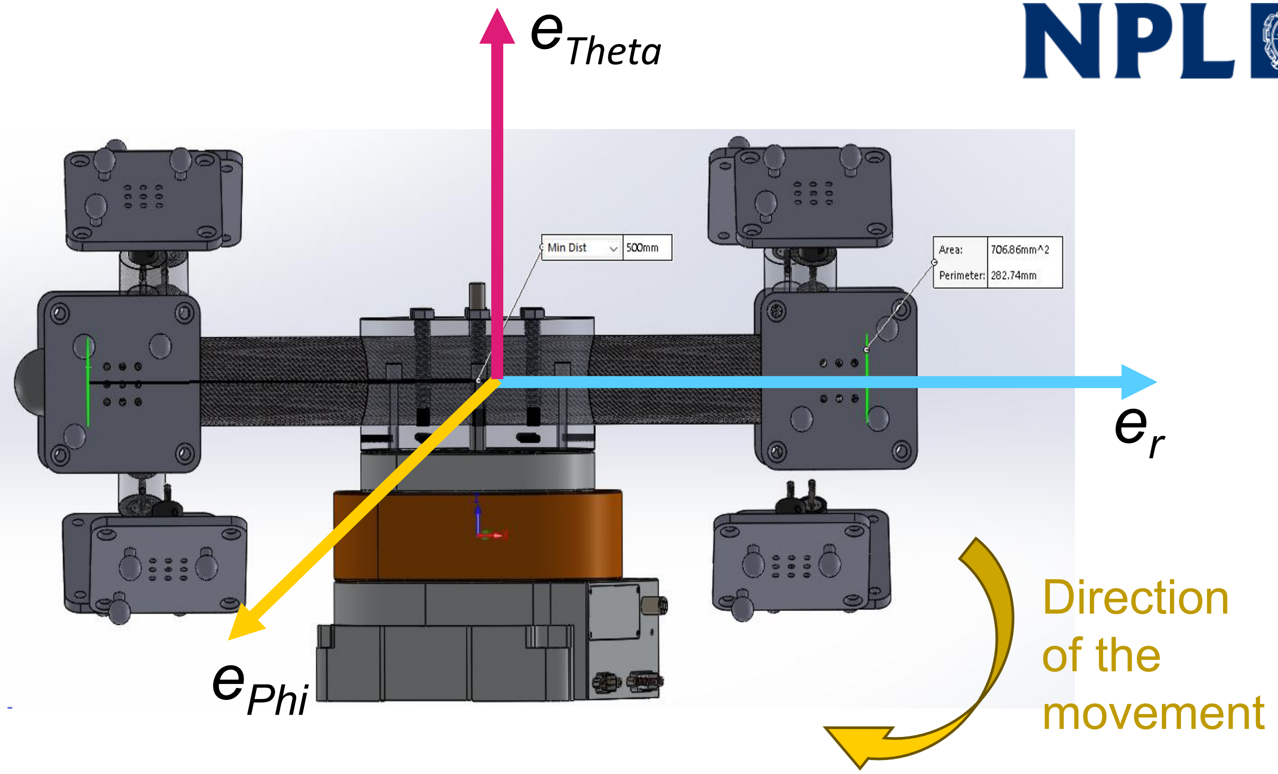
- A **latency is observed** between the motion registered by the encoder and by the IONA.

- Corrected by fitting **an oscillating motion: sine function**.
- An **offset** to be measured :**Δt = -0.4963 ± 0.0038 (95% CI) seconds.**

- This **offset represents temporal latency** between receipt at the DAQ of encoder output from the actuator and pose information from the system under test.
- A **-0.4963 second temporal offset** is assumed **constant** and is used to **align data collection** in the subsequent protocols.

Coordinate system





Axis of Rotation

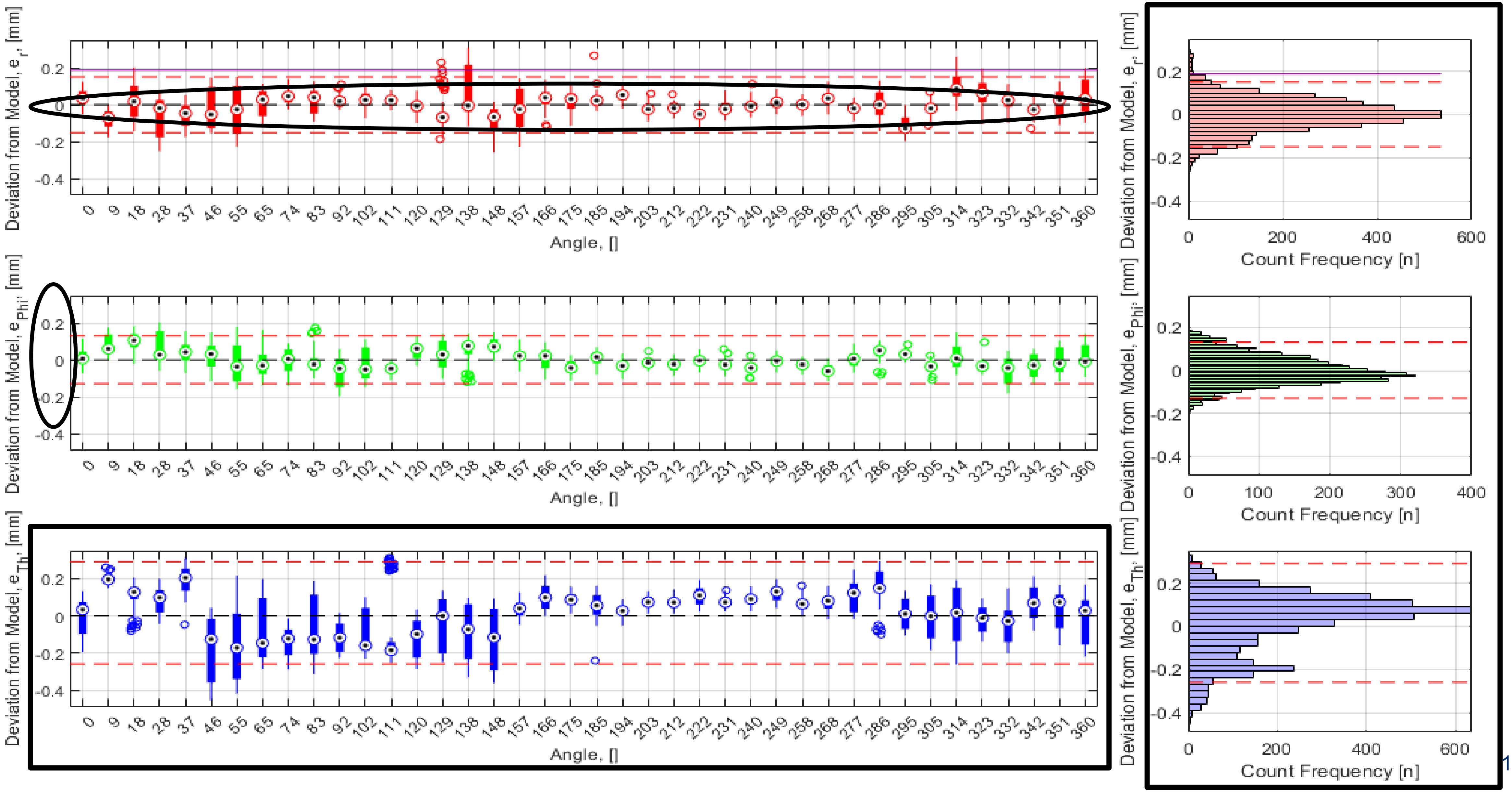
$= P_{AxisGlobal}(x,y,z), \overrightarrow{Axis}(xe_x, ye_y, ze_z)$

$= P_{AxisLocal}(r, Phi, Theta), \overrightarrow{Axis}(e_\theta)$

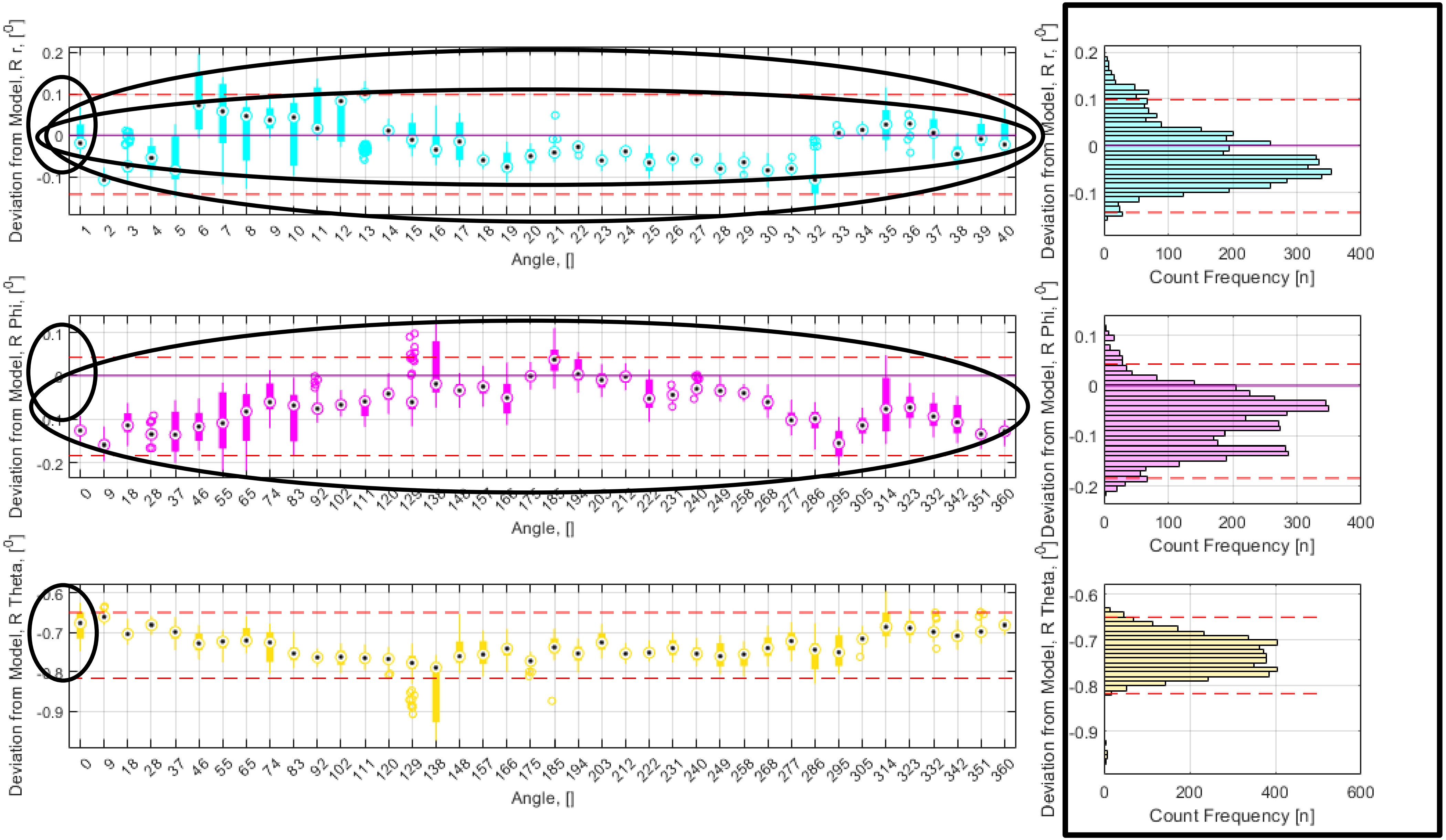
- Data analyse in the intrinsic coordinate system of the path → **spherical coordinate system**
- To transform from Cartesian (x, y, z) to Spherical (r, Phi, Theta) coordinates:

$$\rho = \sqrt{x^2 + y^2 + z^2}$$
$$\theta = \arctan(y/x) \text{ (adjusting for quadrant)}$$
$$\varphi = \arccos(z/r)$$

Stop/Start Protocol: Positional information

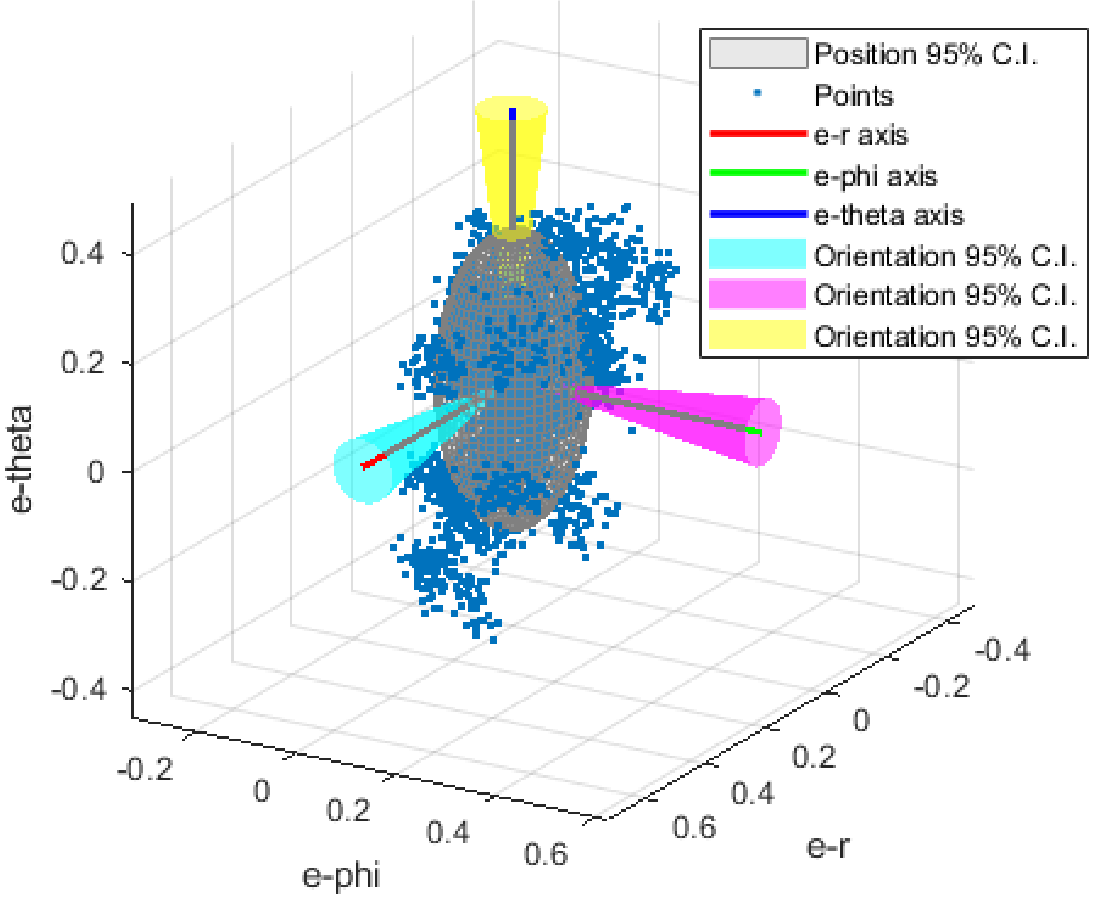


Stop/Start Protocol: Orientation information



Stop/Start Protocol: Positional information

Representation of the uncertainties on the path



*Results in spherical coordinate system

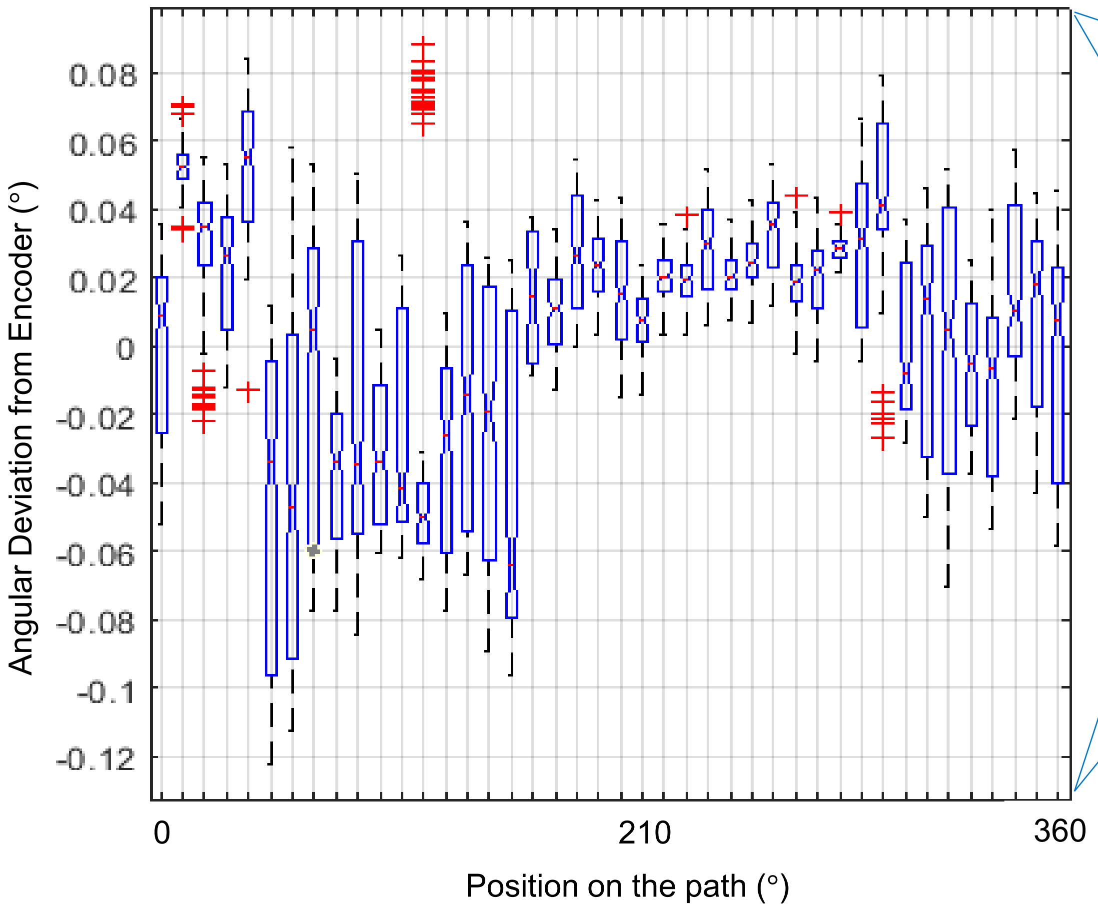
- e_{r} **and** e_{phi} **well clustered around 0.**
- e_{theta} and e_{Phi} might exhibit a structural effect deviating as a function of location on the path.
- The radius $\mathbf{r}$ **is** $\sim$ **0.2 mm smaller than reference values**.

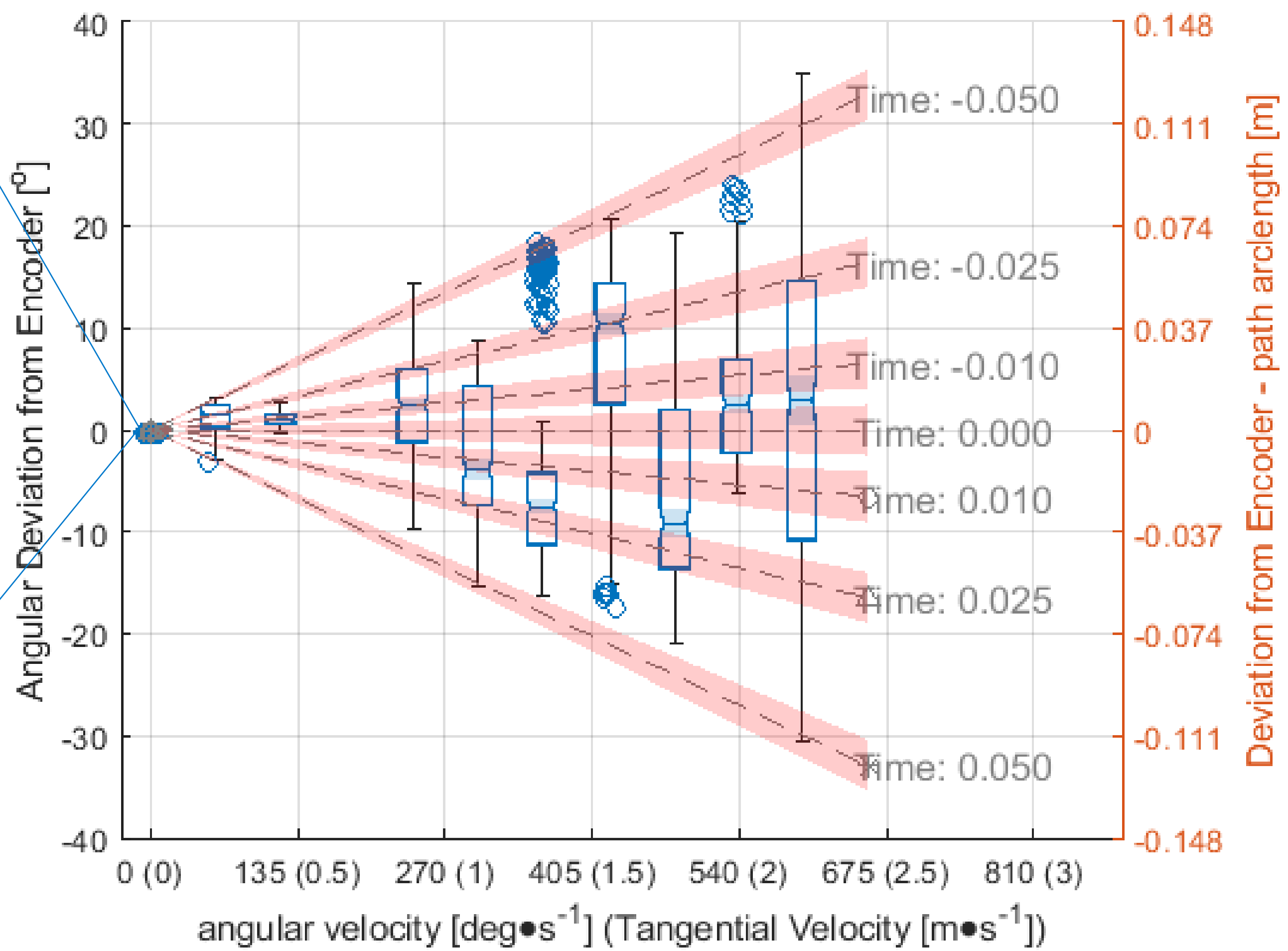
- **Potential scale error in the calibration or system under test**

- R_theta shows **a bias** with values centred **around -0.72°**, also observable with the other constellation → **systematic effect.**

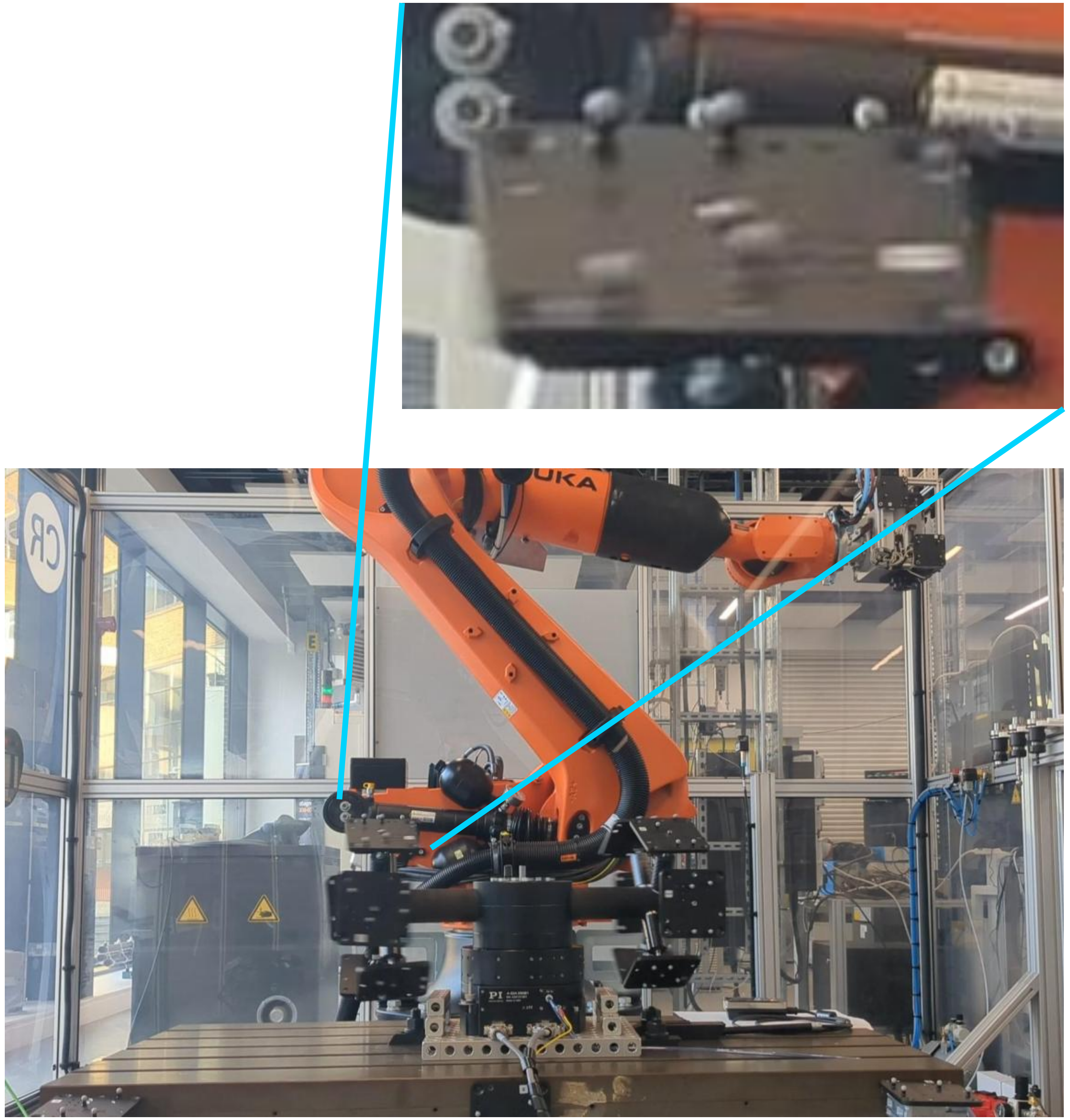
- **Potential target displacement**

Continuous motion protocol





Continuous motion protocol



- Angular deviation from actuator encoder values corresponding to an equivalent temporal latency of **~0.06 seconds.**

- The deviation could be explained by **spatial blurring of the targets if the image capture integration period was of a similar order.**

- **Issues regarding contrast** have been noted related to the adverse **ambient lighting** conditions within the test cell which is located next to a glass external wall.

- **The results may highlight the importance of in situ system optimisation and (re)verification procedures**.

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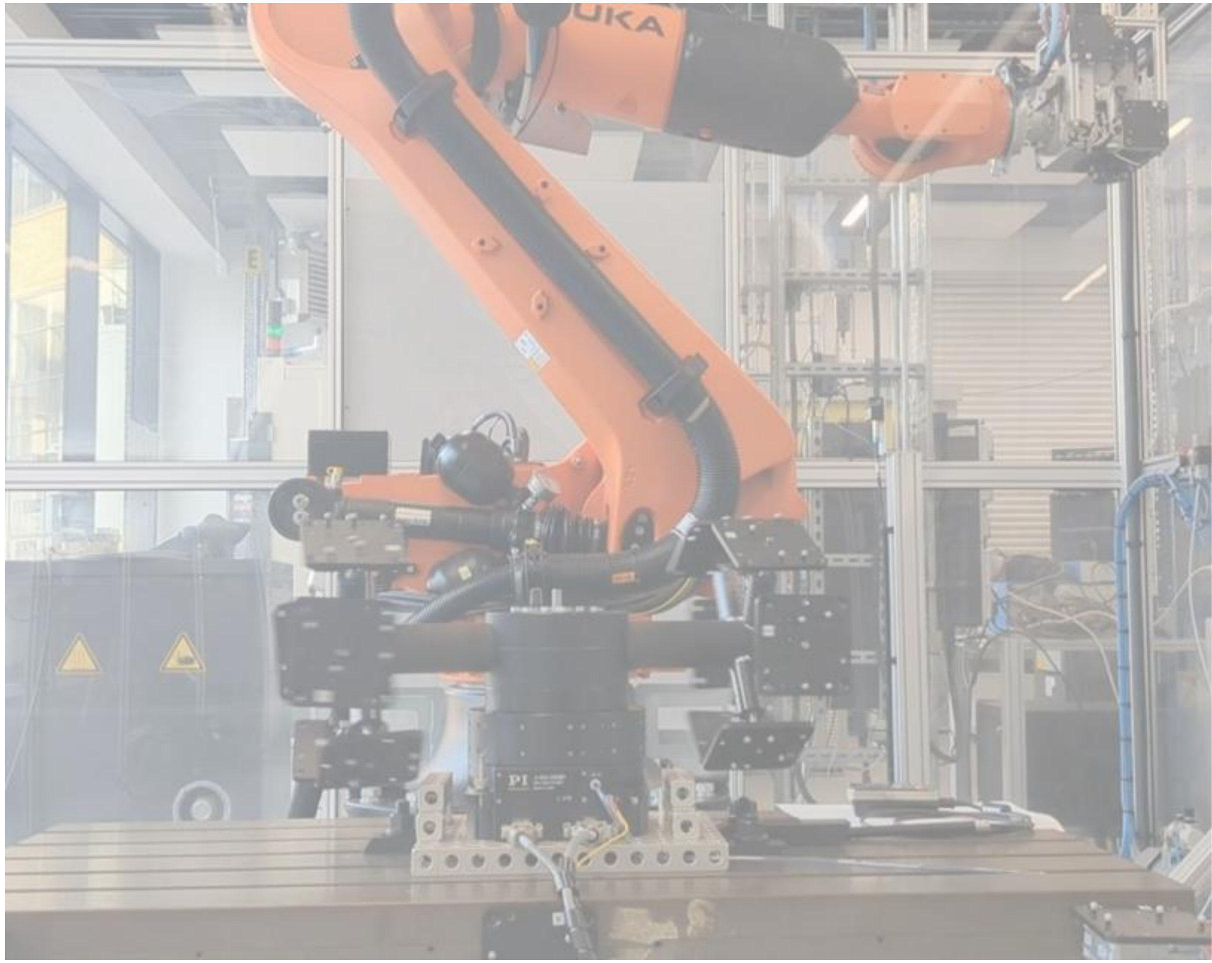

Conclusion

- Identification a critical gap in the present standards landscape:
  - Not technology agnostic framework.
  - Lack of dynamic test method.

- Initial trial with a multi-nodal distance-camera to demonstrate the value and robustness of the approach:
  - Constant latency of ~0.5 s.
  - A velocity-dependent angular error equivalent to ~0.06 s
  - Additional latency at 2.4 m s^{-1}, increasing variance as a function of speed, and spatially non-uniform dispersion around the reference path.

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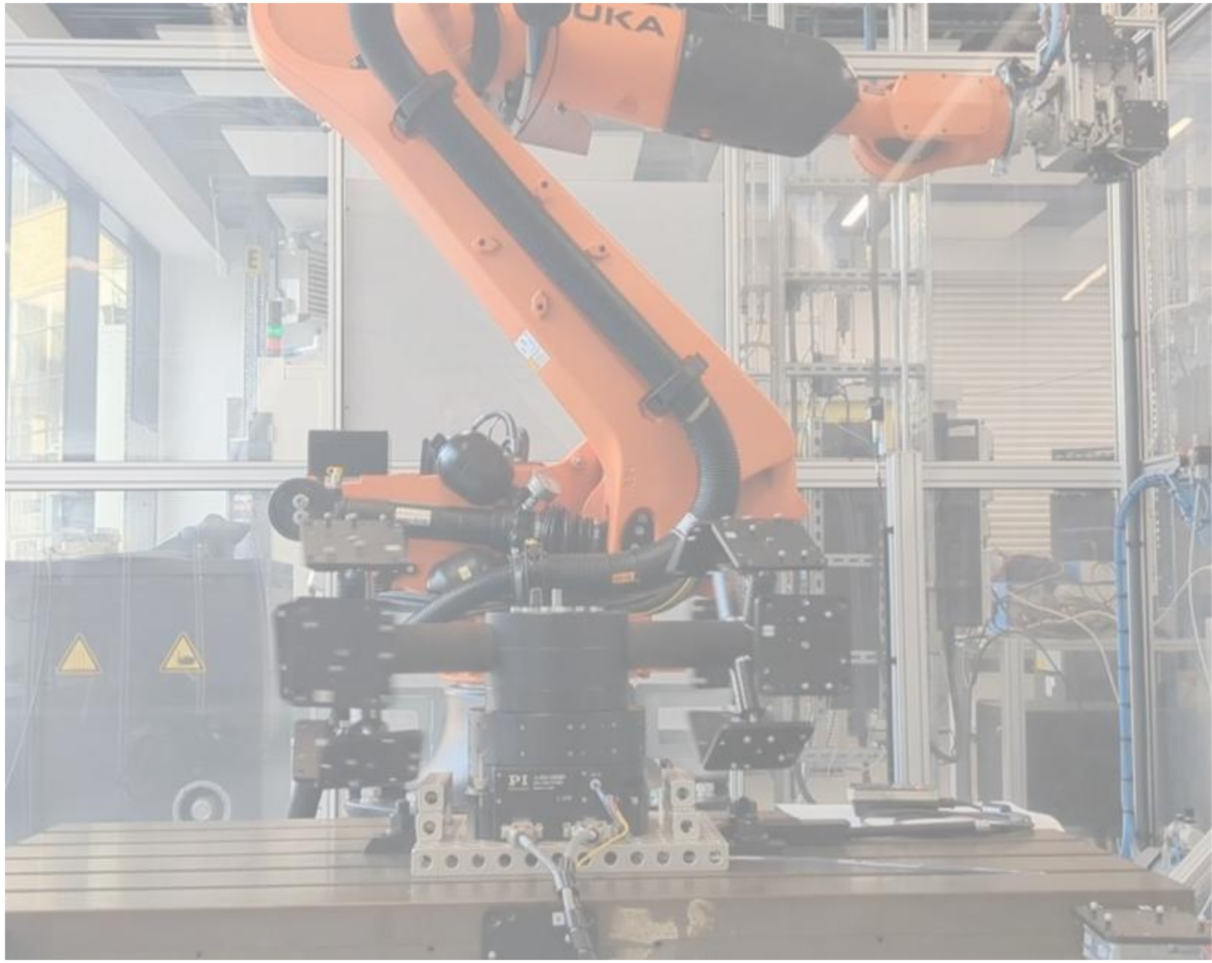
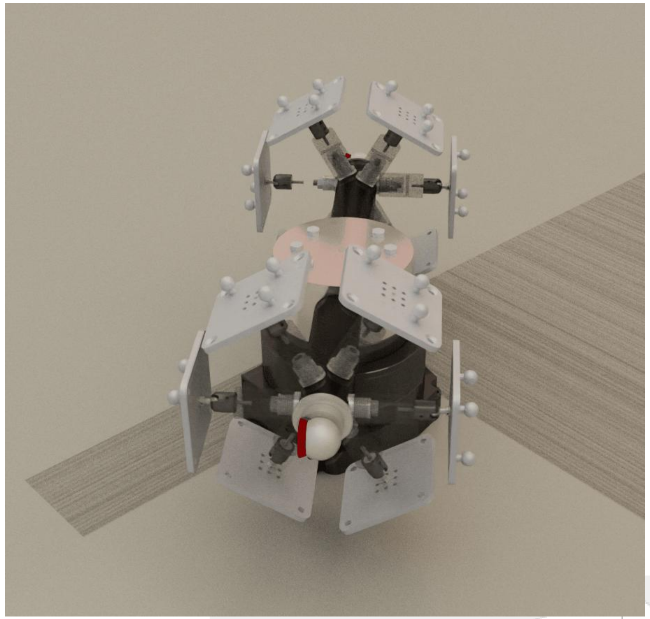
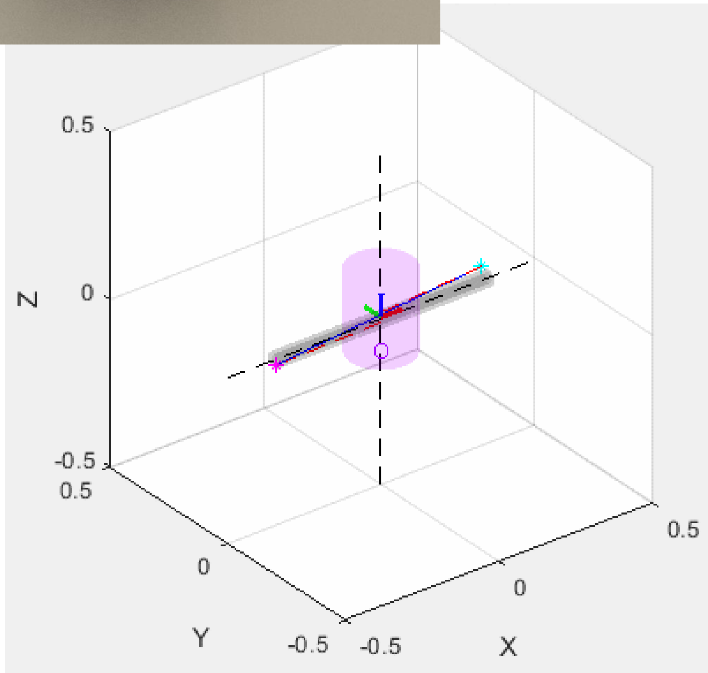


Ongoing Work: Error Modelling

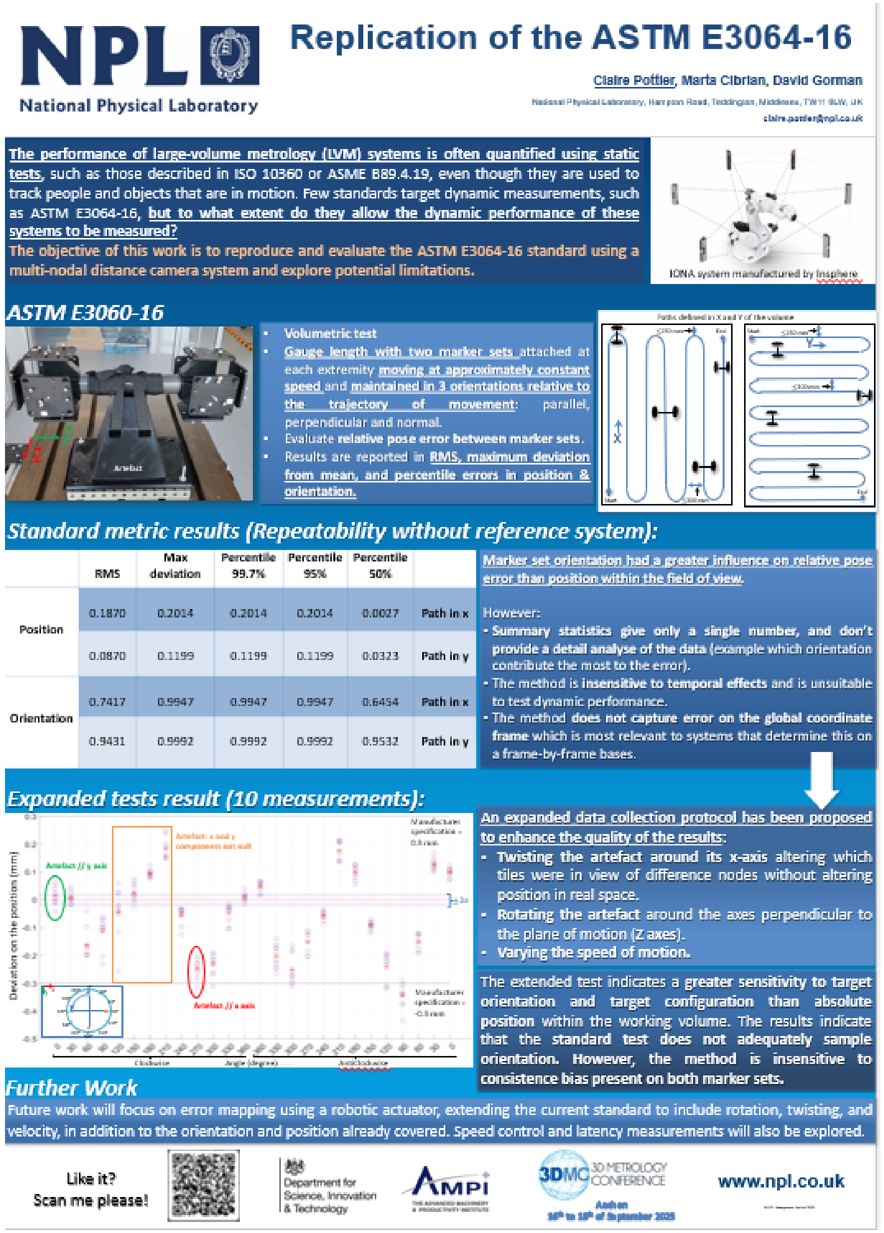
- Uncertainty estimation:
  - Reference Measurement Uncertainty
  - Structural Stability
    - FEA (Ansys Mechanical)
    - Experimentally derived
  - Analytical Uncertainty Model (MATLAB)
    - Dynamic Error Model + Monte Carlo Method
- Scene Modelling (Ansys SPEOS)





Ongoing Work

- Integration of grandmaster time source.
- Run test over lower range of velocities (0 ms-1 – 0.5 ms-1).
- Complimentary lightweight test(s): See Poster for more explanation.
- Stakeholder engagement: Running the test at other facilities, on other LVM systems (Vicon for example).



National Physical Laboratory

Replication of the ASTM E3064-16

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The performance of large-volume metrology (LVM) systems is often quantified using static tests, such as those described in ISO 10360 or ASME B89.4.19, even though they are used to track people and objects that are in motion. Few standards target dynamic measurements, such as ASTM E3064-16, but to what extent do they allow the dynamic performance of these systems to be measured?

The objective of this work is to reproduce and evaluate the ASTM E3064-16 standard using a multi-nodal distance camera system and explore potential limitations.

IONA system manufactured by Insphere

ASTM E3060-16

- Volumetric test
- Gauge length with two marker sets attached at each extremity moving at approximately constant speed and maintained in 3 orientations relative to the trajectory of movement: parallel, perpendicular and normal.
- Evaluate relative pose error between marker sets.
- Results are reported in RMS, maximum deviation from mean, and percentile errors in position & orientation.

Paths defined in X and Y of the volume

Standard metric results (Repeatability without reference system):

	RMS	Max deviation	Percentile 99.7%	Percentile 95%	Percentile 50%	
Position	0.1870	0.2014	0.2014	0.2014	0.0027	Path in x
	0.0870	0.1199	0.1199	0.1199	0.0323	Path in y
Orientation	0.7417	0.9947	0.9947	0.9947	0.6454	Path in x
	0.9431	0.9992	0.9992	0.9992	0.9532	Path in y

Marker set orientation had a greater influence on relative pose error than position within the field of view.

However:
- Summary statistics give only a single number, and don't provide a detail analyse of the data (example which orientation contribute the most to the error).
- The method is insensitive to temporal effects and is unsuitable to test dynamic performance.
- The method does not capture error on the global coordinate frame which is most relevant to systems that determine this on a frame-by-frame bases.

Expanded tests result (10 measurements):

An expanded data collection protocol has been proposed to enhance the quality of the results:
- Twisting the artefact around its x-axis altering which tiles were in view of difference nodes without altering position in real space.
- Rotating the artefact around the axes perpendicular to the plane of motion (Z axes).
- Varying the speed of motion.

The extended test indicates a greater sensitivity to target orientation and target configuration than absolute position within the working volume. The results indicate that the standard test does not adequately sample orientation. However, the method is insensitive to consistence bias present on both marker sets.

Further Work

Future work will focus on error mapping using a robotic actuator, extending the current standard to include rotation, twisting, and velocity, in addition to the orientation and position already covered. Speed control and latency measurements will also be explored.

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Actual Path:

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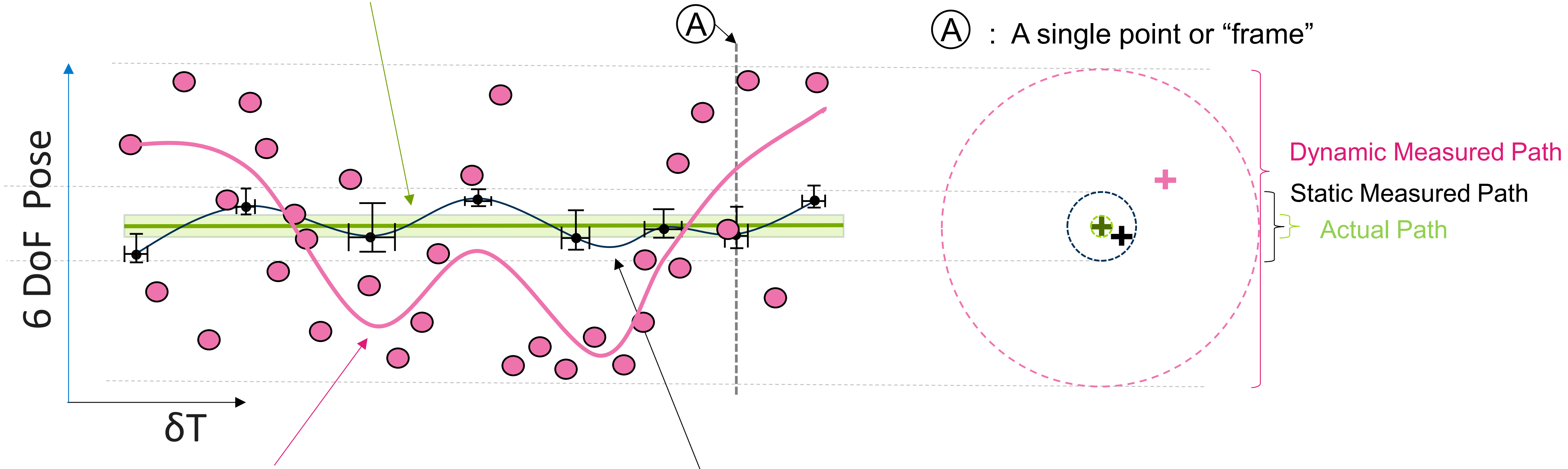

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