

## Generalised test for evaluating the performance of large volume metrology systems when measuring objects in motion

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### Abstract

Traditional robotic manipulators are proficient at performing repeat tasks in controlled environments, but limitations including kinematic description fidelity, task (re)programming burden, and complex validation and calibration requirements reduce their operational flexibility. Increasingly sophisticated guidance and control methods are becoming available that broaden the range of automatable tasks, and which could drive productivity gains across industries that do not yet benefit from wide scale automation. One such method involves the integration of external distributed large-volume metrology systems (DLVM) into the control loop. These systems are capable of simultaneously measuring multiple targets in six degrees of freedom (6 DoF) whilst overcoming occlusion issues inherent in single node methods. The ability to track several objects over large working envelopes within a single coordinate frame allows the creation of control zones in which generalist robotic actuators can perform precision operations. Current applications include stop/start processes such as assembly, however, with the addition of motion these operations could be expanded to include dynamic processes such as welding, spraying, or machining. This paper introduces a technology agnostic test method that provides static and dynamic performance evaluation within a single framework thereby addressing gaps in the existing standards landscape.

Keywords: distributed large-volume metrology; dynamic accuracy; latency; compliant robots; standardisation

### 1 Introduction

The feasibility of using low measurement frequency external metrology systems to improve robot accuracy has been demonstrated, for example utilising adaptive Kalman filter sensor fusion methods [1]. However, although multiple standards exist across dimensional metrology, motion tracking, indoor positioning, robot guidance, and machine tool accuracy, there is no harmonized, technology-agnostic, standard that fully encompasses the unique challenges of 6 DoF DLVM systems for dynamic applications. The absence of this standard is a barrier to the adoption of external metrology for dynamic applications [2].

A method to facilitate third-party certification, (re)verification, and (re)acceptance testing will be presented. The test establishes the position and orientation of a target or constellation of targets with respect to location on a path. The location of the targets on that path at a given time is known to high degree of accuracy. The output of the DLVM system is then compared against this established ground truth with errors reported in the intrinsic co-ordinates of the path.

### 2 Methodology

#### 2.1 Equipment

Reconfigurable target constellations are mounted on spokes around a carbon-fibre tube clamped to a precision Pglide RM Rotation Stage with Air Bearing and absolute optical encoder as shown in Figure 1. Encoder angle  $\phi$ , combined with traceable CMM calibration to determine constellation centroids and the axis of rotation, define a location on a circular path. In the presented configuration the radius of the constellation centroid is  $\sim 0.25$  m. Determination of the static position of the actuator

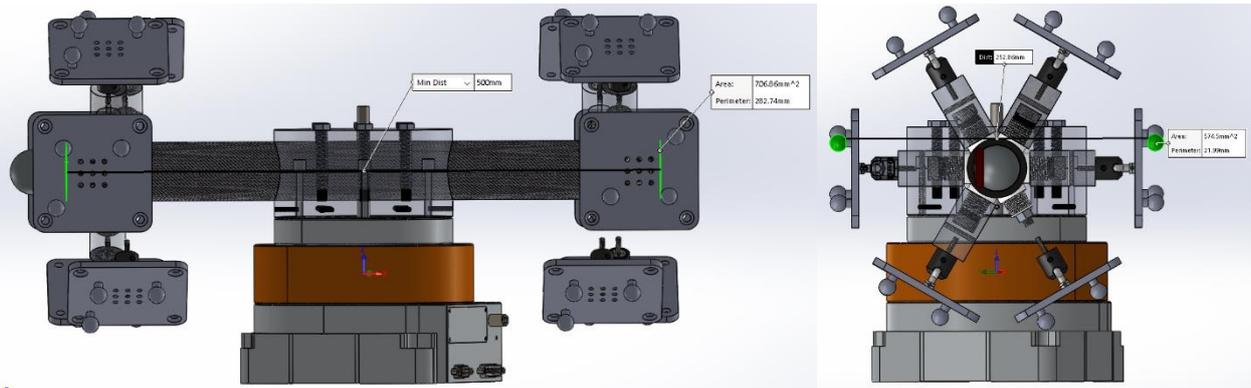
within the working volume establishes the transformation between the global coordinate system and the intrinsic coordinates of the circular path in 6-DoF.

#### 2.2 Data-collection and Processing

Data is streamed off the rotation actuator via EtherCAT network to a data acquisition computer with time supplied via a GNSS synchronised grand master clock, Thunderbolt 330, using precision timing protocol with 5ns (1-sigma) temporal stability. Data is telegraphed by the system under test using the vendors preferred method, e.g. MQTT, and captured using data acquisition computer (DAQ). The test includes three data collection protocols.

Protocol 1 – Oscillation ( $\pm 5^\circ$ ): phase difference between the sinusoidal motion measured by the encoder and the system under test allows for the determination of a consistent temporal offset if present. Even if the DAQ and system under test are synchronised, this protocol allows direct measurements of residual latency that can arrive from delayed between data capture events and time stamping.

Protocol 2 – Stop-measure-move: samples a reference path in the coordinate frame of the system under test and maps static volumetric error as a function of encoder value. A reference path is determined by interpolation between the discrete statically measured points. Interpolation is performed by fitting a circular model or, alternatively if the measurement values deviate from expected tolerance, by fitting a spline. The intrinsic coordinates of the path are spherical polar ( $e_r, e_\theta, e_\phi, R_r, R_\theta, R_\phi$ ) where  $e_r$  is the radius vector,  $e_\theta$  is parallel to the axis of rotation, and  $e_\phi$  is tangential to the circular path collinear with the vector of



**Figure 1** CAD representation of the reconfigurable rotating artefact and the actuator

motion. Uncertainty represented as the 95% confidence interval on dispersion around the path in 6 DoF.

Protocol 3 – Continuous motion: repeats the rotational motion at discrete angular velocities up to a maximum tangential speed of  $2.5 \text{ m s}^{-1}$ . Results are reported as a deviation from the reference path in the intrinsic coordinates of the path.

### 3 Results

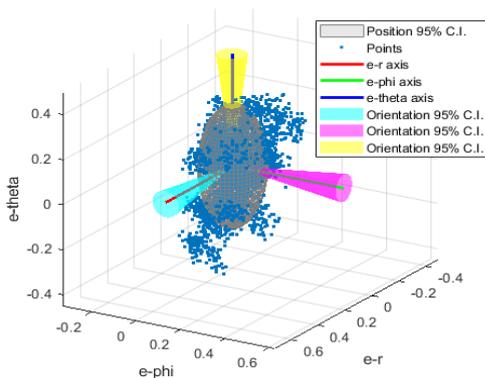
The focus of this work was to develop a test methodology. The results are therefore preliminary and only indicative of the information reported by the test. They are not yet a true reflection of the performance of the system under test.

#### 3.1 Temporal Offset: Oscillation Protocol

Measure constant latency  $\Delta t$  (observed  $-0.496 \pm 0.004 \text{ s}$ ) at the point of data receipt. Latency is an important metric for implementing control. Other metrics include packet loss and temporal stability relative to the grandmaster. They are the subject of ongoing work.

#### 3.2 Reference Path : Stop-Measure-Move Protocol

The path was well described by a circular model though some structural effects were present. *Figure 2* shows the 95% c.i. on the circular path. A scale error of 0.2 mm was identified which manifests as a consistent and significant bias from expected radius. An orientation bias of  $0.7^\circ$  was also observed in  $R_\theta$  and believed to come from misalignment of the targets. Dispersion in the position ( $e_r, e_\phi$ ) was  $\pm 0.15 \text{ mm } k=2$ , and  $e_\theta \pm 0.2 \text{ mm } k=2$ .

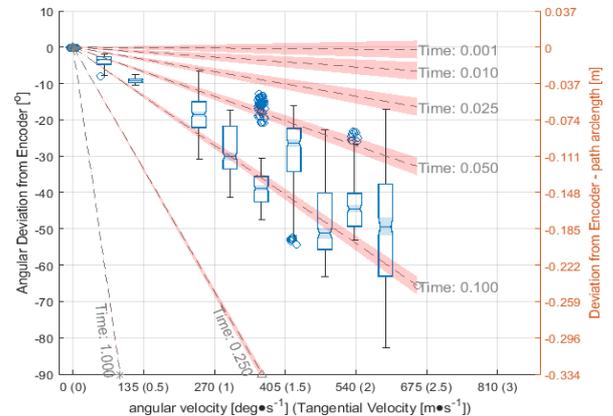


**Figure 2** Graphic representation of static measurements plot in the intrinsic coordinates of the path with encoder angular position subtracted from the measured angular position. The representation of orientation 95% C.I. has been amplified by a factor of 100 so as to be observable.

#### 3.3 Dynamic Performance: Continuous Motion Protocol

For clarity, the influence of motion has been expressed as deviation from encoder value in degrees and arc length. A consistent bias of  $\sim 0.75$  seconds is observed with dispersion also increasing with rotational speed. The increase in dispersion

could be explained by temporal jitter which could have been in the order of 10s of milliseconds. Work is ongoing to characterise and minimise this error source.



**Figure 3** CAD representation of the rotating artefact

### 4 Evaluation

The test can accommodate a variety of technologies and systems that are both strongly and weakly integrated with respects to synchronisation. The preliminary results are encouraging, however, more rigor is required to identify the contribution of and control for influence factors, e.g. temperature, with modelling and physical testing ongoing. Data analysis is also ongoing to deconvolve spatial and temporal sources of error.

The 0.2 mm deviation in radius was likely caused by calibration error and distortion during transportation. New procedures have been implemented to perform artefact calibration in-situ using an articulated arm CMM. The optional adjustable spokes are being exchanged for monolithic supports.

Targets metrics for ongoing work include; Dynamic Range ( $0.01\text{-}3 \text{ ms}^{-1}$ ), Occlusion-resilience Index, sensitivity to position and orientation within the field of view, sensitivity to target configuration, and technology specific factors e.g. ambient lighting, noise, or vibration.

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### 5 References

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