

# METROLOGY ENHANCED TOOLING FOR AEROSPACE (META): A LIVE FIXTURING, WING BOX ASSEMBLY CASE STUDY

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## ABSTRACT

Aerospace manufacturers typically use monolithic steel fixtures to control the form of assemblies; this tooling is very expensive to manufacture, has long lead times and has little ability to accommodate product variation and design changes. Traditionally, the tool setting and recertification process is manual and time consuming, monolithic structures are required in order to maintain the tooling tolerances for multiple years without recertification. As part of a growing requirement to speed up tool-setting procedures this report explores a coupon study of live fixturing; that is, automated: fixture setting, correction and measurement. The study aims to use a measurement instrument to control the position of an actuated tooling flag, the flag will automatically move until the Key Characteristic (KC) of the part/assembly is within tolerance of its nominal position. This paper updates developments with the Metrology Enhanced Tooling for Aerospace (META) Framework which interfaces multiple metrology technologies with the tooling, components, workers and automation. This will allow rapid or even real-time fixture re-certification with improved product verification leading to a reduced risk of product non-conformance and increased fixture utilization while facilitating flexible fixtures.

## KEYWORDS

Dimensional Metrology, Measurement, Tooling, Fixture, Assembly, META

## 1. BACKGROUND

In the wider community tooling can include a wide spectrum of tools, in the context of this paper tooling is used to refer to *Assembly Tooling*, this encompasses both *Jigs* and *Fixtures*.

Monolithic aerospace assembly fixtures consist of large traditional steel structures configured for a single aircraft. For stability, the tooling is secured to the reinforced-concrete factory floor. This

traditional build philosophy controls all the features by: common jig location, master jig datum, jig setting, certification points, build slips and pin diameters. The positional, dimensional and geometric accuracy of the assembly is implied from the tooling. That is to say, if the tooling is correct and the components are positioned correctly within the tooling, then the assembly is correct. These mechanical metrology checks ensure tolerances are maintained.

Verification involves manually rotating pins and moving slips to ensure that the assembly is correctly positioned and held within the fixture. However, the combined tolerance of the fixture and location pins/slips must be less than the assembly tolerances; ideally <10% although this is rarely possible at the wing assembly scale; often the design tolerances are <300 $\mu$ m over 30m. Subsequently, tooling is built to a tolerance of around 150 $\mu$ m, consuming up to 50% of the assembly tolerance budget. Next Generation Composite Wings (NGCW) hold new challenges as the composite materials cannot be reworked easily if concessions are identified. Consequently, more accurate assemblies - and therefore assembly fixtures - will be required. These requirements will further drive up the cost of traditional fixtures.

In addition, the size and complexity of fixtures means that they typically have construction lead times in excess of 6 months making late design changes or the employment of concurrent engineering a challenge. It is estimated that assembly tooling accounts for approximately 5% of the total build cost for an aircraft (Rooks, 2005) or 10% of the cost for the air frame (Burley et al, 1999). Fixture manufacture times and non-recurring costs (NRCs) could be reduced if assembly fixtures moved away from traditional *hard* tooling and moved towards *soft* tooling, that is: away from large, rigid structures and towards reconfigurable and flexible tooling. A strong measurement platform and infrastructure is required to maintain the required tolerances within the tooling and the assembly process.

## 2. INTRODUCTION

The key requirement for large-scale assembly is to overcome the constraints associated with the physical size of products and assemblies and the corresponding dimensional and form tolerances (Maropoulos et al, 2008). Advances in large volume metrology are increasingly important in order to achieve this; subsequently the realisation of metrology enhanced tooling will become possible.

### 2.2. METROLOGY ENHANCED TOOLING FOR AEROSPACE (META)

Gauge-less and fixture-less manufacture are reliant on the exploitation of advanced metrology in the dimensional inspection and monitoring of the tooling, components and assemblies. Firmly embedded metrology systems within the manufacturing processes are still not a reality as most systems are outside of the tooling, and not *embedded* within it. Metrology-assisted robotic processes are being developed within manufacturing cells with an emphasis on assembly, and not

conventional automated drilling processes (Jayaweera and Webb, 2010). In order to place metrology systems within the control loop of a manufacturing cell prerequisites such as: autonomous operation, high reliability, high speed measurement, and flexibility are paramount (Gooch, 1998). This exploitation of technologies is stifled due to the lack of integration with core design and assembly processes.

The future of metrology enhanced tooling relies on the effective synergy of complimentary interfaces accommodated by a strong software platform. These hybrid systems could utilise many metrology technologies, for example: a macro coordinate system could be set-up using photogrammetry or a network of lasers – this would effectively surround and monitor key characteristics of the tooling. Localised metrology could sit within this larger metrological environment – laser radar, portable co-ordinate measurement machines (PCMMs), actuators, sensors, arms, scanners, etc. – providing fine measurement of difficult features, freeform surfaces, tooling pick-ups, part location and verification. Potentially this environment could provide the prerequisite of any automation attempt, determining the sources and magnitude of any dimensional variations of the components that are currently being experienced during the manual assembly stage (Saadat and Cretin, 2002). Figure 1 gives an overview of the Metrology Enhanced Tooling Aerospace (META) environment introduced by Martin et al (2010).

The META framework's primary function is to monitor the key characteristics of the tooling and assembly requiring a real-time or quasi-real-time metrology system – ensure the *fixture condition*. This monitoring eliminates the need to recertify fixtures periodically removing the need to take the fixture out of production – current practice can take weeks to recertify and rework a fixture, causing down time that will have increasing impact as production rates increase. Secondary functions - *Enhanced Processes* - such as 'live' tooling do not require real-time feedback as the movements can be iterative, unlike a machining operation. Machining operations and automation where an iterative loop is not appropriate must run directly from information fed from the instrument – for example a laser tracker – and not through the core software.

The META framework's tertiary function is the collection of information. This information could not only enhance the tooling and assembly during operation, but begin a large scale data collection for the use of SPC, providing learning for future optimization of the assembly processes.

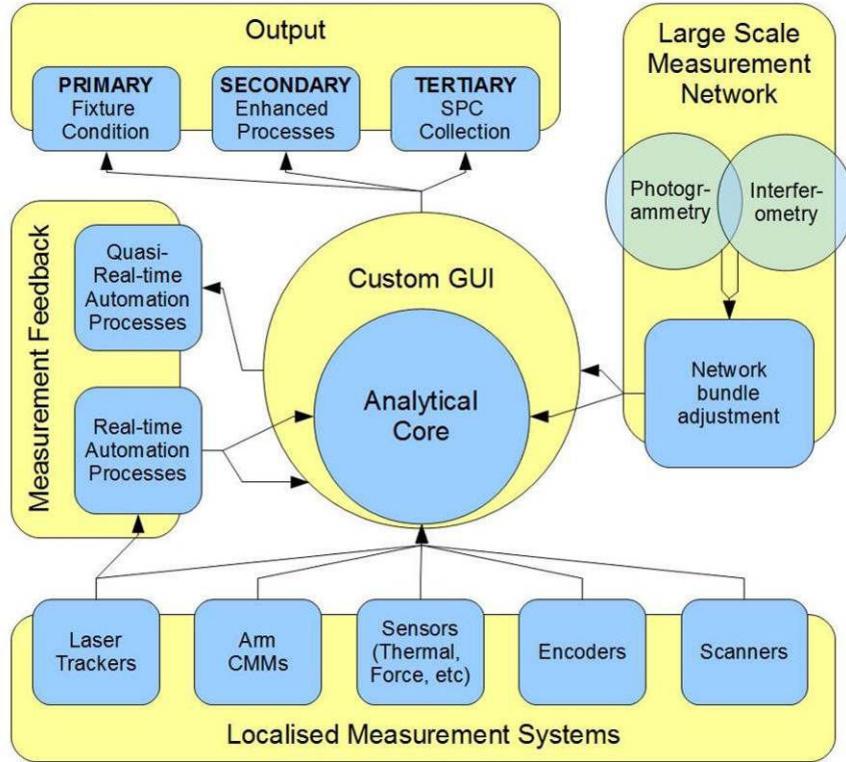


Figure 1 - META Framework Overview

## 2.2. DATA FUSION

The META framework relies on instrument networks for a number of reasons, mainly: reducing measurement uncertainty, increasing the measurement volume and providing complementary technologies to enhance data collection. Due to the expense of measurement instruments, instrument networks can be performed by roving or multi-hop systems using a single instrument many times. Instrument hardware networks have many challenges; using the data from each instrument in the most efficient way is paramount. As different instruments have differing strengths – data management has to have an awareness of such attributes and respond appropriately. Multi-sensor data fusion is a method for centrally combining and processing data from a number of different sensors (Huang et al, 2007). The data fusion can be described as either: complementary, competitive and cooperative (Durrantwhyte, 1988). Complementary if sensors are independent but can offer additional information by complementing other another; competitive if the sensors are independently measuring the same area/targets in order to eliminate random error and reduce measurement uncertainty; and co-operative sensors are independent but different from each other and the combination of sensors provides a level of information that each sensor cannot achieve alone. Within dimensional metrology, examples of such

multi-sensor data fusion include: field of image fusion, tactile and optical coordinate metrology, coherent and incoherent optical measuring techniques, computed tomography and scanning probe microscopy (Weckenmann et al, 2009). It is likely that the future of multi-sensor data fusion will become increasingly important as higher levels of integration with fast processing speeds become a necessity for full field - large volume metrology and automation.

## 3. CASE STUDY: FIXTURE AUTOMATION

This paper looks at the *Secondary Function* of the META framework, metrology as an enabler of ‘live’ fixtures, as part of a growing requirement to speed up tool-setting procedures; that is, automated: fixture setting, correction and measurement. The case study aims to use a measurement instrument to control the position of an actuated tooling flag, the flag will automatically move until the Key Characteristic (KC) of the part/assembly is within tolerance of its nominal position. This reduces the measurement uncertainty stack-up associated with constructing and employing tooling held tolerances; effectively the tolerance budget is only occupied by the instrument’s uncertainty and not the manufacturing tolerances of the fixture. In the META framework the measurement can focus on assembly/component and *not* the fixture.

In the case of this study the actuated flag is a Hexapod from Physik Instrumente (PI) and the KC is the hinge line axis that runs through the hinge bracket's bore. This trial was carried out concurrently with the Airbus Tooling Hub activities, based at the University of Nottingham.

### 3.1. HEXAPOD LOCATION

The methods used to build the trial fixture (Figure 2) cannot perfectly align the native co-ordinate frame of the hexapod (Figure 3) to the jig co-ordinate frame; aligning these frames accurately would be a time consuming and laborious exercise. A more robust and quicker method is to identify the location and orientation of the hexapod's frame and transform the relevant information into the jig co-ordinate system when required; if calculations are completed with an appropriate degree of accuracy no loss of information will occur when changing from frame-to-frame. This method allows the hexapod to be approximately placed in its nominal position without considering the hexapod's position and orientation. This speeds up the tool setting processes – making reconfiguration fixtures quicker. However, in order to manipulate the hexapod into its CAD nominal position, firstly the hexapod's native co-ordinate frame must be defined relative to the jig axis system.

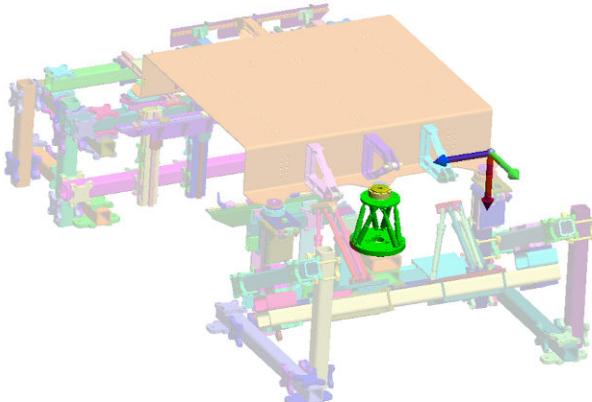


Figure 2 - Location of study on the demonstration fixture; highlighted: the jig's co-ordinate frame



Figure 3 - Native hexapod co-ordinate frame in its CAD nominal position

The hexapod is moved to the extreme of each axis in isolation using PI's proprietary software interface (Figure 4); each axis extremity is measured using a *Leica AT901* laser tracker and *New River Kinematic's: SpatialAnalyzer* (SA). This enables the definition of the working envelope ( $x=50mm$ ,  $y=50mm$ ,  $z=25mm$ ) and the creation of the physical, native co-ordinate frame of the hexapod relative to the fixture's co-ordinate frame. Subsequently, the hexapod can be manoeuvred into its CAD nominal position by obtaining the translations  $[x, y, z]^T$  and rotations  $[\alpha, \beta, \gamma]^T$  from the SA function: *compare to CAD*. This method is consistent with the fixture build philosophy used for the construction of the fixture. In turn the physical location of hexapod's frame can be compared to the CAD nominal location of the hexapod frame (Figure 5). The transformation matrix from native to CAD nominal (Equation-1) gives us the offsets required to reach the intended CAD nominal position.

This is a specific transformation matrix that uses the sequence: rotate about  $x$  ( $\alpha$ ), followed by  $y$  rotation ( $\beta$ ), then rotated about  $z$  ( $\gamma$ ), finally, performing a translation in  $x$ ,  $y$ ,  $z$ ; this is the sequence that the SA software uses.

$$T = \begin{bmatrix} \cos \alpha \cos \beta & \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & x_t \\ \sin \alpha \cos \beta & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & y_t \\ -\sin \beta & \cos \beta \sin \gamma & \cos \beta \cos \gamma & z_t \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

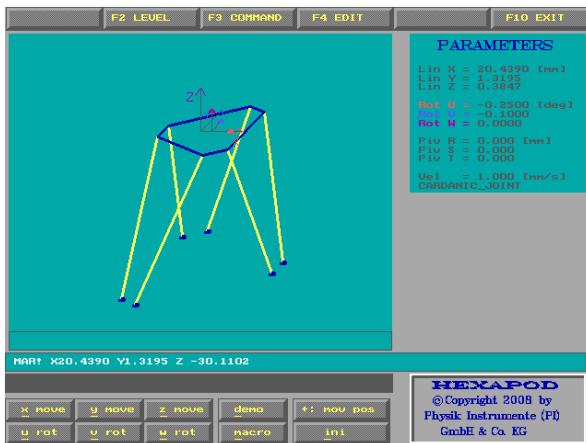


Figure 4 - PI hexapod controller interface

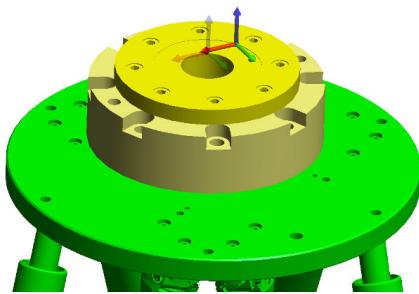


Figure 5 - Actual position of the Hexapod's native co-ordinate frame

### 3.2. HEXAPOD COMMUNICATION AND CONTROL

The measurement information from the laser tracker is continuously streamed into SA. SA converts the native spherical co-ordinates from the laser tracker to the Cartesian co-ordinates required for the hexapod control. This post-processed data is streamed via a User Datagram Protocol (UDP) to a bespoke program created by the University of Bath (UoB); designed to bridge the interface gap between the PI hexapod interface and SA. The UoB interface program (Figure 6) samples the UDP data stream, checks whether the KC is within tolerance, sends the required corrective movement to the hexapod and checks whether the hexapod is stationary before cycling again. The communication paths between the hardware and software are shown in Figure 7. The program also enabled the control of a selection of parameters, such as: the tolerance threshold, hexapod velocity, enabling and disabling the hexapod's degrees of freedom and closed or open loop control.

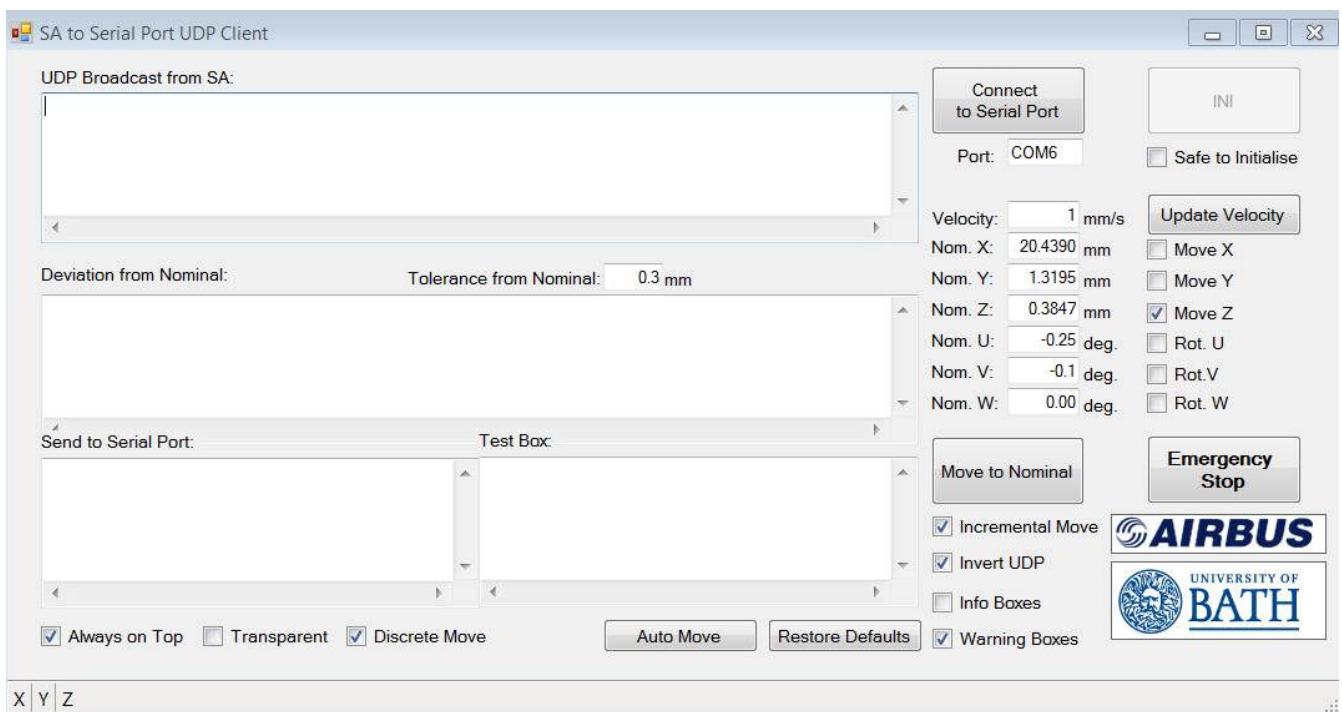


Figure 6 - UoB SA - Hexapod interface software

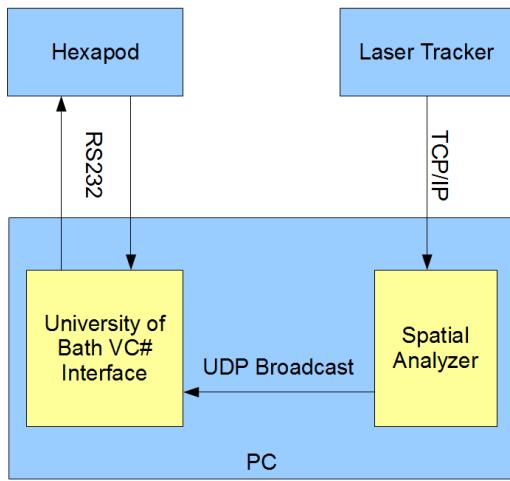


Figure 7 - Schematic of hardware/software communication

### 3.3. METROLOGICAL FEEDBACK

The metrology requirement is to measure the deviation from the hinge bracket's bore to its nominal CAD position; the hexapod will move, attempting to reclaim the hinge line's CAD nominal position. The hexapod is attached to the spar via a *zero point clamp* (Figure 8), there is a substantial offset from the point of attachment to the point of interest (POI) (Figure 9) between hexapod and the POI are compliant connective elements: zero point clamp, spar, hinge bracket and vector bar. As the relationship between the hexapod and the POI cannot be considered as a rigid body the metrology feedback will have to be in a closed loop (Figure 10); if however there was a rigid relationship or a predictable relationship between the movement of the hexapod and the POI, the PI hexapod is inherently accurate enough to support an open loop system - this is quicker and less resource intensive (Figure 11). An open loop system is advantageous when considering measurement resources and time; a closed loop system requires continuous measurement, whereas an open loop system requires a single measurement. If many POIs require measurement and actuation, closed loop systems are *bottlenecked* by the metrology resource, this

happens to a much lesser extent with an open loop system; as the measurement system can sequentially measure each POI without stopping.

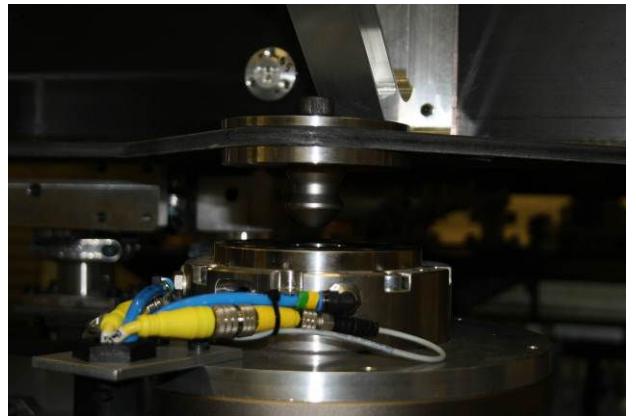


Figure 8 - Close up of the Zero point clamp

Figure 9 highlights the hexapod's native co-ordinate after the origin has been translated to the POI; it follows that measurements taken from this new co-ordinate frame are essentially deviations from the POI's nominal position. Consequently, the co-ordinates - and hence the deviations from nominal - are streamed from SA via the UDP.

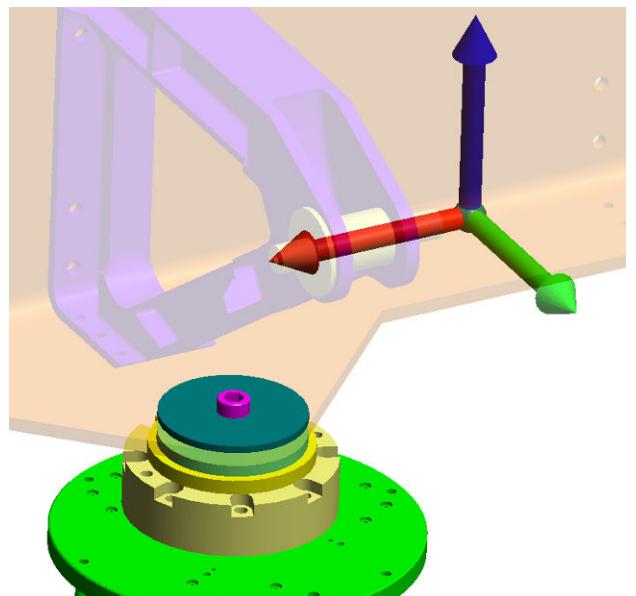


Figure 9 - Hexapod's native co-ordinate frame after transformation to CAD nominal position of hinge line axis

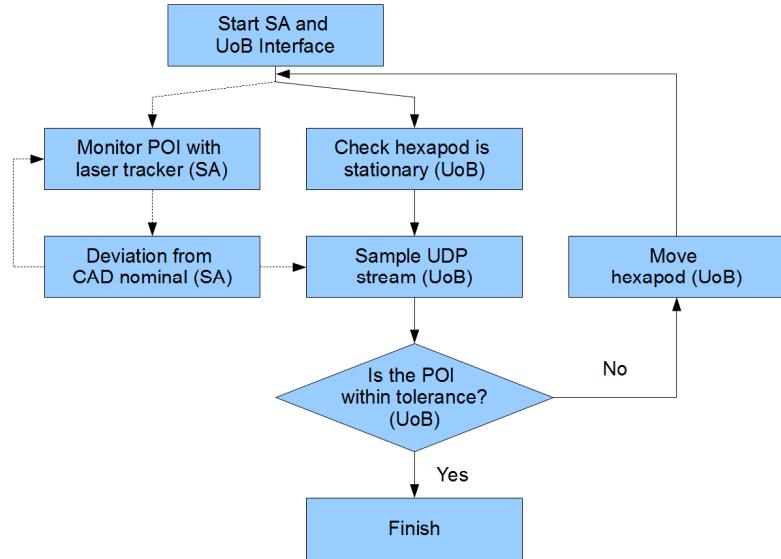


Figure 10 - Closed loop control of fixture

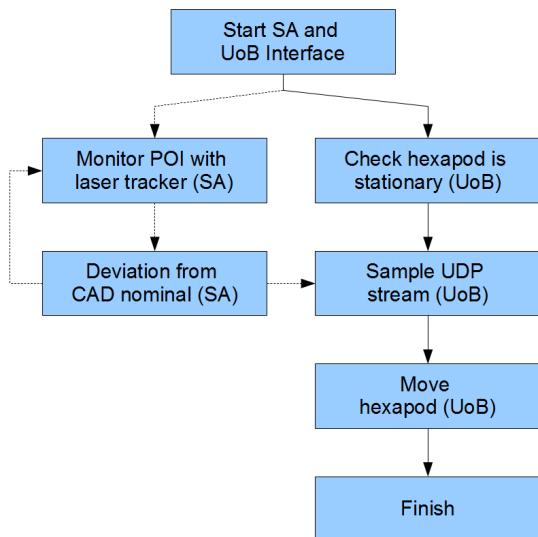


Figure 11 - Open loop control of fixture

The measurement instrument used for the trial was a *Leica AT901* laser tracker, this was a readily available instrument with a good level of accuracy capable of real-time, three dimensional measurement. 3D co-ordinates were assumed as appropriate since the compliance of the material is limited to two dimensions and this phase of the trials is assessing the feasibility of the metrology enhanced tooling philosophy. Figure 12 shows the laser tracker point of measurement relative to the zero-point clamp attachment point.

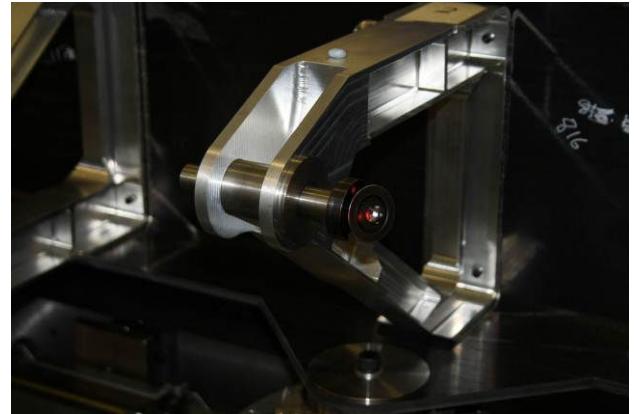


Figure 12 - Facility tooling for targeting the hinge line

#### 4. RESULTS

The trial focus on moving two axis, without rotation; engaging the hexapod's *y-axis* (Figure 9: Green Arrow) and *z-axis* (Figure 9: Blue Arrow). The reason for not actuating the *x-axis* was structural: as longitudinal movement was likely to add additional stress to the fasteners as the structure had high rigidity in this plane. Rotational movements were excluded at this stage because only one POI was monitored, rotational movement is more appropriate when best-fitting multiple points. The most out of tolerance axis was *z*. The closed loop configuration moved the POI a total of  $0.421\text{mm}$  in the *y-axis* and negative  $1.572\text{mm}$  in *z-axis*; the hexapod achieved the designated tolerance threshold ( $\pm 300\mu\text{m}$ ) within two iterative cycles – this is summarized in Figure 13.

However, the hexapod's encoders registered a movement of  $1.103\text{mm}$  in the *y-axis* (Figure 14) and negative  $2.412\text{mm}$  in the *z-axis* (Figure 15); this

difference can be attributed to the material compliance. This confirms the assumption that the POI and hexapod do not act as a rigid body.

However, Figure 14 and Figure 15 show that after around 5 iterations the deviation between the

POI and hexapod displacements begin to level out, reducing the significance of the component deflection and offset.

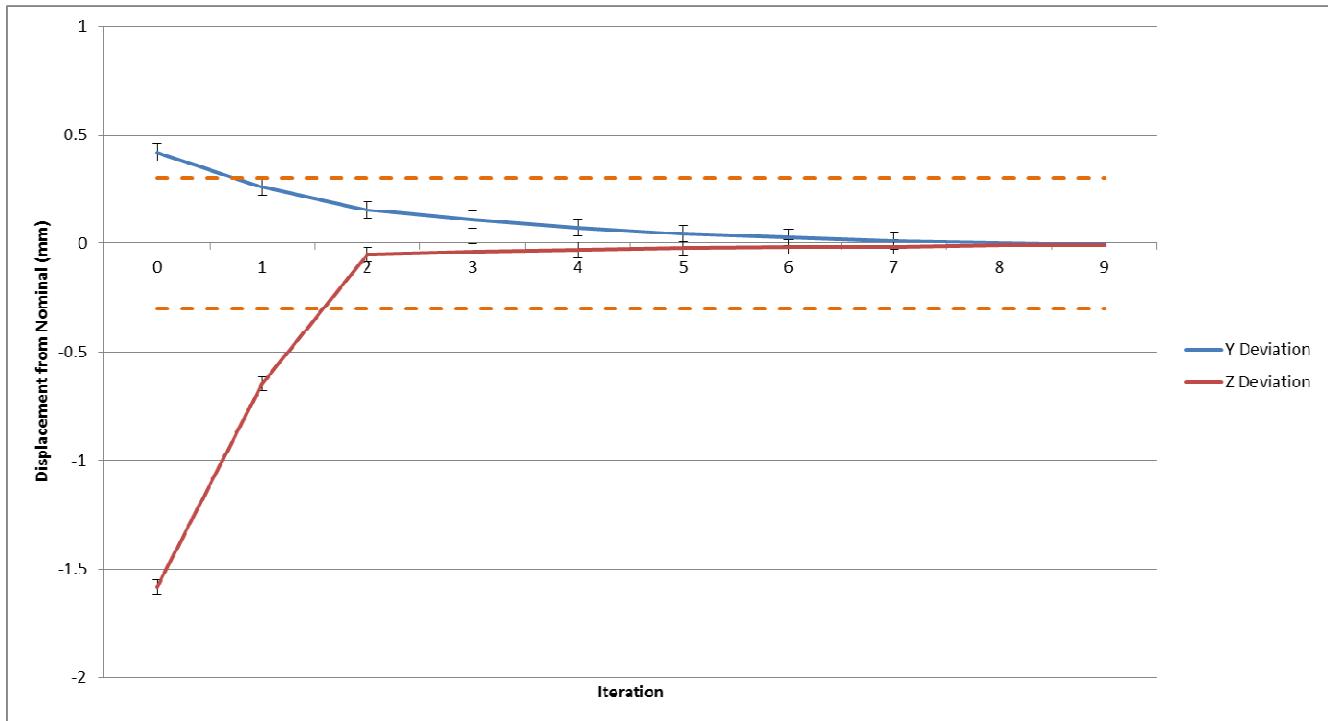


Figure 13 - POI displacement from nominal in *y*-axis and *z*-axis after each move iteration, with measurement uncertainty bars indicated

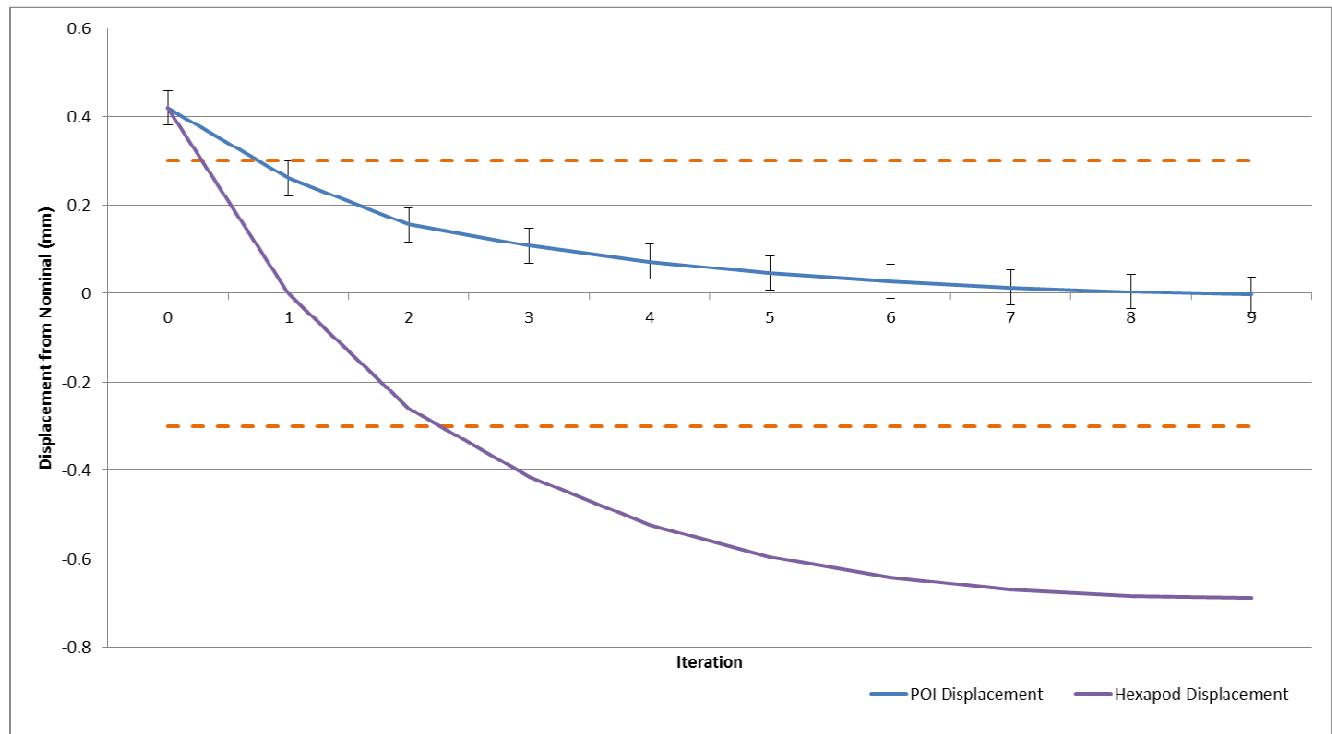
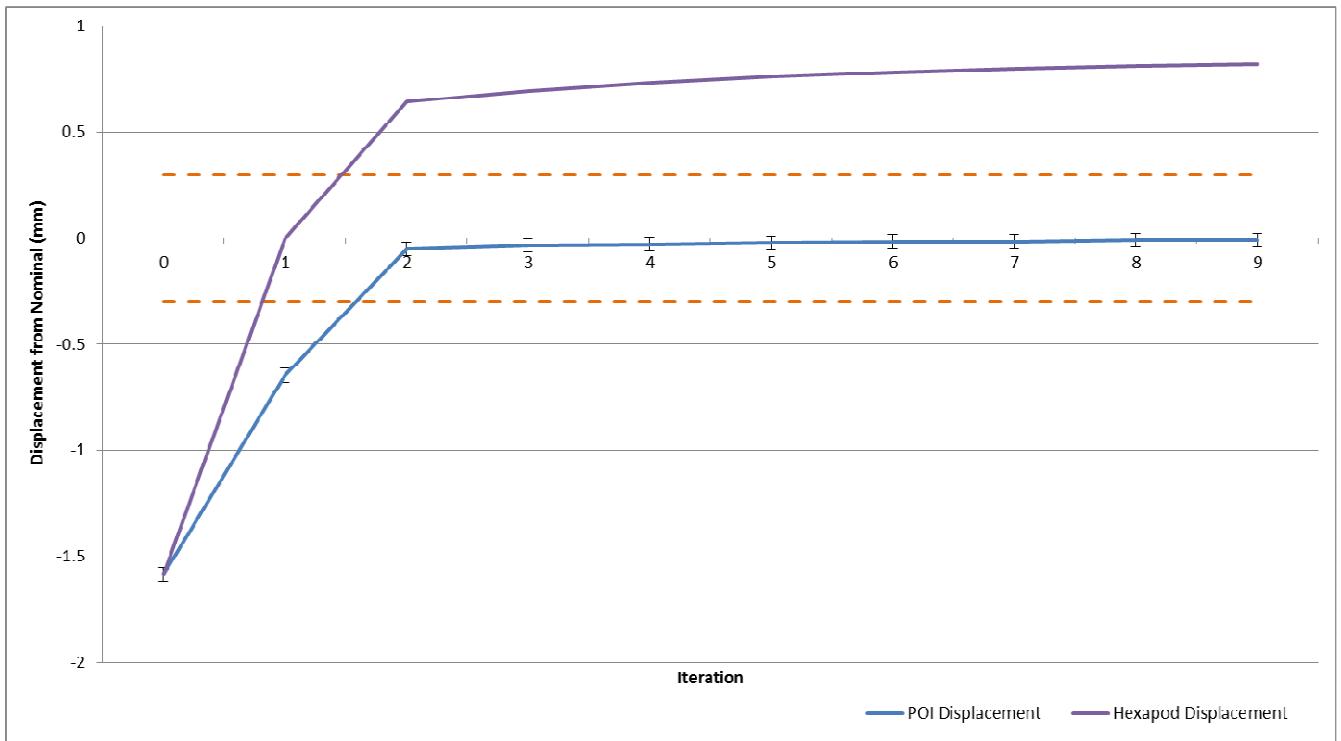


Figure 14 - Measured POI displacement (with uncertainty indicated) compared with displacement from hexapod's encoders; in the *y*-axis



**Figure 15 - Measured POI displacement (with uncertainty indicated) compared with displacement from hexapod's encoders; in the z-axis**

## 5. CONCLUSIONS

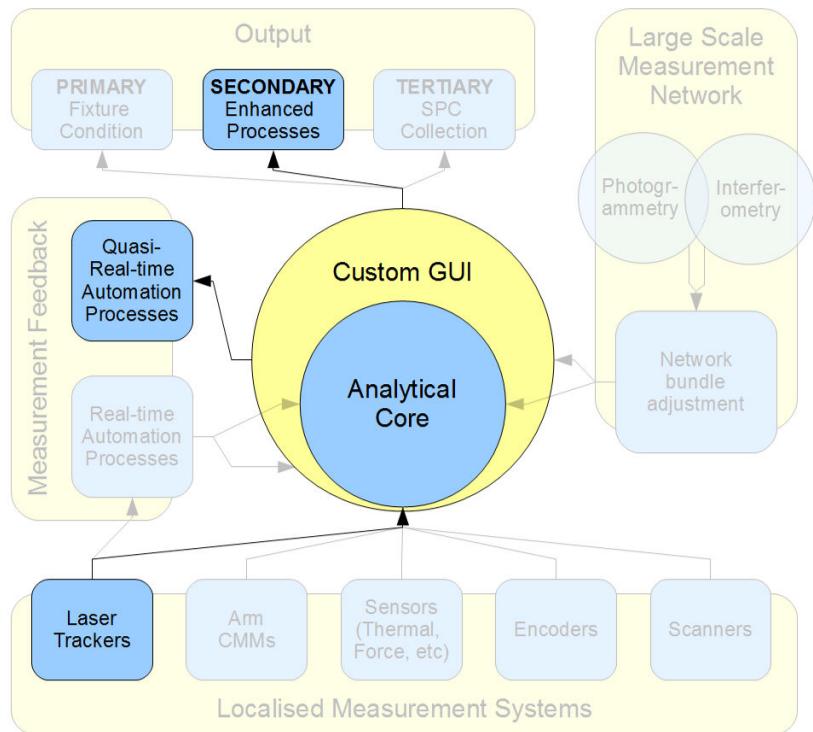
Figure 16 shows the elements of the META framework exercised through the live fixturing study.

The closed loop model holds obvious limitations in terms of measurement resources; if the fixturing requires 3DOF or 6DOF manipulation within a global co-ordinate system then the measurement instrument is likely to be prohibitively expensive for deployment on each actuated part. Subsequently, the closed loop model has to multi-hop instruments to each actuated pick-up. This is an inherently time consuming process; however, bottle-necking due to metrology resource on multiple POIs could be reduced by cycling through each of the POIs and assuming that a small number of iterations is necessary to achieve the tolerance. This would negate the requirement of metrology monitoring and

is substantiated in Figure 13, Figure 14 and Figure 15. However this is reliant on a degree of actuator accuracy.

On the other hand, a closed loop model does mean that the actuators do not need to be accurate, just a fine resolution of movement. If the pick-up only needs local measurement or describing in one or two dimensions then inexpensive measurement systems could be deployed on each manipulator and closed loop systems could be used.

Open loop systems may be a more economical solution as an enabler to live fixturing; one laser tracker or photogrammetric survey could measure all the POIs and the accuracy on the actuators could be relied on to position the pick-ups to within tolerance. However, this would need rigid body relationships to be established, or known deflections compensated for.



**Figure 16 - META Framework with aspect utilized in hexapod control highlighted**

## 6. ACKNOWLEDGMENTS

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