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Metrology Enhanced Tooling for Aerospace (META): Strategies for Improved Accuracy of Jig Built Structures

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ABSTRACT

The accuracy of many aerospace structures is limited by the accuracy of assembly tooling which is in turn limited by the accuracy of the measurements used to set the tooling. Further loss of accuracy results from different rates of thermal expansion for the components and tooling. This paper describes improved tooling designs and setting processes which have the potential to significantly improve the accuracy of aerospace structures. The most advanced solution described is environmentally isolated interferometer networks embedded within tooling combined with active compensation of component pick-ups. This would eliminate environmental effects on measurements while also allowing compensation for thermal expansion. A more immediately realizable solution is the adjustment of component pick-ups using micrometer jacking screws allowing multilateration to be employed during the final stages of the setting process to generate the required offsets.

INTRODUCTION

The terms jig and fixture are often used interchangeably when referring to *work holding* [1]; strictly speaking there is a distinction between the terms: jigs hold and position the workpiece whilst guiding a material removal operation; whereas fixtures only hold and position the workpiece or assembly [2]. Fixtures can be thought of as both a means for validation and verification; the tooling not only places the components correctly for the assembly operations but also checks the assembly is correct. The fixture must locate and control all relevant degrees of freedom (DOF) on both a component and assembly level. A key driver for hard tooling is that the fixture acts as a *quality gate* and it is difficult to get equivalently stable and repeatable positional accuracies when employing modular tooling [3]. The assembly and components need to be held rigidly with a stability that ensures the relative and global positions of the parts are maintained, ensuring that the tooling remains stable between fixture setting, checks and certifications is an additional driver for monolithic, welded structures; as any movement between certifications could allow a number of concessions to go undetected.

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. However, in order to achieve this paradigm shift a strong metrological infrastructure is required to maintain the required tolerances within the tooling and the assembly process [4]. An alternative method to reduce the dependency and impact of tooling is to design determinate assemblies [5] – however this still requires work holding structures, and it is likely that a complex assembly (such as those found in aerospace) cannot be completely determinate.

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 [6] or 10% of the cost for the air frame [7]. Figure 1 shows how these issues are a consequence of the traditional build philosophy.

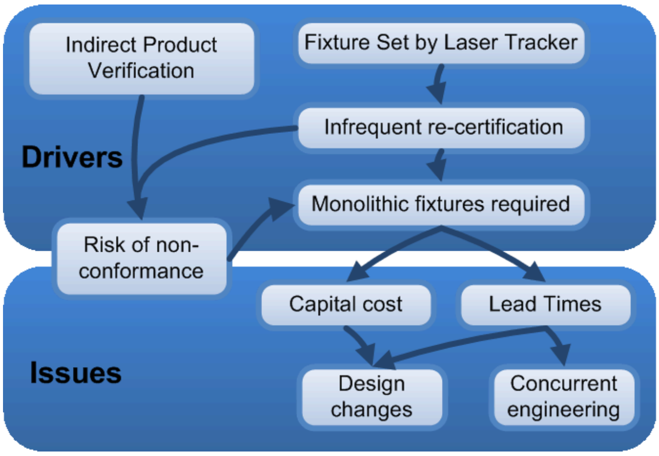

Figure 1 - Issues caused by Traditional Build Philosophy

CURRENT LIMITATIONS ON ACCURACY

Traditional 'monument' aerospace assembly fixtures consist of large, static steel structures secured to the reinforced-concrete factory floor - these fixtures are configured for one aircraft type only. This traditional build philosophy controls all the features by: *common jig location, master jig datum, jig setting, certification points, build slips* and *pin diameter*. 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 determined to be correct. These mechanical metrology checks ensure tolerances are maintained.

The combined tolerance of the fixture and location pins/slips must be less than the assembly tolerances; ideally <10% although this is rarely possible [8]. Verification involves manually rotating pins and moving slips to ensure that the assembly is correctly positioned and held within the fixture. Assembly tolerances for a metallic wing build are in the order of 0.3mm [9]; the tooling is built to a tolerance of around 0.15mm 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.

The accuracy of the jig built structure is dependent on the accuracy of the fixture, which is in turn dependent on the process and measurement system used to set the fixture; the accuracy of the processes used to set components in the jig; and the accuracy of the slips and pins. The traceability route for a jig built assembly is therefore as shown in Figure 2.

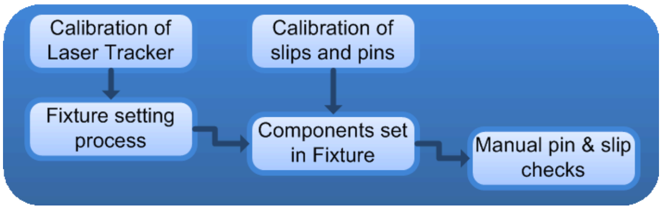

Figure 2- Traceability Route for Assembly Dimensional Uncertainty

The accuracy to which a fixture can be set will be determined in part by the type of pick-up used since this will determine the type of measurement system which can be used. Subsequently, the measurement system's accuracy will limit the setting of the pick-ups. For example pads with holes require setting in six degrees of freedom, pins require setting in five degrees of freedom and split bearings require setting in three coordinates only. Split bearings are hemispheres designed to be located in a kinematic mount consisting of a three point contact typically with a retaining magnet as shown in Figure 3. The split bearing its-self can be readily removed and replaced with a laser tracker spherically mounted retroreflector (SMR) to provide feedback for setting in the form of the coordinates of the center of the sphere. The split bearing can then rotate to align its-self with a surface effectively providing a point contact always located at the center of the sphere.

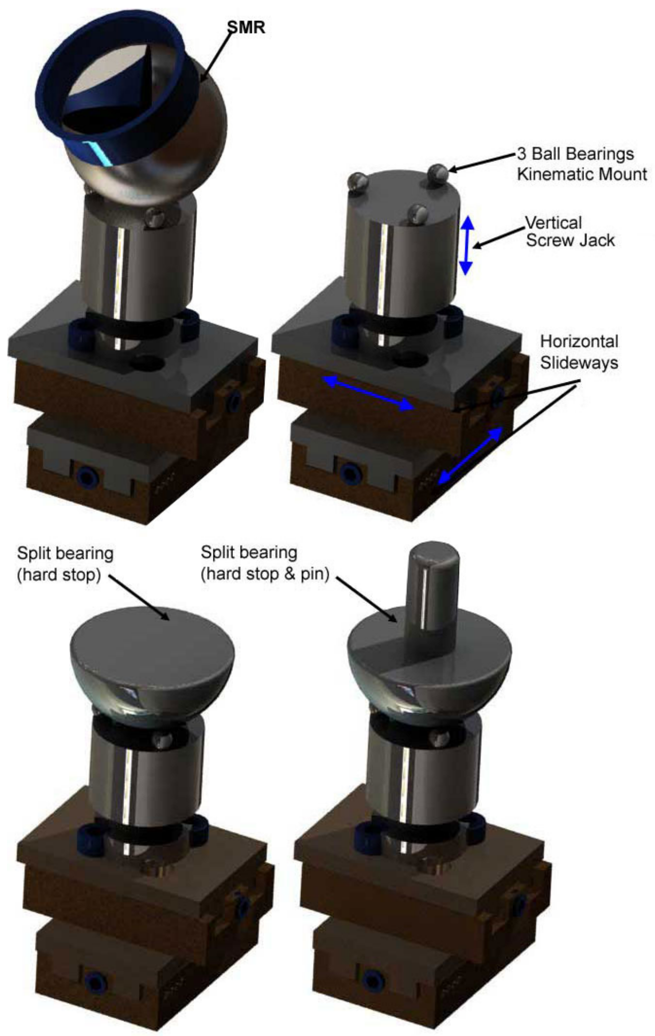

Figure 3 – Split Bearing Located on Kinematic Mount and Three-Way Linear Slide

METROLOGICAL LIMITATIONS

Since the accuracy of fixtures is dependent on the accuracy of the measurement systems used to set them, metrological factors are of key importance to jig built structures. For large assembly fixtures laser trackers are most commonly used. These consist of a laser interferometer or absolute distance measurement (ADM) device to measure the range, combined with a tracking head which measures the elevation and azimuth angle to the target reflector as shown in Figure 4. The range and angular information can be combined to give three dimensional Cartesian coordinates of target locations. The accuracy of the angular encoders is inherently lower than for the range measurements and for coordinate measurements the angular errors therefore dominate [10-12].

Due to temperature and pressure gradients causing changes in the refractive index the laser beam will also be bent and 'stretched' along its path causing additional errors where again angular errors are typically greater than range errors. The fractional error in the radial direction is the error per unit length in a measurement of range, this is given in the ASME standard for spherical coordinate measurement systems [13] as

$$e_R = \frac{\overline{\delta T}}{n(T_m)} \frac{\partial n}{\partial T} \qquad (1)$$

Where $\overline{\delta T}$ is the difference between the average temperature over the optical path and the temperature at the instrument, $n(T_m)$ is the estimated refractive index at the measured temperature and $\partial n / \partial T$ is the sensitivity of the refractive index to changes in temperature which can be calculated using the Ciddor equation [14, 15].

Additional errors due to turbulence of a few tens of microns can also be expected [16], these can however be greatly reduced by averaging over time which a period of 2 seconds typically rendering turbulence of negligible effect.

Where a number of repeatable target positions can be measured from at least three independent laser tracker stations it is possible to determine the coordinates of the targets using the range information alone, a technique known as multilateration. The larger angular errors will therefore not contribute to the coordinate measurements resulting in significantly more accurate measurements. Typically a weighted least squares best fitting algorithms is used to perform this type of multi-station measurement in which the angular errors are not completely ignored but they are given very low weightings, this allows more rapid calculation while making no practical difference to the accuracy achieved [17-19].

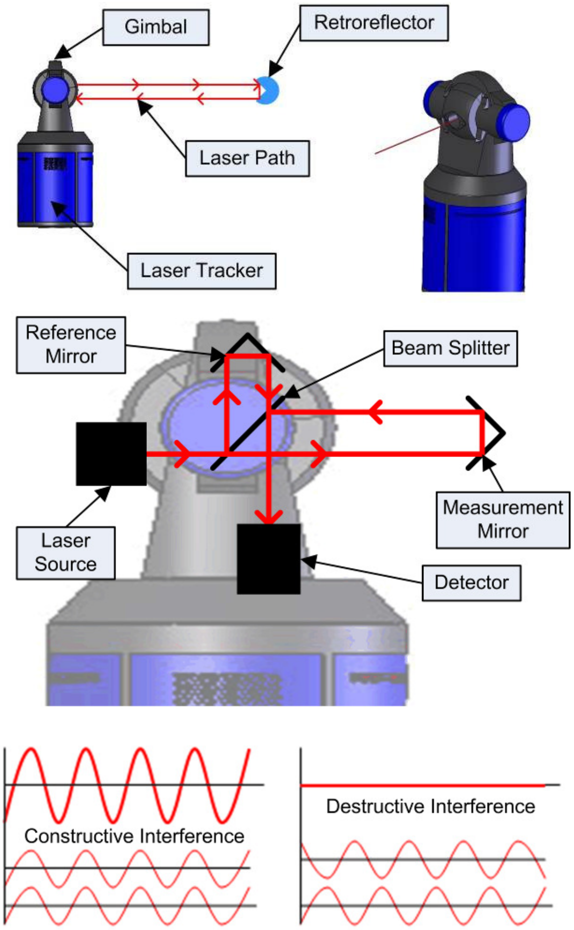

Figure 4 – Laser Tracker

THERMAL EXPANSION

All materials are subject to thermal expansion and the specified dimensions of a component or assembly in fact relate to the size of the component or assembly at 20°C [20], unless stated otherwise. Components and assemblies with comparatively tight tolerances relative to their overall dimensions must consider the effects of thermal expansion and contraction during the fixture design process. Thermal expansion and contraction has a profound effect and can easily cause an assembly to exceed its required tolerance. Since it is often not practical to control the temperature in a production environment the temperature of the part should be measured and corrections made for thermal expansion [21] using Equation (2).

$$L_{20} = L_T + (20 - T) \cdot \alpha \cdot L_T \tag{2}$$

where L_{20} is the length at 20 ℃, L_T is the length at the measurement temperature, T is the measurement temperature and α is the coefficient of thermal expansion.

Consider a steel fixture 12.5m in length undergoes a uniform 1˚C temperature change; if no thermal compensation techniques are employed then the expansion is 150µm across its length, which is enough to force out a typical 150µm global fixture tolerance. However, temperature change and distribution is rarely uniform, as a case study 12 temperature sensors were positioned over the 12.5 m steel fixture, these were left in-situ for two weeks to assess the extent of temperature variations over time and the difference in temperature at any one time over the fixture. The measured temperature difference across the fixtures averaged 1.5 ˚C, with a minimum difference of 0.8 ˚C and a maximum of 2.5˚C, hence a linear model is not appropriate for high tolerance builds. A thermal expansion compensation is often applied (using a linear expansion model) to scale measurements back to their nominal state – and subsequently fixtures are checked against their nominal/designed values.

Consequently the fixture is ‘set’ to its 20˚C state; however, this may not be appropriate when constructing an assembly with a significantly different CTE value. In its 20˚C state a fixture should hold the assembly correctly, however if the build temperature is systematically higher by an arbitrary 2˚C or the temperature changes with the seasons then the fixture will expand at a different rate to the assembly. For example, if the steel fixture is used to construct a CFRP structure – such as a wing – in its nominal state the wing will be held correctly, however at the factory temperature of 22˚C the fixture is 300µm larger and the CFRP wing has only expanded by 75µm. Consequently when measuring the fixture and scaling back to nominal it could be correct – but due to the differing rates of thermal expansion the CFRP wing may actually be 225µm out of nominal, which is likely to exceed the required tolerances. Hence a mechanical solution is to build the fixture out of similar material to the assembly, e.g. if an aluminium structure is being assembled then may be regarded as an advantage that the jig expands and contracts at a similar rate. Aluminium jigs may therefore be regarded as the ideal and steel to be quite acceptable. Where a carbon fibre structure is being assembled within a steel jig the thermal expansion of the jig becomes a serious issue and a CFRP fixture may be prohibitively expensive. Table 1 gives a summary of material CTE values, the expansion over 12.5m and the compensation residuals if using a steel fixture.

Table 1-Linear Thermal Expansion over 12.5

	Coefficient of Thermal Expansion	**Expansion (over 12.5m, ΔT = 2℃)**	**Expansion Relative to Steel**
	10^{-6}/K	**µm**	**µm**
Steel (Structural A36) [22]	12	300	0
Aluminium Alloy (6061-T6) [22]	24	600	300
Invar [23]	1.5	38	262
CFRP (estimate)	3	75	225
Granite [23]	7.5	188	112

SOLUTIONS

Two different forms of metrology enhanced tooling are presented as solutions to the current issues with achieving accurate setting tolerances for assembly tooling. A third solution is also presented which specifically addresses the issue of thermal expansion of the tooling.

EMBEDDED INTERFEROMETER NETWORKS

Multilateration could be applied to a network of multiple interferometers arranged in a tessellating arrangement of tetrahedral and octahedral elements, as shown in Figure 5, to provide highly accurate real time measurement of tooling for the purpose of setting and in-service monitoring. If these interferometer lines were located within the structure of the jig or fixture then it would also be possible to control the environmental parameters to achieve significant improvements in accuracy. Using independent laser systems for each interferometer line would result in very high costs. There has however been a demonstration of a similar arrangement of several hundred fibre-coupled interferometers sharing a single laser source [24-26] which was used to monitor particle detectors within the Large Hadron Collider at CERN. This demonstrates that it is possible to apply a multiple interferometer strategy cost effectively.

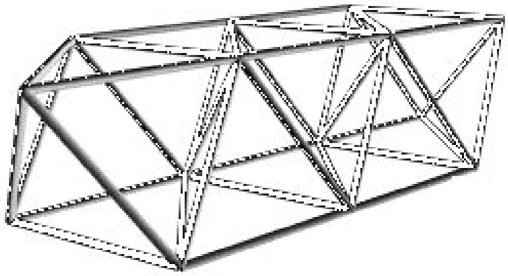

Figure 5 - Tessellating arrangement of tetrahedral and octahedral elements

This type of system would be capable of tracking key positions of the structure with measurements which are not effected by temperature, equipped with actuated pick-ups it could provide different levels of thermal compensation for areas of the jig supporting components constructed from different materials. Temperature sensors on the components could be used to drive this temperature compensation and for the highest accuracy this could be linked to Finite Element Analysis (FEA) models describing how the part would expand where it is not at a uniform temperature. It would then be possible to build a structure within an uncontrolled environment which would closely conform to specified dimensions when at the reference temperature of 20°C.

Considerable development would however be required to realize such a solution.

SEQUENTIAL MULTILATERATION FOR TOOL SETTING

Sequential multilateration is a technique which is currently employed within production typically using a single laser trackers which is moved sequentially to multiple stations. Using this technique it is possible to achieve an expanded (k=2) uncertainty of measurement of 10 µm over a 10 x 10 x 2 m volume within a typical production environment [27], however this requires a large number of measurement stations and careful analysis of the results. The method requires a range measurement to be made at several measurement locations, the tracker to be moved, all range measurements repeated and so forth for all measurement stations before the coordinates of the measurement locations can be calculated. For obtaining accurate measurements this is appropriate (Figure 6). For providing feedback for an iterative setting process this is far too time consuming. The current techniques of applying adjustments to fixtures by tapping with a mallet or using uncalibrated jacking screws is therefore not compatible with the use of multilateration.

If pick-ups are located on slideways equipped with some form of localized measurement system it would be possible to use offsets generated from multilateration measurements to set the fixture right first time. The localized metrology could consist of a vernier scale, linear encoders or simply a dial gauge which is located on each slide way in turn before making any adjustments.

The process would therefore be:-

1) Rough set the fixture using a laser tracker in a single station operating in coordinate measurement mode

2) Measure all component pick-ups using multilateration

3) Calculate the offsets for each pick-up and apply coordinate transformations to convert these from the global xyz values into movements along the axis of each slideway

4) Adjust the pick-ups using local measurement system such as linear encoders on the slide ways or a dial gauge.

Experiments were carried out to determine the uncertainty of measurement for single and multi-station laser tracker measurements under normal production environmental and usage conditions, these show a significant improvement for multilateration, Figure 6.

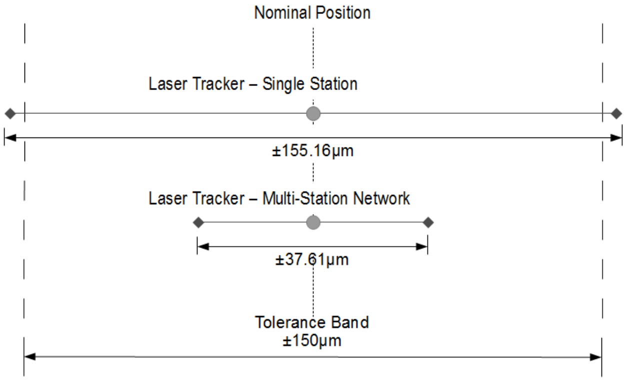

Figure 6 - Experimentally determined uncertainty (±3σ) over a max distance of 14.5m in an uncontrolled environment; illustrating the benefit of using multi-lateration to reduce the impact uncertainty has on a tolerance budget.

ACTIVE THERMALLY COMPENSATED TOOLING FOR UNCONTROLLED ENVIRONMENTS

This solution aims to reduce the effects of thermal expansion and contraction during assembly. The temperature of the tooling and assembly must be monitored during the manufacturing process to enable this *active compensation*. This can be achieved in a number of ways however the number and deployment of sensors could be a limiting factor. The temperature information can be passed downstream to drive active tooling pick-ups that negate the thermal movement, this is unlikely to completely eliminate the thermal effects, but rather reduce the expansion/contraction to a manageable level. However this has inherent challenges, these include:

- Material differences between: tooling and assembly components
- Non-linear behaviour of material expansion
- Non-uniform distribution of temperature.

Material differences between the tooling and assembly components cause an expansion disparity, as described above. To compensate for this effect a large number of temperature sensors would be required and for complex assemblies that are not dominated by a single material – a well-developed FEA thermal model would be required to actively compensate appropriately. The linear thermal expansion model is quite well suited to the square, geometric shapes that often dominate fixture design, however, complex aerospace assemblies are unlikely to exhibit linear behaviour. The non-linear behaviour of the thermal expansion in the assembly needs to be assessed a quantified in order to apply the compensation. Issues of thermal gradients present in uncontrolled environments complicate modelling – and therefore compensation – further.

Utilising embedded interferometers combined with active compensation could eliminate virtually all of the issues associated with temperature. In this case, embedded interferometer (described above) would be environmentally isolated – providing absolute scale – subsequently the pick-ups could actuate into the nominally correct position. If however static tooling is manually set, then thermal expansion of the jig is a very significant source of error. In either case it is vital that component temperature is monitored and thermal expansion accounted for.

CONCLUSIONS

Metrological factors involved in the setting of tooling such as instrument uncertainty, environmental variability and thermal expansion of structures limits the accuracy of assembly fixtures which in turn limits the accuracy of the assemblies produced. A number of solutions have been presented which have the potential to significantly improve the accuracy of assemblies by improving the accuracy with which fixtures can be set and held to required tolerances.

Interferometer networks embedded within tooling could potentially give very substantial improvements in instrument accuracy while also negating the effects of the environment on measurements. This would allow fixtures to be set to the required tolerances without any influence from the production environment. Such an approach could be combined with monitoring of component temperature and actuated component pick-ups to provide active compensation for thermal expansion. It would then be possible to produce highly accurate assemblies without any requirement for thermally controlled production environments.

A more immediately realizable solution to improve the accuracy of assembly fixtures is to employ multilateration during the setting of otherwise generally standard tooling. Currently offsets are measured globally and these are then applied without any local feedback. Such an approach is not suited to multilateration since each measurement requires measurement from multiple instrument stations. The novel approach is therefore to set all fixtures approximately using the conventional approach and to then determine the required final setting offsets for all fixture setting points using a single multilateration survey. These offsets can then be applied to each fixture setting point in turn using some form of local measurement feedback such as a micrometer jacking screw or a dial indicator.

SUGGESTIONS FOR FURTHER WORK

Tests should involve construction of simplified assemblies within uncontrolled environments. The completed assemblies should then be thermally soaked in a temperature controlled lab before being measured. This will provide statistical data on the effectiveness of the approaches. Carrying out the tests will also be useful in terms of gaining experience of how to build tooling.

Initially one-dimensional arrangements should be examined with a single interferometer located within an environmentally controlled channel. This should be used to drive an adjustment screw and linked to temperature measurements of component. This research activity will be valuable in understanding how an interferometer can be protected from environmental effects and therefore different levels of protection should be trailed such as a full vacuum enclosure and open enclosures with measurement of temperature, pressure, humidity, carbon dioxide etc. There will also be valuable learnings regarding compensation for thermal expansion of the part and the control of active pick-ups.

Also running in parallel will be the development of modular tooling systems which facilitate the integration of interferometer networks.

The next stage of this work will be to integrate the elements to demonstrate a modular reconfigurable tooling system which has environmentally isolated interferometer networks embedded within it which provide accurate three-dimensional measurements of nodes in the structure. The system will also incorporate active pick-ups controlled using the node position and component temperature measurements.

Finally it will be possible to use this thermally isolated active fixturing system to develop temperature compensation for part temperature.

REFERENCES

1. BOYES, W.E., *JIGS AND FIXTURES*. 1980, MICHIGAN: SOCIETY OF MANUFACTURING ENGINEERS.
2. POLLOCK, H.W., *TOOL DESIGN 2ND ED*. 1988, NEW JERSEY: PRENTICE HALL.
3. LEOPOLD, J., A. POPPITZ, M. KLARNER, A.K. SCHMIDT, AND J. BERGER, *INTERACTION BETWEEN MACHINING AND NEW FIXTURING PRINCIPLES FOR AEROSPACE STRUCTURES.* INTERNATIONAL JOURNAL OF MATERIAL FORMING, 2008. 1(COMPENDEX): P. 531-533.
4. MARTIN, O.C., J.E. MUELANER, AND P.G. MAROPOULOS. *THE METROLOGY ENHANCED TOOLING FOR AEROSPACE (META) FRAMEWORK.* 2010. MANCHESTER, UK.
5. MUELANER, J.E. AND P.G. MAROPOULOS, *DESIGN FOR MEASUREMENT ASSISTED DETERMINATE ASSEMBLY (MADA) OF LARGE COMPOSITE STRUCTURES.* JOURNAL OF THE CMSC, 2010. 5(2): P. 18-25.
6. ROOKS, B., *ASSEMBLY IN AEROSPACE FEATURES AT IEE SEMINAR.* ASSEMBLY AUTOMATION, 2005. 25(2): P. 108-111.
7. BURLEY, G., R. ODI, S. NAING, A. WILLIAMSON, AND J. CORBETT, *JIGLESS AEROSPACE MANUFACTURE - THE ENABLING TECHNOLOGIES*, IN *SAE TECHNICAL PAPER SERIES*. 1999, SAE INTERNATIONAL DOC
8. FLACK, D., *MEASUREMENT GOOD PRACTICE GUIDE NO. 42: CMM VERIFICATION*. 2001: NATIONAL PHYSICAL LABORATORY.
9. KAYANI, A. AND J. JAMSHIDI. *MEASUREMENT ASSISTED ASSEMBLY FOR LARGE VOLUME AIRCRAFT WING STRUCTURES*. IN *4TH INTERNATIONAL CONFERENCE ON DIGITAL ENTERPRISE TECHNOLOGY*. 2007. BATH, UNITED KINGDOM. P. 426-434
10. LEICA, *PCMM SYSTEM SPECIFICATIONS: LEICA ABSOLUTE TRACKER AND LEICA T-PRODUCTS*. 2008.
11. AUTOMATED PRECISION INC, *TRACKER3 LASER TRACKING SYSTEM*. 2008.
12. FARO, *LASER TRACKER ION TECH SHEET*. 2010.
13. ASME, *PERFORMANCE EVALUATION OF LASER-BASED SPHERICAL COORDINATE MEASUREMENT SYSTEMS*, IN *B89.4.19*. 2006.
14. CIDDOR, P.E., *REFRACTIVE INDEX OF AIR: NEW EQUATIONS FOR THE VISIBLE AND NEAR INFRARED.* APPL. OPTICS, 1996. 35: P. 1566-1573.
15. STONE, J.A. AND J.H. ZIMMERMAN. *INDEX OF REFRACTION OF AIR*. 2000 7TH DECEMBER 2004 [CITED 28 JULY 2008]; CALCULATE WAVELENGTH IN AMBIENT CONDITIONS USING CIDDOR EQUATION]. AVAILABLE FROM: HTTP://EMTOOLBOX.NIST.GOV/WAVELENGTH/CIDDOR.ASP.
16. ESTLER, W.T., K.L. EDMUNDSON, G.N. PEGGS, AND D.H. PARKER, *LARGE-SCALE METROLOGY - AN UPDATE.* CIRP ANNALS - MANUFACTURING TECHNOLOGY, 2002. 51(2): P. 587-609.
17. MUELANER, J.E., Z. WANG, O. MARTIN, J. JAMSHIDI, AND P.G. MAROPOULOS, *ESTIMATION OF UNCERTAINTY IN THREE DIMENSIONAL COORDINATE MEASUREMENT BY COMPARISON WITH CALIBRATED POINTS.* MEASUREMENT SCIENCE AND TECHNOLOGY, 2010. 21 (2): P. 9 PAGES.
18. CALKINS, J.M., *QUANTIFYING COORDINATE UNCERTAINTY FIELDS IN COUPLED SPATIAL MEASUREMENT SYSTEMS* IN *MECHANICAL ENGINEERING*. 2002, VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY: BLACKSBURG. P. 226.
19. SANDWITH, S. *AUTOMATING LASER TRACKER CALIBRATION AND TECHNIQUE COMPARISON*. IN *LARGEVOLUME METROLOGY CONFERENCE*. 2007
20. BSI, *GEOMETRICAL PRODUCT SPECIFICATIONS (GPS) — STANDARD REFERENCE TEMPERATURE FOR GEOMETRICAL PRODUCT SPECIFICATION AND VERIFICATION*, IN *BS EN ISO 1*. 2002.
21. FLACK, D. AND J. HANNAFORD, *FUNDAMENTAL GOOD PRACTICE IN DIMENSIONAL METROLOGY - MEASUREMENT GOOD PRACTICE GUIDE NO. 80* MEASUREMENT GOOD PRACTICE GUIDE. 2005: NATIONAL PHYSICAL LABORATORY NPL.
22. HIBBELER, R.C., *MECHANICS OF MATERIALS*. 5TH ED. 2003, NEW JERSEY: PEARSON EDUCATION, INC.
23. ENGINEERING-ABC.COM. *TRIBOLOGY: MECHANICAL PROPERTIES OF MATERIALS*. 2010 [CITED; AVAILABLE FROM: HTTP://WWW.TRIBOLOGY-ABC.COM/ABC/PROPERTIES.HTM.
24. COE, P.A., D.F. HOWELL, AND R.B. NICKERSON, *FREQUENCY SCANNING INTERFEROMETRY IN ATLAS: REMOTE, MULTIPLE, SIMULTANEOUS AND PRECISE DISTANCE MEASUREMENTS IN A HOSTILE ENVIRONMENT.* MEASUREMENT SCIENCE AND TECHNOLOGY, 2004. 15(11): P. 2175-2187.
25. COE, P., D. HOWELL, R. NICKERSON, AND A. REICHOLD (2000) *AN FSI ALIGNMENT SYSTEM FOR THE ATLAS INNER DETECTOR AND SOME EXTRAPOLATIONS TOWARDS NLC.* VOLUME,
26. GIBSON, S.M., P.A. COE, A. MITRA, D.F. HOWELL, AND R.B. NICKERSON, *COORDINATE MEASUREMENT IN 2-D AND 3-D GEOMETRIES USING FREQUENCY SCANNING INTERFEROMETRY.* OPTICS AND LASERS IN ENGINEERING, 2005. 44(1): P. 79-95.
27. HUGHES, B., A. FORBES, W. SUN, P.G. MAROPOULOS, J.E. MUELANER, J. JAMSHIDI, AND Z. WANG, *IGPS CAPABILITY STUDY*, IN *NPL REPORT* NO. *ENG 23*. 2010, NPL: TEDDINGTON. P. 35, DOC