Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 56 (2016) 61 – 66
www.elsevier.com/locate/procedia
9th International Conference on Digital Enterprise Technology - DET 2016 – "Intelligent Manufacturing in the Knowledge Economy Era

Design for Verification

Andrew Francis[a]*, Paul Maropoulos[b], Glen Mullineux[a], Patrick Keogh[a]

[a]*Mehcanical Engineering, University of Bath, Bath, BA2 7AY, England*
[b]*Aston University, Birmingham, B4 7ET, England*

* Corresponding author. Tel.: +44 (0) 1225 385138. *E-mail address:* andyjohnfrancis1@gmail.com

Abstract

Increased competition in the aerospace market has placed additional demands on aerospace manufacturers to reduce costs, increase product flexibility and improve manufacturing efficiency. There is a knowledge gap within the sphere of digital to physical dimensional verification and on how to successfully achieve dimensional specifications within real-world assembly factories that are subject to varying environmental conditions. This paper describes a novel Design for Verification (DfV) framework to be used within low rate and high value and complexity manufacturing industries to aid in achieving high productivity in assembly via the effective dimensional verification of large volume structures, during final assembly. The 'Design for Verification' framework has been developed to enable engineers to design and plan the effective dimensional verification of large volume, complex structures in order to reduce failure rates and end-product costs, improve process integrity and efficiency, optimise metrology processes, decrease tooling redundancy and increase product quality and conformance to specification. The theoretical elements of the DfV methods are outlined, together with their testing using industrial case studies of representative complexity. The industrial tests have proven that by using the new Design for Verification methods alongside the traditional 'Design for X' toolbox, resulted in improved tolerance analysis and synthesis, optimized large volume metrology and assembly processes and more cost effective tool and jig design.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Design for Verification; Metrology; Process Management; Product Design; Manufacturing Planning, Uncertainty Estimation

1. Introduction

The primary aim of this paper is to present a novel framework termed as "Design for Verification" (DfV) to complement the existing rules of Design for Excellence or 'X' (DfX) with a particular focus in large volume and integration processes during assembly [1]. The role of DfV is to enable and ensure paths for product conformance, with reduced manufacturing and metrology costs. This will determine the assembly and tooling philosophy, improve efficiency and increase rates of production. The secondary aim of DfV is to develop process models for analysis tools to assist designers in defining critical tolerances for large volume assemblies. This is founded upon instrument specification based algorithms for optimised measurement planning and uncertainty reduction for trade-off against cost and time. This is designed to be a four-pronged approach to cost modelling, with focus areas of tolerancing, measurement uncertainty, assembly methods and tooling methods. The achievable benefits and changes as well as the spillover effect which occurs with alterations is highlighted [2], [3].

2. Background and Structure

The proposed DfV framework assists designers for low rate high value products with a tool to optimise design for quality and cost with an improved success rate of RFT manufacturing. This depends upon the optimisation of four key areas: tolerancing, assembly, tooling and measurement.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.10.017

2.1. DfX

Success of DfX within manufacturing industries has traditionally been achieved by integrating small, focused engineering teams to ensure that parts are designed with manufacturability and ease of assembly, with interchangeable parts. Product design optimisation within a single design for 'x' parameter can cause detrimental consequences. For example, if one were to optimise a product purely for manufacture alone, the product may become significantly simplified and lose functionality. This dilemma inherently invokes a trade-off analysis between the DfX optimisation parameters and has led to various attempts at a solution to resolve the conflict between optimising parameters against other parameters. This is a well-recognised challenge, often referred to as the principle of design parameter sensitivity, further discussed by Franciosa et al.[4] [5] [6]. The traditional approach to design optimisation is a sequential method, often referred to as a Fixed Point Iteration method [4]. The challenge associated with this method is that it places heavy emphasis upon the skill set of individual designers. Franciosa et al. [6] describe the lack of effective product optimisation due to limitations imposed on product design by a prevalent feedforward approach. The DfX approach uses a feedback loop to significantly improve optimisation efforts. Attempts to overcome this challenge have been initialised through the implementation of multidisciplinary design optimisation (MDO) methods, which have aided closing the knowledge gap between distinct design sectors within large aerospace organisations. Applications of MDO have enhanced the synergy between various design disciplines, pushing for a higher level of product optimization [7]. Franciosa et al. propose a novel methodology to optimise heterogeneous design tasks with competing parameters [5].

Recent attempts to have been made to modernise DfA and DfM techniques based upon the state of the art manufacturing capabilities within aerospace facilities. The quantification of process capability for individual processes plays a significant role within the optimisation of DfA and DfM. Process capability is calculated through the dimensional analysis of repeat parts from a given manufacturing or assembly process. It provides a quantitative definition of the accuracy and precision of the particular process. It has been recognised that there is a clear knowledge gap within manufacturing and assembly process design with pre-existing process capability data. Whiteside et al. [8] produced a methodology to incorporate process capability into early stage design using historic measurement data for a given process. Measurement planning for uncertainty reduction is the means by which conformance of a product or process can be improved. It is integral within manufacturing and assembly processes, although it does not feature within DfX guidelines.

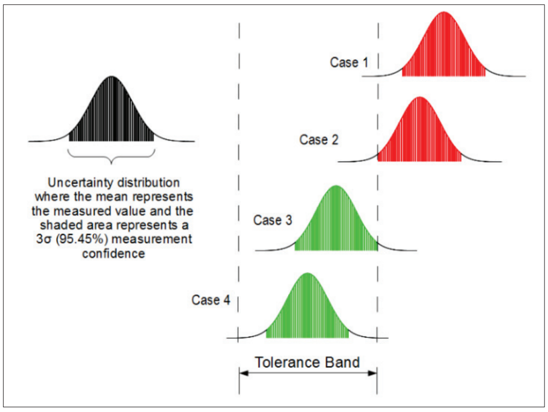

Figure 1: Measurement Uncertainty and Tolerance Bands

2.2. Metrology

The role of metrology within high value, large scale, low rate manufacturing is fundamentally crucial to the successful implementation of assembly and integration processes. There is a knowledge gap within design and manufacturing communities for large aerospace structures with respect to design for measured reality and assigning tolerances based upon estimated measurement uncertainty. This has often left metrologists at the mercy of technical drawings that demand unachievable measurements over the specified volumes.

The dominant challenges that metrologists face are due to the limitations imposed on them by their measurement hardware or by design specifications. For example, the most commonly used metrology system within aerospace for tool setting, jig verification and product conformance evaluation is the laser tracker. Specifications of different laser trackers are similar, the stated uncertainty for Hexagon's flagship laser tracker, the Absolute Tracker 901 (AT901) is stated as 15 μm + 6 μm/m at a confidence level of 2 σ [9]. Consider an assembly tolerance of +/-50 μm parallelism over 5 m. A laser tracker measuring at a distance of 5 m would typically have an MPE/uncertainty value of +/-15 μm + (6 μm multiplied by 5) = 45 μm at 2 σ, illustrated in Figure 2.

This poses a significant challenge because the laser tracker operator must achieve the parallelism requirement of +/-50 μm within a much tighter tolerance band of only +/- 5 μm to ensure that the assembly conforms to specification. Whilst this calculation gives a simplified view of the problem, it is still the most current method that a majority of technicians employ to calculate uncertainty on the shop floor. The effect of measurement uncertainty upon tolerance bands is shown in Figure 1. This image shows the effects of measurement uncertainty consuming the majority of the tolerance allocation, which subsequently allows very little room for

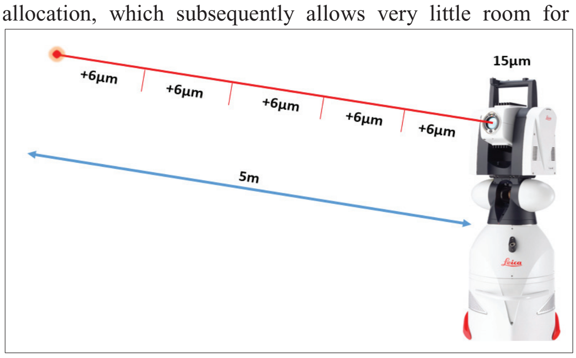

Figure 2: Laser Tracker Measurement Uncertainty

component deviation to ensure confidence in conformance. It is based upon an example using a confidence interval of 2 σ.

Advances in fundamental research for laser tracker measurement planning have significantly progressed since 2011. A Matlab based code was developed by the UK's National Physical Laboratory (NPL) for estimating laser tracker measurement uncertainty. It uses a network measurement model based upon a complex laser tracker simulator [10]. This then gave rise to further research for improving laser tracker accuracy: using the NPL laser tracker simulation code. Z. Wang at the University of Bath used the NPL code and bundled it in an optimisation algorithm for positioning laser trackers. The code also supports the ability to import CAD models so that the optimisation code can consider line of sight (LOS) challenges, which are inherent with laser tracker operation. It provides operators with a method to calculate the measurement uncertainty for a given process and also reduce the measurement uncertainty by optimising the position of the laser tracker [11].

The angular encoders within a laser tracker are significantly less accurate than the distance measuring laser which creates an uncertainty 'cloud' that is not 2 dimensional nor is it uniform or spherical as is usually assumed when single uncertainty figures are stated such as +/-15 μm + 6 μm/m at 2 σ within the previous example. The uncertainty cloud for the laser tracker is in fact elliptical.

The understanding of this allows measurement uncertainty to be reduced significantly by digital overlap of measurements from different laser tracker locations as well as optimising the position of the laser tracker. This was tested and proven using a simple single point measurement, 5 station study. The results of the study using the laser tracker model within NRKs Spatial Analyzer[12], displayed within Figure , show a progressive reduction in uncertainty as a point is measured from additional stations. The value of uncertainty reduction gradually decreases through stations 1-5 revealing that the benefits from adding more than 4 or 5 stations becomes less valuable. Considering the timescales involved in adding additional stations, it becomes a trade-off analysis depending upon the accuracy required.

This study proved the importance of the work conducted by NPL and the subsequent pattern searching algorithm which uses the model to optimise the position of laser trackers within a 3D measurement environment [13] [14].

Wang's optimisation model [11] has shown potential to be used within the manufacturing sphere. However, it has yet to be deployed within early structure design which is where the author believes it could be a most valuable factor within the DfV framework for tolerance allocation and process planning which would have a significant influence upon structural design.

Maropoulos et al. proposed a novel approach to large volume high value manufacturing under the title of Metrology Assisted Assembly (MAA) [15]. The MAA framework proposed a novel method using the state of the art in large volume metrology systems to provide real time metrological verification for jig setting and assembly alignment. The paper outlined the latest developments in aircraft wing assembly with respect to MAA and developed a process to promote RFT manufacturing during the assembly stages. The paper outlined a novel approach to assembly tolerance analysis but did not consider a metrology system uncertainty feedback loop into the design phase. Previous research highlighted a need to consider measurement uncertainty in early stage design to enrich tolerance allocations. Maropoulos et al. [13] recognised the need to consider laser tracker uncertainty within high value aerospace structures design, building upon works such as 'Advanced Tolerancing Techniques' by H. Zhang [14] who presented the general concept. This work however neglected established methods for uncertainty quantification and estimation such as the standards UKAS M3003 and the Guide to Measurement Uncertainty (GUM), rendering the process invaluable and ineffective.

The metrology literature review revealed the necessity for measurement planning during early stage design, coupled with traceable uncertainty quantification and analysis. The measurement process drives the accuracy of the final assembly as well as process confidence. In order to ensure that aerospace products conform to specification, the specification must be based upon measurement process capability. Tools such as the laser tracker position optimisation code, based upon NPL's traceable simulator, provide beneficial early stage design limits when implemented within the DfV framework to establish rules for assigning tolerance limits and desired confidence levels.

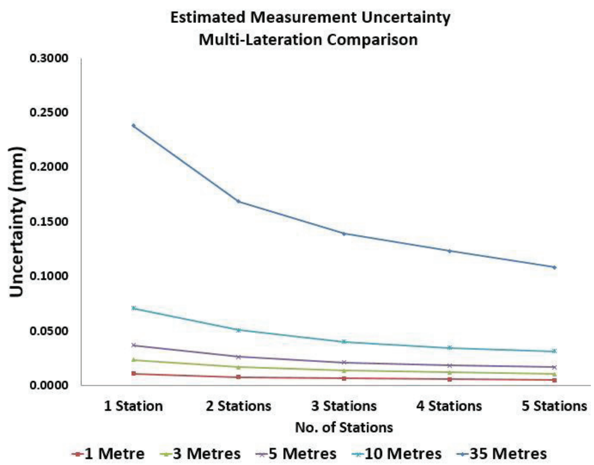

Figure 3: Estimated Measurement Uncertainty Reduction through Additional Station Measurements

2.3. Tolerancing

The Geometric Product Specification (GPS) is the current BS EN ISO standards for defining the maximum permissible degree of variation of a component by allocating the shape, dimensions and surface characteristics of the given component in a standard format with reference to drawing datums.

Datums are established within engineering drawings to aid in defining the location and orientation of tolerance zones. A datum casts constraints upon methods for component measurement when assessing geometric deviation. Careful consideration should be taken when defining datum structures as the measurement system can become significantly limited if the datum has been poorly positioned. Measurement consideration should occur before tolerances and datums are defined to ensure successful product verification. This has been recognised as a key area which is not currently fully realised within aerospace industries [13].

Estimated laser tracker uncertainty can be superimposed on 3D CAD models as seen within Figure 4. The three stars represent laser tracker positions and the black and red ellipses show the uncertainty clouds.

Overlaid measurement uncertainty on 3D CAD gives designers the ability to visualise the effects of assigning tolerances that are too tight to verify. This provides a pathway to ensure that tolerances would be consistently met and

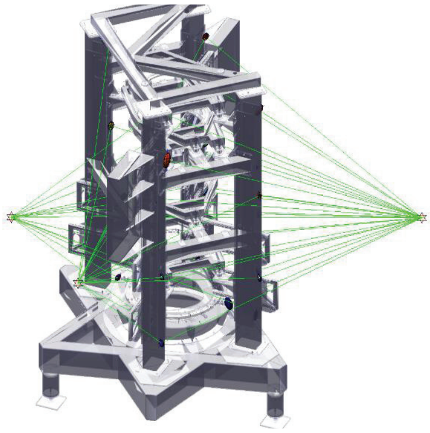

Figure 4: Laser Tracker Uncertainty Estimation on Assembly Tooling

product quality could be assured. Due to measurement uncertainty being stated with a degree of confidence, the tolerance would be assigned based upon a probability density function. The cost of increasing or decreasing tolerances is a well-understood. It is commonly referred to as the tolerance-cost relationship. Cheng et al. [18] developed a tolerance-cost methodology aimed specifically at optimising tolerances based upon cost.

2.4. Assembly and Tooling

The design of fixtures and jigs within the low rate high value manufacturing sector has been slow to take up innovative solutions when compared with the automotive industry. This is mostly due to the risk associated with manufacturing high value products and the associated costs involved. Automotive industries have had the benefits of high rate and comparatively loose assembly tolerances to allow a rapid evolution of assembly technology. The synergy between tooling designers and metrology experts is beginning to develop. Flynn et al. [19] published a paper focusing upon the need to integrate automated metrology into the assembly of wing structures. They highlighted the time delays in the

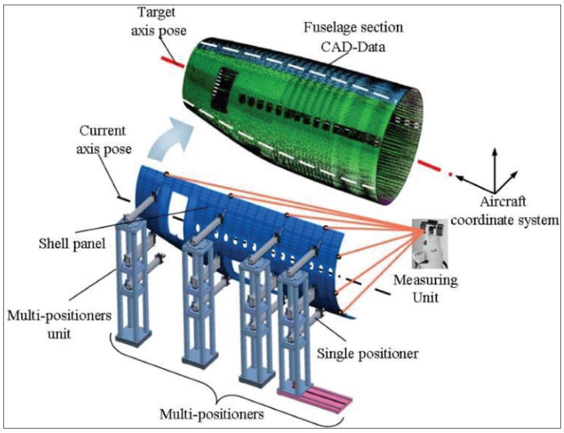

Figure 5: DURR Ecopositioner , image taken from http://www.sae.org/dlymagazineimages/web/516/11154_14220.jpg

current process where recertification and verification of a wing assembly jig can cause it to be unusable for up to a week. The solution proposed was to develop a software solution to deskill the metrology operation and decrease the amount of time taken. The paper concludes that it was a challenging task but there is a strong possibility to improve the process.

The integration of metrology systems into tooling structures has been explored previously by Muelaner et al. [20]. The purpose of embedding interferometry directly within steel jigs is to shield laser beams from the environment to reduce uncertainty accrued from measurement so that a highly accurate measurement network can be formulated. Millar et al. [21] worked with an academic organisation to initiate the use of an immature reconfigurable tooling proposal. The paper showed the advantages of using the reconfigurable tooling but highlighted the disadvantages inherent within the system such as the difficulty in reconfiguring the tooling and the advanced expertise required. An alternative is to design products to enable jigless assembly. Naing et al. [22] constructed a framework proposal for achieving jigless assembly of an A320 aircraft. The framework included an assembly analysis of error propagation through a statistical approach. Software for calculating optimal best fit parameters for individual components has been developed to assist large volume assembly operations such as wing to fuselage and fuselage to fuselage mating processes [23]. This has been largely progressed from research into industrial solutions and is at a relatively mature stage, being employed globally for the assembly of military aircraft. The enabling technology is provided by various tooling suppliers such as DURR with the Ecopositioner, illustrated in Figure 5 [24].

Vakil [25] published a methodology for measuring Key Characteristics (KCs) using multi-instrument networks in order to obtain a common datum. The proposal presented methods commonly used within the metrology community for locating a variety of instruments including photogrammetric systems, articulated arms, laser scanners and trackers into a global reference system. The paper highlighted the best practice in attempt to make designers aware of the requirements for metrology systems. The paper is a valuable resource for use during early stage design although it did not communicate the importance of measurement uncertainty and network optimisation [25].

3. Design for Verification Framework

The first key consideration in the development of DfV was the recognition of the previous work undertaken to synthesise and channel information between design teams to holistically engineer optimal products based upon skills across multidisciplinary organisations. The DfV framework complemented this work so as to be readily implementable into current industrial processes [26].

The second key factor considered was the work undertaken to incorporate process capability into DfX strategies. Process capability forms an integral part of product verification estimation for mass produced parts. Whilst this does not directly apply to low rate, high value manufacturing processes, concepts and learnings were employed for the creation of the DfV framework to encourage predictive process capability modelling through alternative means such as instrument specific uncertainty modelling [8].

Tolerancing for final assembly tooling has also been highlighted as an area for improvement with the DfV framework. The practice within spacecraft manufacturing for final stage assembly uses flexible fasteners to wash out tolerance stacks. This means that the tolerance analysis should primarily be driven by metrology uncertainty analysis and operator capability for interface setting. For this reason, step 1 of the Light Controlled Factory process flow is fed by the DfV process step which focuses upon metrology system uncertainty analysis.

The realisation of measurement design is accomplished through measurement uncertainty analysis and optimization. Through altering the measurement strategy of large volume metrology systems to reduce measurement uncertainty, the methods and plan design are simultaneously derived. This plan forms the basis for driving the DfV principle.

Opportunities within early stage aerospace concept design phases within the areas of metrology process design, tolerance synthesis and analysis as well as manufacturing and assembly process design have also been identified. The four key areas have been summarised within the literature review and illustrated within Figure 6 for the integration into the DfV framework. The literature review highlighted the need for a trade-off analysis between the four key aspects within product design to ensure end stage dimensional verification. The DfV framework enables and promotes collaboration of multidisciplinary design teams to achieve maximum design optimisation of both product and process. The DfV

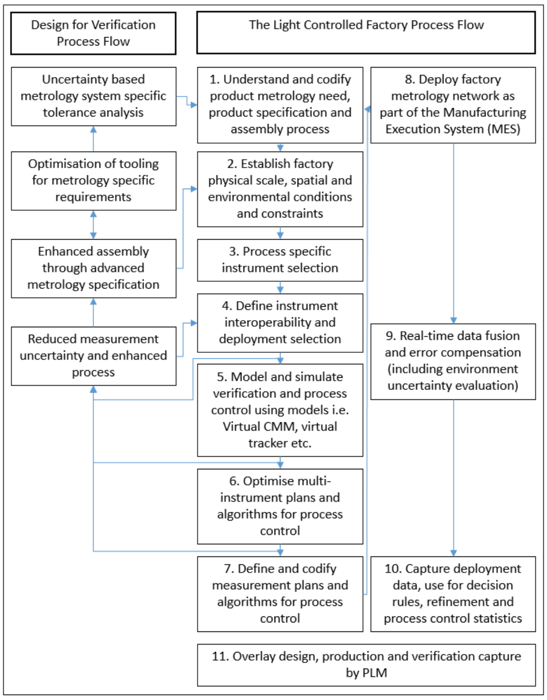

Figure 6: DfV Framework within the Context of the Light Controlled Factory (EPSRC grant EP/K018124/1)

framework, Figure6, promotes a trade-off analysis between the following to establish an optimised design for end stage dimensional verification:

1. Tooling Design Parameters
2. Tolerancing Synthesis and Analysis
3. Assembly Process
4. Metrology Process

The Light Controlled Factory Process Flow (EPSRC grant EP/K018124/1), illustrated within Figure6 details the state of the art in metrology process planning. DfV has been designed to complement the process flow in order to achieve successful end stage dimensional verification.

4. Conclusions

A novel DfV framework has been established that provides unique pathways for designers of complex assemblies to achieve the dimensional verification of large structures at the final assembly stages, at a specified confidence level. The DfV framework was realised and tested via its implementation into the Light Controlled Factory process flow.

Definitions of verification have been explored and the authors have shown the necessity for developing new Design for Verification (DfV) methods within DfX and proposed a methodology for their implementation. Design for verification is a vital ingredient of design development and its rules, algorithms and implementation methodology are directly linked to knowledge and data arising from product and process verification via the deployment of metrology. In this context, DfV is intrinsically linked to the theory and implementation process of the Light Controlled Factory that is a new concept for the factories of the future that will have embedded verification capability via the widespread deployment of optical metrology systems for parts verification and process capability enhancement. In order for DfV to be most effective, it is vital that its application starts early during design and process planning and the process is an integral element of the future Light Controlled Factory network of functions and implementation processes.

5. Acknowledgments

The authors would like to gratefully acknowledge the financial support of the EPSRC, grant EP/K018124/1, "The Light Controlled Factory". Thanks also go to the industrial collaborators for their contribution as well as the Department of Mechanical Engineering at the University of Bath.

6. References

[1] J. G. Bralla, Design for Excellence. McGraw-Hill, 1996.
[2] K. Yang and B. EI-Haik, Design for Six Sigma: A Roadmap for Product Development. McGraw Hill Professional, 2008.
[3] G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, Engineering Design: A Systematic Approach. Springer Science & Business Media, 2007.
[4] M. Balesdent, N. Bérend, P. Dépincé, and A. Chriette, "A survey of multidisciplinary design optimization methods in launch vehicle design," Struct. Multidiscip. Optim., vol. 45, no. 5, pp. 619–642, Sep. 2011.
[5] G. F. Barbosa and J. Carvalho, "Analytical model for aircraft design based on Design for Excellence (DFX) concepts and use of composite material oriented to automated processes," Int. J. Adv. Manuf. Technol., vol. 69, no. 9–12, pp. 2333–2342, Aug. 2013.
[6] P. Franciosa and D. Ceglarek, "Hierarchical synthesis of multi-level design parameters in assembly system," CIRP Ann. - Manuf. Technol., vol. 64, no. 1, pp. 149–152, 2015.
[7] J. Herskovits, Ed., Advances in Structural Optimization, vol. 25. Dordrecht: Springer Netherlands, 1995.
[8] A. Whiteside, E. Shehab, C. Beadle, and M. Percival, "Developing a current capability design for manufacture framework in the aerospace industry," Compet. Des. - Proc. 19th CIRP Des. Conf., pp. 223–228, 2014.
[9] Hexagon Metrology, "Leica Absolute Tracker AT901," ASME B89.4.19-2006 Specifications. [Online]. Available: http://www.leica-geosystems.co.uk/downloads123/m1/metrology/AT901/brochures-datasheet/Leica Absolute Tracker_ASME Specifications_en.pdf.
[10] B. Hughes, A. Forbes, A. Lewis, W. Sun, D. Veal, and K. Nasr, "Laser tracker error determination using a network measurement," Meas. Sci. Technol., vol. 22, no. 4, p. 045103, Apr. 2011.
[11] P. Maropoulos. Z. Wang, A. B. Forbes, "Laser tracker position optimization," J. C., vol. 9, no. 1, pp. 8–12, 2014.
[12] N. R. Kinematics, "Overview of Spatial Analyzer," SA Applications, 2015. [Online]. Available: http://www.kinematics.com/spatialanalyzer/. [Accessed: 10-Sep-2015].
[13] P. G. Maropoulos, D. Zhang, S. Rolt, P. Chapman, and B. C. Rogers, "Integration of measurement planning with aggregate product modelling for spacecraft design and assembly," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 220, no. 10, pp. 1687–1695, Jan. 2006.
[14] H.-C. Zhang, Advanced Tolerancing Techniques. John Wiley & Sons, 1997.
[15] P. G. Maropoulos, J. E. Muelaner, M. D. Summers, and O. C. Martin, "A new paradigm in large-scale assembly—research priorities in measurement assisted assembly," Int. J. Adv. Manuf. Technol., vol. 70, no. 1–4, pp. 621–633, Sep. 2013.
[16] B. E. ISO, "Geometrical product specifications (GPS) — Geometrical tolerancing — Datums and datum-systems," BS EN ISO, vol. 2006, no. 50, 2006.
[17] "BS EN ISO 5459 : 2011 BSI Standards Publication Geometrical product specifications (GPS) — Geometrical tolerancing — Datums and datum systems," BS EN ISO, 2011.
[18] L.-M. Qiu, S.-Y. Zhang, C.-W. Xu, and C.-L. Huang, "Automatic assembly planning of configuration product based on mapping," Zhejiang Daxue Xuebao (Gongxue Ban)/Journal Zhejiang Univ. (Engineering Sci., vol. 43, no. 3, pp. 406–413, Mar. 2009.
[19] R. Flynn, K. Christensen, and R. Ryan, "Automated Metrology Solution to Reduce Downtime and De-Skill Tooling Recertification," SAE Int. J. Aerosp., vol. 5, no. 1, pp. 2012–01–1869, Sep. 2012.
[20] J. E. Muelaner, O. Martin, and P. Maropoulos, "Metrology Enhanced Tooling for Aerospace (META): Strategies for Improved Accuracy of Jig Built Structures," 2011.
[21] A. Millar and H. Kihlman, "Reconfigurable Flexible Tooling for Aerospace Wing Assembly," in Aerospace Technology Conference and Exposition, 2009, p. 10.
[22] S. Naing, G. Burley, R. Odi, A. Williamson, and J. Corbett, "Design for Tooling to Enable Jigless Assembly - An Integrated Methodology for Jigless Assembly," 2000.
[23] B. Marguet and B. Ribere, "Measurement-Assisted Assembly Applications on Airbus Final Assembly Lines," 2003.
[24] T. Mbarek, A. Meissner, and N. Biyiklioglu, "Positioning System for the Aircraft Structural Assembly," SAE Int. J. Aerosp., vol. 4, no. 2, pp. 2011–01–2637, Oct. 2011.
[25] K. Vakil, "Meeting Challenges of Key Characteristics (KC) Measurements in Aerospace Manufacturing," in SAE 2012 Aerospace Manufacturing and Automated Fastening Conference & Exhibition, 2012, p. 7.
[26] P. G. Maropoulos, J. E. Muelaner, M. D. Summers, and O. C. Martin, "A new paradigm in large-scale assembly-research priorities in measurement assisted assembly," Int. J. Adv. Manuf. Technol., vol. 70, no. 1–4, pp. 621–633, 2014.