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Procedia CIRP 00 (2013) 000–000

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Forty Sixth CIRP Conference on Manufacturing Systems 2013

Achieving Low Cost and High Quality Aero Structure Assembly through Integrated Digital Metrology Systems

J E Muelaner*, O C Martin, P G Maropoulos

Laboratory for Integrated Metrology Applications (LIMA), Department of Mechanical Engineering, The University of Bath, Bath, BA2 7A, UK

* Corresponding author. Tel.: +44 (0) 7743-845-124; fax: +44 (0) 1225-38-6928; .*E-mail address*: j.e.muelaner@bath.ac.uk.

Abstract

Measurement assisted assembly (MAA) has the potential to facilitate a step change in assembly efficiency for large structures such as airframes through the reduction of rework, manually intensive processes and expensive monolithic assembly tooling. It is shown how MAA can enable rapid part-to-part assembly, increased use of flexible automation, traceable quality assurance and control, reduced structure weight and improved aerodynamic tolerances. These advances will require the development of automated networks of measurement instruments; model based thermal compensation, the automatic integration of 'live' measurement data into variation simulation and algorithms to generate cutting paths for predictive shimming and drilling processes. This paper sets out an architecture for digital systems which will enable this integrated approach to variation management.

Selection and/or peer-review under responsibility of Professor Pedro Filipe do Carmo Cunha

Keywords: Measurement Assisted Assembly; MAA; Assembly

1. Introduction

Aircraft assembly involves tooling which determines structure form, manual fitting and through assembly drilling [1]. Achieving rapid assembly using interchangeable parts has not been possible due to demanding interface tolerances and large flexible components. Automation of drilling [2, 3] remains costly and inflexible due to the use of gantry based machines. The use of heavy steel structures built on a concrete foundation for assembly tooling further contributes to high capital costs and a lack of flexibility [4].

Industrial drivers to overcome these challenges include; ramp-up in production volume; component variability issues inherent in the move to composite structures; and pressure on established manufacturers from low wage economies. Carbon emission targets coupled with increasing fuel costs require significantly improved performance for new aircraft through weight reduction and the tightening of aerodynamic profile tolerances. These industrial drivers are captured by five objectives for the next generation of aircraft assembly processes:-

- **Part-to-part assembly**: An assembly process where all component forming is conducted pre-assembly allowing rapid one-way assembly [5]. The move to composites and more tightly toleranced aerodynamic profiles makes this more challenging.
- **Low cost flexible tooling and automation**: Expensive bespoke assembly tooling and gantry based automation should be replaced by reconfigurable tooling and standard industrial robots, the requirement for assembly tooling may also be reduced through increasingly determinate assemblies.
- **Traceable quality assurance and control**: Traceable measurements, tolerance analysis and machine capability studies should be applied to ensure that the assembly is built right first time and with improved accuracy of aerodynamic profiles.
- **Elimination of excess weight**: Fettle and shim allowances should be removed and improved accuracy should reduce the factors of safety required.
- **More accurate aerodynamic profiles**: Reduced tolerances are likely to be required in order to improve aerodynamic performance. This will place additional demands on the requirements for part-to-part assembly and traceable measurement.

This paper first defines Measurement Assisted Assembly (MAA) and then shows how it can achieve each of the above objectives.

2. Measurement assisted assembly

Measurement Assisted Assembly (MAA) involves using measurements to guide assembly, for example:-

- **Predictive processes** (fettling, shimming [6] and drilling) in which component measurements are used to adaptively form interfaces ensuring fit in assembly. This allows craft based fitting processes to be automated and performed prior to assembly without parts being 'offered up' in assembly.
- **Assemble-Measure-Move (AMM)** [5] processes where a component is iteratively positioned, measured and re-positioned until within tolerance.
- **Active tooling** which utilizes actuated component pick-ups to adapt to feedback from dimensional measurement of the tooling and thermal measurement of the components.
- **Closed loop control** with feedback from external metrology systems to improve the accuracy of flexible automation systems such as industrial robots.

3. Part-to-part assembly

Part-to-part assembly, one-way assembly of parts which are fully formed prior to assembly, is conventionally achieved using interchangeable parts. Where Interchangeability (ICY) cannot be achieved predictive processes can facilitate part-to-part assembly. This involves, measuring components, predicting how they will interface with each other and then forming bespoke interfaces to achieve the required form and fit. If predictive processes were applied to both surface-to-surface contact and hole-to-hole interfaces it would be possible to achieve determinate assembly without requiring assembly tooling to control structure form.

This Measurement Assisted Determinate Assembly (MADA) approach would require aircraft structure design modifications and improved measurement capabilities [5]. Predictive processes may however achieve part-to-part component location without any fettling or shimming, followed by in-tool drilling. For one-way assembly to avoid disassembling, deburring, cleaning and re-assembling after drilling improved drilling processes such as orbital drilling [7] are required.

Design for manufacture is vital to realizing part-to-part assembly; a decision process is shown in figure 1 for the rational selection of structure designs. This involves generating multiple structure designs and then using tolerance analysis and optimization to determine which assembly philosophy can achieve the required form and fit tolerances. The selection process gives precedence to assembly philosophies in which the least component forming takes place during assembly and which have the least reliance on assembly tooling. When carrying out tolerance analysis for predictive processes the uncertainty of measurement should be included as a source of assembly variation [8]. Detailed uncertainty evaluation and simulation may be impractical during the iterative design phase and therefore typical known uncertainties for standard MAA processes should be provided within tolerance analysis software.

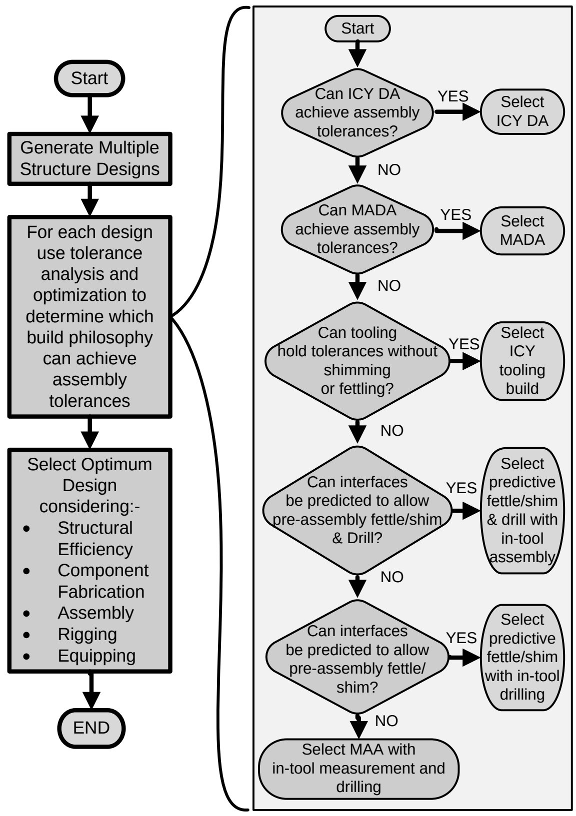

Fig. 1. Design for assembly decision process

4. Low cost flexible tools and automation

The requirement for lost cost flexible tools and automation is generally divided into assembly tooling (jigs and fixtures) and automation (machines and robots). Reconfigurable tooling has the potential to increase flexibility and reduce cost for assembly tooling by utilizing standard parts which enable a streamlined design process, economies of scale in production, modification in use and reuse of components. Moving from bespoke automation towards the use of standard industrial robots will reduce non-recurring costs since the capital costs of bespoke machines are considerably higher than standard robots while also increasing flexibility. Increased human-robot interaction will also enable this flexible automation to be implemented in a wider range of applications.

Currently, tooling is used both to control the form of emerging assemblies and as a gauge for verification [9]. Although reconfigurable tooling is established in other industries it is difficult to employ in aircraft assembly due to the critical requirement for stability arising from its use dual use as tool and gauge, tight interface tolerances and large scales.

The demands on tooling may be reduced by using assemble-measure-move for assembly and independent measurements for verification. The extent to which measurements can be made independent of the tooling may be limited however since; 1) while the structure is in-tool critical features are occluded; and 2) measurement after removal from tooling adds to process time while in-tooling rework is no longer possible.

Determinate assembly reduces demands on tooling as well as process complexity and should be a long term goal, but accuracy demands mean it is unlikely to provide a widespread solution in the foreseeable future.

There is therefore a requirement for more dimensionally stable reconfigurable tooling systems which cannot be met by conventional passive tooling. Active tooling allows for dimensional drift and thermal expansion of the assembly to be compensated using actuators located close to key interfaces with the assembly. The accuracy of this approach depends on the ability to measure accurately and directly the key characteristics of the tooling or assembly. Due to occlusions within tooling during assembly it is extremely difficult to measure the key characteristics using the current state of the art large volume measurement instruments such as laser trackers and photogrammetry. Additionally, variations in the refractive index across the production environment lead to overly high uncertainties of measurement.

An alternative approach to providing dimensional feedback for active tooling is to embed measurement within the tooling using networks of interferometers [10], an approach first used for particle accelerator alignment [11]. Embedded metrology tooling avoids the limitations of occlusions preventing direct measurements and of environmental uncertainties by propagating optical measurements within the tooling structure.

The adoption of standard industrial robots in aircraft assembly is made difficult by factors such as:-

- Accuracies of 0.2 mm to 0.02 mm required for drilling, fettling and component location operations cannot currently be achieved by industrial robots [12]
- Large numbers of unique operations
- Concurrent manual operations in a confined space

The accuracy of industrial robots can be improved using external metrology systems in different ways for different processes. Global referencing or *Adaptive Robotic Control* (ARC) enables holes to be drilled within ±0.2 mm relative to datums a few meters away [13]. Scanning and vision based sensors mounted on the end effector can be useful to reference local features when drilling [14] or placing components [15]. These techniques cannot achieve the ±0.02 mm accuracy required to match up hole patterns for interference fit fasteners which are commonly used in aircraft assemblies. For this it is possible to mimic manual alignment using vision get holes approximately aligned and then inserting tapered pins to achieve final alignment. The compliance required for this can be implemented in a robotic system using force feedback.

Programming robots to perform many unique operations requires efficient off-line programming and sufficient accuracy so that manual teaching of robots is not required. Improved human-robot cooperation and safety mechanisms are required to enabled concurrent manual operations within a confined space to continue while robots operate.

5. Traceable quality assurance and control

Quality Assurance (QA) demonstrates that product specifications **will be** fulfilled while Quality Control (QC) demonstrates they **are being** fulfilled, typically by final product inspections. QC involves explicit verification, ensuring that a product meets specification; validation is also implied since the product specification should be validated to ensure the product requirements.

Established QC methods, including six sigma [16], involve product measurement using ‘capable’ instruments and acceptance of products where the measurement results fall within specification limits (tolerances). Instrument capability is determined by ensuring instruments are calibrated and by performing gauge repeatability and reproducibility (Gauge R&R) studies to ensure that the ratio of measurement variability to product tolerance (‘P/T’) is less than 10% [17]. This approach does not ensure that out of tolerance parts are rejected since uncertainties arising from sources such as the temperature and calibration reference standard are not properly considered, results very close to the specification limit are accepted and it is also often impractical to achieve a P/T ratio of less than 10%.

A more rigorous approach to QC, described within the ISO Geometrical Product Specification standards is the use of *Decision Rules for Proving Conformance* [18]. According to this approach every measurement must be accompanied by an evaluation of its uncertainty. A conformance zone is then determined by offsetting specification limits towards the nominal value of the dimension by the measurement uncertainty. Assuming the uncertainty of measurements is correctly evaluated

[19] this approach gives a valid statistical confidence that out of tolerance parts will be rejected.

Current uncertainty evaluations for measurements of aircraft structures are incomplete as they do not fully account for temperature variation which influences optical measurements due to refractive index changes; and causes thermal expansion of the assembly. The state of the art of industrial optical measurements involves compensating for the refractive index at a single point and estimating the uncertainty due to variation throughout the working volume. This is valid but to improve accuracy it will be necessary to compensate for temperature throughout the working volume.

State of the art compensation for thermal expansion involves measuring the assembly at multiple locations and scaling measured results in zones back to the reference temperature of 20°C using the material's coefficient of thermal expansion. This approach ignores the bending and twisting which temperature gradients across a large structure may induce. For a valid evaluation of uncertainty estimates of these errors must be included. Model based methods are required to evaluate the uncertainty due to thermal expansion and facilitate compensation for these errors.

Assembly tooling is often used as a gauge for verification with checks such as rotating of location pins and inserting slip gauges used to determine component position relative to the tooling. The problem with this approach is that since the tooling is in continuous use for assembly it is more susceptible to damage than a gauge, while at the same time recalibration of the tooling causes significant disruption to production. The development of active tooling with embedded interferometer networks as described in the preceding section will provide continuous in service calibration of the tooling, while also negating uncertainties due to refractive index variation within the production environment.

Traceable quality assurance and control will involve frequent measurements with known uncertainty during assembly. Uncertainties will be reduced through embedded interferometer systems which are not significantly affected by the external environment and through model based evaluation and compensation of errors due to thermal expansion of the assembly. Incorporating these measurements into tolerance analysis models; replacing nominal values with measured values and component variability with measurement uncertainty; will provide an estimate of the final assembly tolerances based on the latest data available and with known statistical confidence intervals. This will enable informed and possibly automated decisions to be taken regarding rework ensuring that this always takes place at the earliest opportunity but only when required.

6. Elimination of excess weight

In addition to the production efficiency gains from interchangeable parts there is also a reduction in assembly weight since fettling allowances, all of which are not normally removed, or shims are not required. Predictive fettling can in some cases also remove the requirement for any fettling allowance to remain on the finished part and therefore achieve the same level of strength to weight performance as an interchangeable part. This Whole-Part Predictive Fettling (WPPF) uses measurements of an interfacing part to fettle the interfacing surface but also remove any excess material around the interface zone as shown in figure 2 using the example of rib foot fettling for an aircraft wing.

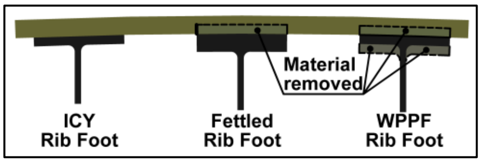

Fig. 2. Whole-part predictive fettling to reduce weight of predictive fettled parts

WPPF is generally not practical when fettling components within an assembly. If however measurement and subsequent adaptive machining is used to carry out WPPF during component manufacturing then it does become possible to remove weight without adding to process time. For example measurements made of recently fabricated composite wing covers and spars could be used to carry out WPPF on rib feet while they are still fixtured in a machine tool.

As traceable quality assurance and control becomes increasingly established this will enable factors of safety (FoS) to be reduced leading to further reductions in structure mass.

7. An integrated approach to dimensional variation management

The use of MAA to achieve all of the benefits described above will result in a significant increase in complexity of decision making processes and data management. This will require an integrated approach to the management of dimensional variation which starts during the initial selection of structure designs and continues throughout the production process.

An architecture for this Integrated Dimensional Variation Management (IDVM) [20] is illustrated in figure 3 showing two domains; 1) The design and process planning domain where different structures and assembly processes are developed within a 3D CAD based environment; and 2) The manufacturing executable (MES) domain where measurement data is captured, model based compensations are made, decision rules are applied to the data and it is used to control automation systems carrying out predictive fettling and drilling operations, as well as to inform production managers of quality metrics of the product.

Within the design and process planning domain, the structure design and build philosophy are first selected as detailed in Figure 1 and the structure design is then refined applying DfM principles. Step three involves detailed assembly process planning and detailed tolerance modeling including measurement simulation for the final structure design. In the final stage of the design and process planning domain algorithms are defined which will perform functions such as the integration of multi-sensor measurements, thermal compensation, applying decision rules to flag non-conformance and controlling fettling or drilling operations. The manufacturing executable domain, carried out during production, involves these algorithms running in real-time on automation systems to carry out quality assurance/control and to drive MAA processes.

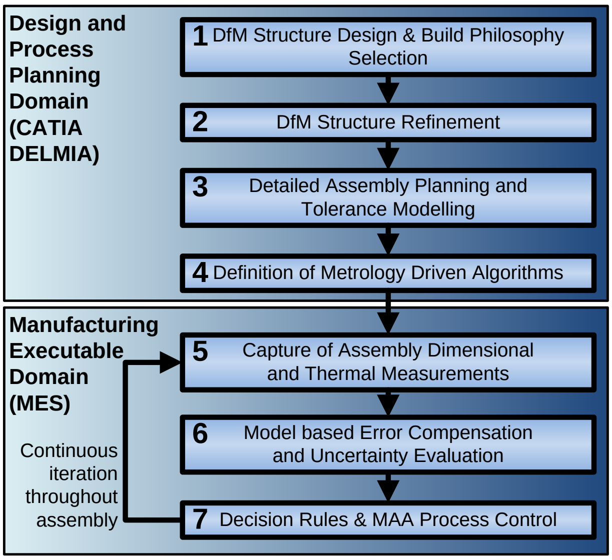

Fig. 3. Summary of Integrated Dimensional Variation Management

8. Research priorities

The realization of measurement assisted assembly (MAA) in order to meet the objectives for enhanced aircraft assembly depends fundamentally on the development of IVDM. The IDMV architecture must enable design for manufacture within an MAA manufacturing system. Specific areas for development include: the definition and verification of standardized methods of carrying out tolerance analysis for MAA processes; measurement uncertainty evaluation and compensation algorithms for optical measurements; thermal expansion modeling and compensation for large structures; and digital tools to enable simulation models developed during design and process planning to seamlessly develop into algorithms controlling a Manufacturing Execution System (MES) which is capable of incorporating data from disparate sites to allow predictive forming processes.

IDVM implies the presence of automated metrology networks monitoring components, assemblies, tooling and automation throughout the manufacturing process. These networks will include both frameless optical instruments such as laser trackers and photogrammetric cameras and metrology embedded within tooling. Target recognition, tracking of multiple targets across the field of view for multiple instruments, thermal compensation and data fusion must all be automated. There is also a specific requirement for more accurate measurement of hole positions on large structures. For metrology embedded within tooling new types of instruments should be developed which enable low cost interferometer networks to directly reference the key characteristics of active tooling and structures fixtured within the active tooling.

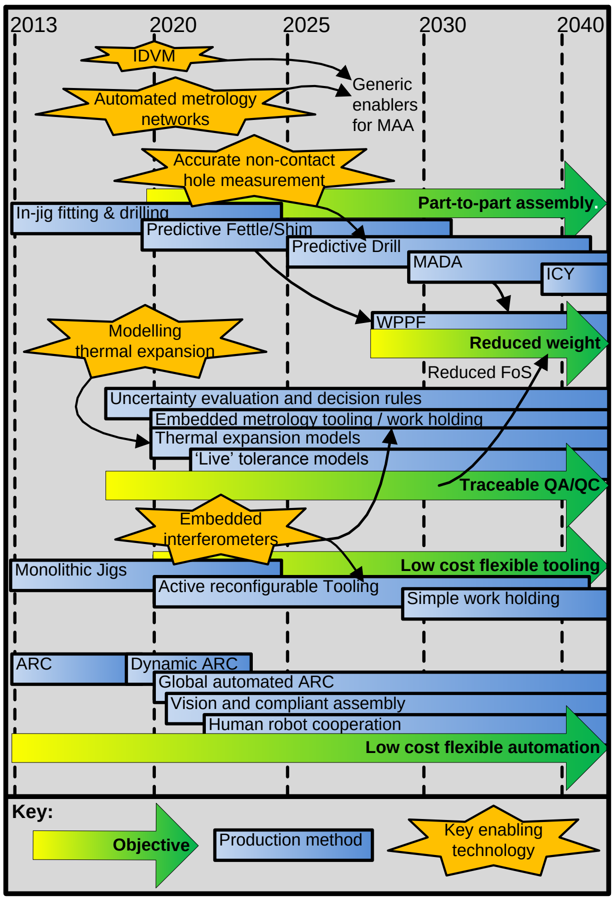

Fig. 4. Measurement Assisted Assembly research roadmap

Figure 4 illustrates the way in which the key technologies where research effort is required will enable new production methods and in turn how these will meet the objectives defined for aircraft assembly. This roadmap also gives an approximate indication of the time frame over which these developments might take place assuming that sufficient research effort is applied in the areas identified.

Acknowledgements

This work has been carried out as part of the EPSRC, IdMRC at the Mechanical Engineering Department of the University of Bath, under grant No. EP/E00184X/1.

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