A New Paradigm in Large Scale Assembly - Research Priorities in Measurement Assisted Assembly

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Abstract: This paper presents for the first time the concept of Measurement Assisted Assembly (MAA) and outlines the research priorities of the realisation of this concept in industry. MAA denotes a paradigm shift in assembly for high value and complex products and encompasses the development and use of novel metrology processes for the holistic integration and capability enhancement of key assembly and ancillary processes. A complete framework for MAA is detailed showing how this can facilitate a step change in assembly process capability and efficiency for large and complex products, such as airframes, where traditional assembly processes exhibit the requirement for rectification and rework, use inflexible tooling and are largely manual, resulting in cost and cycle time pressures. The concept of MAA encompasses a range of innovative measurement-assisted processes which enable rapid part-to-part assembly, increased use of flexible automation, traceable quality assurance and control, reduced structure weight and improved levels of precision across the dimensional scales. A full scale industrial trial of MAA technologies has been carried out on an experimental aircraft wing demonstrating the viability of the approach while studies within 140 smaller companies have highlighted the need for better adoption of existing process capability and quality control standards. The identified research priorities for MAA include the development of both frameless and tooling embedded automated metrology networks. Other research priorities relate to the development of integrated dimensional variation management, thermal compensation algorithms as well as measurement planning and inspection algorithms linking design to measurement and process planning.

1 INTRODUCTION

The assembly of high quality large scale and complex structures such as airframes typically involves fixturing large flexible components within assembly tooling which controls the shape of the emerging structure. Gaps are assessed using slip gauges and other manual inspection techniques and components are shimmed or fettled to ensure that interface tolerances are maintained. Holes are then drilled through the components and they are fastened together [1]. The examples and case study below relate to the assembly of a civil aircraft wing box although many of the methods described have applicability in applications as diverse as spacecraft and wind turbines.

The development of interchangeable parts which facilitated rapid assembly in many industries [2, 3] has not been possible in large scale assembly. The combination of demanding interface tolerances and large flexible components has prevented interchangeability, meaning that components often have to be fettled or shimmed [4] while patterns of holes used to fasten components together have to be drilled through the stack of components within the assembly [5].

Up to 40% of the total manufacturing cost of an airframe is incurred during assembly, with drilling a significant contributor to assembly time [6]. Although significant progress has been made to automate drilling operations [7-10] current production solutions rely on costly and inflexible gantry based machines.

The assembly tooling which is used to control the form of assemblies is typically a heavy steel structure built on a concrete foundation. This monolithic tooling is very expensive to manufacture, has long lead times and has little ability to accommodate product variation and design changes [11]. Assembly tooling accounts for approximately 10% of the total manufacturing cost of an airframe [12].

Ramp-up in production volume, component variability issues inherent in the move to composite structures and pressure on established manufactures from low wage economies are all increasing the requirement to overcome the issues described above and improve production efficiency [13, 14]. Additionally, increasing fuel costs and CO_2 emission reduction targets require significantly improved performance from new aircraft which means that excess weight must be removed and aerodynamic profile tolerances tightened.

The demands for enhanced production capability, efficiency and product performance are captured by five objectives for the next generation of large scale assembly processes:-

- **Part-to-part assembly**: An assembly process where all component forming is conducted pre-assembly allowing a rapid one-way assembly process [15]. The move to composite structures makes this more difficult as composite components generally have more dimensional variability.
- **Low cost flexible tooling and automation**: Expensive bespoke assembly jigs and gantry based automation should be replaced by reconfigurable tooling and standard industrial robots, additionally the requirement for assembly tooling may be reduced through the adoption of 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.

In the following sections Measurement Assisted Assembly (MAA) is first defined and it is then shown how MAA can achieve each of the above objectives.

2 MEASUREMENT ASSISTED ASSEMBLY

Measurement Assisted Assembly (MAA) denotes a paradigm shift in assembly for high value and complex products and encompasses the development and use of novel metrology processes for the holistic integration and capability enhancement of key assembly and ancillary processes. This definition of MAA places in context previously reported MAA methods [4]. Typical MAA processes include:-

- **Predictive processes (fettling, shimming** [16] **and drilling)** in which component measurements are used to adaptively form components' interfaces so that they fit to one another before physically assembling them. This essentially means using measurements to facilitate the automation of fitting processes which would conventionally be manual and highly skilled craft based processes. It also allows the bespoke interfaces to be formed prior to assembly as opposed to conventional fitting which relies on 'offering up' parts to each other during assembly.
- **Assemble-Measure-Move (AMM)** [15] processes where a component is positioned approximately in an assembly, the position of the component is measured and then it is moved towards its specified position. This process may be iterated a number of times before the component is within its specified position; alternatively 'real time' measurements may be used to 'track' the component into location.
- **Active tooling** is a form of assembly tooling which utilizes actuated component pick-ups to adapt to feedback from sources such as dimensional measurement of the tooling and thermal measurement of the components. It therefore does not rely on inherent dimensional stability to be maintained for prolonged periods to provide an accurate location for components and can enable reconfigurable tooling.
- **Closed loop control** used to improve the accuracy of flexible automation systems such as industrial robots. All high accuracy automation systems use some form of closed-loop control with encoders located on the axis of movement. An assembly machine is generally only considered to be using MAA when an external metrology system is used to provide closed loop control.

3 PART-TO-PART ASSEMBLY

Part-to-part assembly, where all component forming is conducted pre-assembly allowing a rapid one-way assembly process, this is conventionally achieved using interchangeable parts. Due to demanding interface tolerances and large flexible components this has not been possible for aerospace structures. Predictive processes provide an alternative approach to achieving part-to-part assembly. These processes involve first measuring components to predict how they will interface with each other and then forming bespoke interfaces so that they are able to fit together without excessive gaps or interference and will achieve the required assembly form.

Predictive processes [16] could in theory be used to form all interfaces including both direct surface-to-surface contact between components and hole-to-hole interfaces where fasteners join components.

If predictive processes were fully implemented in this way then it would be possible to achieve an assembly where the way in which components 'stack together' determines the form of the assembly without requiring assembly tooling to control it.

Such *determinate assemblies* are common where small, stiff interchangeable components are used, for example engines, and they have started to replace tooling built structures for lower accuracy areas of aircraft structures such as locating seats inside the cabin of the Boeing 777 [17]. Analysis of the application of determinate assembly to more demanding areas of aircraft structures using predictive processes, referred to as Measurement Assisted Determinate Assembly (MADA), has shown that this would require design modifications to aircraft structures as well as improved measurement capabilities [15].

Partial implementation of predictive processes to achieve part-to-part component location (without any fettling or shimming) followed by in-assembly drilling is achievable using current technology as demonstrated in the industrial trial described below. Achieving one-way assembly using such a process would not be possible using conventional drilling which requires an aero-structure to be disassembled after drilling to debur holes and remove swarf before final assembly and fastening. Using orbital drilling it is however potentially possible to achieve finished holes within a one-way assembly process [18].

The design for manufacture decision process, illustrated in Figure 1, involves multiple design configurations being generated which each involve breaking the complete structure into discrete components and sub-assemblies at different areas of the structure. For each design, tolerance analysis and optimization [19, 20] is used to determine which assembly paradigms are achievable with preference given first to a conventional determinate assembly of interchangeable parts (ICY DA), then to MADA, then jig build with interchangeable (ICY) parts, next predictive fettle/shim & drilling with in-jig assembly, followed by pre-assembly predictive fettle/shim and in-jig drilling and finally MAA with bespoke interfaces formed in-jig. The progression from most preferable process to least preferable process represents an increasing amount of component forming taking place during assembly and increasing reliance on assembly tooling.

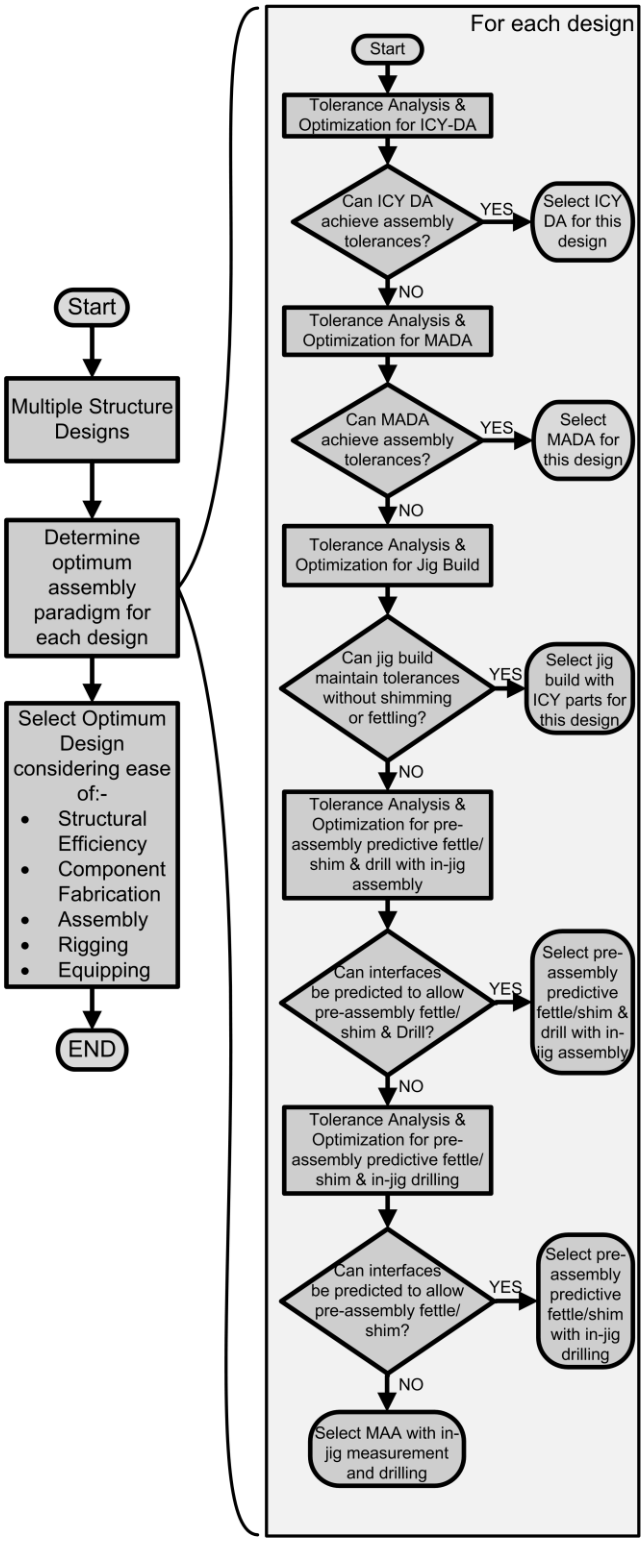

Figure 1: Build Paradigm Selection

Tolerance analysis of predictive processes (MADA etc.) must include the uncertainty of measurements as a source of assembly variation [21] which can be determined for complex measurements using a separate measurement simulation [22]. At this stage in the design process however it may be more efficient to include typical known uncertainties for standard MAA processes within the tolerance analysis software. These standard uncertainties may be dependent on a few parameters which can be easily defined such as component size and operating temperature range.

The definition and verification of standardized methods for tolerance analysis of MAA processes is currently lacking from the state of the art although the case study presented in this paper provides an initial reference for this.

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.

The ways in which reconfigurable tooling, industrial robots and human-machine cooperation might be utilized within large scale assembly, and the challenges involved are discussed below. It should also be noted at this point that there is some overlap between assembly tooling and automation systems, for example where both robots and active tooling may utilize closed loop control with coordinate measurement instruments providing feedback.

4.1. RECONFIGURABLE TOOLING

Reconfigurable Tooling is centrally concerned with replacing traditional jigs and fixtures with a suite of tooling building blocks that can be reconfigured to adopt product variants and new products. Currently, tooling acts as a quality gate for the assembly [23]; holding the components in place during the build, and in many cases the completed assembly is subsequently checked using the tooling; in these instances the tooling can be thought of as a large-scale secondary gauge measurement.

Although reconfigurable tooling systems are widely used for medium scale assembly and systems intended for large scale assembly are commercially available [24, 25] they are currently difficult to employ in large-scale assemblies. Tooling needs to be set to positional tolerances of approximately 0.25 mm over tens of metres; this requires a high level of stability. Traditional tooling consists of heavy, steel welded structures with key interfaces ground and the global structure stress relieved. If reconfigurable tooling is to mimic the passive tooling philosophy of traditional tooling it needs to replicate this stability while using lighter component members and potentially stress-relieving fasteners. This stability will need to last for years to ensure confidence.

The dependence on tooling may be reduced by using MAA processes to locate components and/or features, and by verifying structures independently of the fixture. The extent to which verification can be made independent of the fixture may however be limited since while the structure is in-fixture many critical features will be occluded by the fixture and when the structure is removed measurement activities will add to process time while it will at that stage be too late to perform in-fixture corrections to the structure.

The long-term goal is to move away from fixture-built structures towards determinate assembly where only simple work holding is required. This would negate the requirement for accurate fixturing and the tooling would merely provide support for the components. It is however likely that as the need for aerodynamic performance improvements drives down tolerances there will be a continuing requirement for at least some accurate fixtures in the build process.

The continuing need for tooling combined with an increased accuracy requirement and move towards lighter reconfigurable structures presents major challenges for the traditional passive tooling approach. The application of active tooling may overcome these challenges but success will depend on the ability to measure accurately and directly the key characteristics of the tooling or even of the structure being assembled. Due to the large number of occlusions within assembly tooling during the assembly process 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. Thermal gradients within the production environment also mean that uncertainties of measurement may be too high.

An alternative approach to providing dimensional feedback for active tooling is to embed measurement within the tooling using networks of interferometers, an approach which has been referred to as Metrology Enhanced Tooling for Aerospace (META) [26]. A similar approach has been successfully demonstrated using an arrangement of several hundred fibre-coupled interferometers sharing a single laser source to monitor particle detectors within the Large Hadron Collider at CERN [27-29] with a total system cost equivalent to a single laser tracker. Embedded metrology tooling avoids issues with occlusions preventing direct measurement of key characteristics by allowing optical measurements to propagate within the tooling structure its-self. This will also allow localized environmental control of the optical pathways within the tooling for laboratory accuracy without the cost of controlling large production environments.

4.2. FLEXIBLE AUTOMATION

The advantages of utilizing flexible automation in the form of standard industrial robots have been clear for many years [12]. A number of factors however make the adoption of standard robots in large scale assembly difficult, these factors include:-

- High accuracies required for drilling, fettling and component location operations
- Large numbers of unique operations
- Many concurrent activities, many of which are manual, being carried out within a confined space.

Accuracies required for drilling, fettling and component location vary between 0.2 mm and 0.02 mm which cannot be achieved by even the highest accuracy industrial robots [30] and is a major challenge even with external positional feedback. The accuracy of industrial robots can be improved using both localized sensors and global referencing. Different processes require different approaches.

For drilling holes global referencing can provide useful positional feedback [31] to enable holes to be positioned to approximately 0.2 mm relative to datums a few metres away. The use of localized measurement instruments located on the end effector has also been demonstrated to enable drilling of holes with improved accuracy [32].

For component placement local vision sensors can be used to first measure holes or edges to be aligned and then to bring components together relying on the repeatability of the robotic system [33]. For the patterns of interference fit fasteners which are commonly used in aerospace assemblies it may be more relevant to mimic the manual alignment of components; where vision is used to get holes approximately aligned and then tapered pins are inserted through holes in order to bring components into more accurate alignment. The compliance required for such an operation can be implemented in a robotic system using force feedback [34, 35].

The challenge of programming robots to perform many unique operations requires efficient off-line programming. This is dependent on more accurate robotic systems since currently high accuracy robotic operations often require manual correction during initial setup which would not be feasible for thousands of unique operations each of which is to be carried out once on each aerospace assembly.

Improved human-robot cooperation and safety mechanisms will enable greater use of robots within an environment where large numbers of concurrent activities, many of which are manual, are being carried out within a confined space.

5 TRACEABLE QUALITY ASSURANCE AND CONTROL

Quality assurance (QA) involves ensuring processes are capable of providing confidence that quality requirements **will be** fulfilled while *quality control* (QC) involves ensuring that quality requirements **are being** fulfilled, typically by final product inspections. Quality control involves explicit verification, ensuring that a product meets specification; validation is also implied since the product specification should be validated so as to ensure the product requirements [36].

Established quality control methods, including *six sigma* [37, 38], 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 [39] to ensure that the ratio of measurement variability to product tolerance ('P/T') is less than 10% [40]. This approach does not provide a known level of statistical confidence that out of tolerance parts will not be accepted since uncertainties arising from sources such as the temperature and calibration reference standard are not properly considered; furthermore it is often impractical to achieve a P/T ratio of less than 10%.

A more rigorous approach to quality control, described within the ISO Geometrical Product Specification standards is the use of *Decision Rules for Proving Conformance* [41]. 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. This approach gives a statistical confidence that out of tolerance parts will not be accepted. When evaluating the uncertainty of measurement all sources are evaluated such as the uncertainty of the reference standard used for calibration, repeatability of the measurement, uncertainty of the product temperature etc. these are then combined using the law of propagation of uncertainty to give a single combined uncertainty [42-44].

Case study work with 140 small and medium sized companies within the South West of England between 2010 and 2012 found that not a single company was applying decision rules for proving conformance despite the fact that this approach has been in the ISO and British standards for well over a decade.

Assembly fixtures are used to control the form of structures during assembly as described above. Frequently the fixture is then also used as an inspection gauge where checks such as the free rotation of location pins and insertion of slip gauges are used to determine whether components are located correctly with respect to the fixture. The problem with this approach is that since the fixture is used as an assembly tool as well as an inspection gauge it cannot be cared for in the way that a gauge should be. The rigors of a production environment mean that the fixture may be damaged and recalibration of the fixture is normally a major disruption to production.

A further issue with the use of fixtures as gauges is that it is often difficult to assign valid uncertainty estimates to measurement made in this way. One solution might be to carry out direct measurement of the structure using a frameless measurement system such as a laser tracker, however, as discussed in section 4.1 a better solution to measurement within assembly tooling may be to embed interferometers within the tooling structure which will allow continuous monitoring within the fixture using a highly accurate and traceable measurement system.

Currently all uncertainty evaluations for large industrial structures are incomplete as they do not fully account for temperature effects. Temperature effects are often the dominant source of uncertainty and lead to two major error sources; errors in optical measurement systems due to refractive index changes; and errors in the measurand due to thermal expansion. The current state of the art involves compensating optical instruments for the temperature at a single point and making an estimate for the uncertainty due to changes in temperature throughout the working volume. This approach is valid but to improve accuracy it will be necessary to compensate for temperature throughout the working volume and uncertainty estimations could be improved with a more rigorous consideration of refractive index changes.

Where there is a more fundamental shortcoming in the state of the art is regarding the consideration of thermal expansion in the measurand (the structure being measured). Geometric product specifications give dimensions of products assuming that the product is at a uniform temperature of 20°C. For large assemblies it is not possible to control the temperature of the structure and it is therefore current best practice to measure the temperature of the structure and scale dimensional measurements using the known coefficient of thermal expansion for the material. The problem with this approach is that the temperature may vary by several degrees over large structures and the differing rates of thermal expansion which result can induce bending and twisting which can magnify the thermal errors. Model based methods are required to evaluate the uncertainty due to thermal expansion and facilitate compensation for these errors.

Traceable quality assurance and control will involve first continuously measuring structures throughout the assembly process using instruments for which rigorous uncertainty calculations are available. Structure temperature must also be monitored and model based measurement analysis then carried out which accounts for thermal expansion and considers all uncertainty sources. This will provide known levels of statistical confidence about the range of values within which the actual dimensions of the structure may lie. Incorporating these measurements made during assembly 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 [21]. 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

Assemblies which are made up of parts which are not interchangeable not only require additional finishing operations but they are also normally heavier since additional material is required for fettle allowances (all of which is not normally removed) or shims. Predictive fettling can however 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 improved performance can be achieved using *Whole-Part Predictive Fettling (WPPF)* where measurements of an interfacing part are used not only to fettle the actual interfacing surface but also remove material around the interface zone therefore removing any excess material as shown in Figure 2 using the example of rib foot fettling for an aircraft wing.

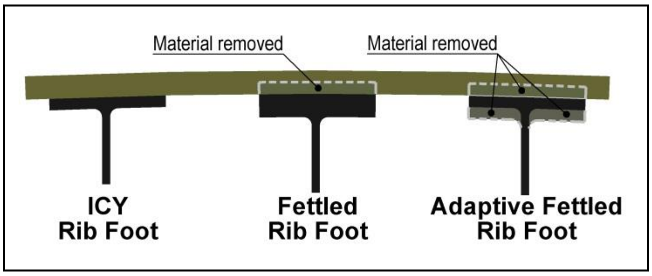

Figure 2: Whole-Part Predictive Fettling to Reduce Weight of Predictive Fettled Parts

It is generally not practical to carry out this type of more complex machining when fettling components within an assembly. If predictive processes are used to determine fettling dimensions at the component manufacturing stage then it does become possible to remove weight in this way without adding to process time. For example measurements could be made of composite wing covers and spars as they leave the autoclave and this information sent digitally to machine tools producing metallic rib feet.

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

7 CASE STUDY: ALCAS RIB FOOT FETTLING

The Advanced Low Cost Aircraft Structures (ALCAS) project had the objective of reducing the weight of an airliner wing by 20% without increasing the cost of manufacture compared to a metallic wing [45]. The demonstration lateral wing box was assembled by Airbus in the UK, Figure 3. The upper cover was produced using a resin infusion moulding technique with a single sided mould tightly controlling the aerodynamic profile, or *outer mould line* (OML) and the inner profile, or *inner mould line* (IML), which interface with the spars and ribs, loosely controlled using a vacuum bag.

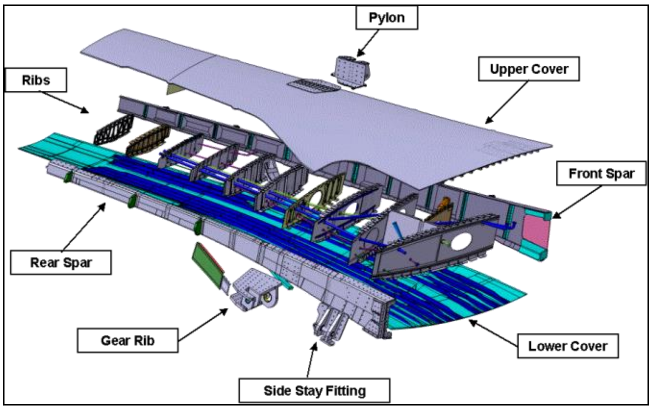

Figure 3: Major Components of the ALCAS Lateral Wing Box

A predictive fettling process was used to maintain the interface between the ribs and the upper cover. Measurements of the cover IML, taken while the cover's OML was held to nominal using a handling fixture, were used to generate machining paths for the fettling of the rib feet. The machining of the rib feet was then carried out after the ribs were assembled using a standard 6-axis industrial robot mounted on a gantry over the wing box to carry out machining using a novel combination of adaptive robotic control [46] and adaptive machining [47, 48]. Measurements of an initial roughing cut, made by a photogrammetry system, were used to apply corrections to the finishing cut. Drilling of holes through the cover and rib feet was carried out after the cover was assembled and therefore part-to-part hole assembly was not required. This assembly sequence is illustrated in Figure 4.

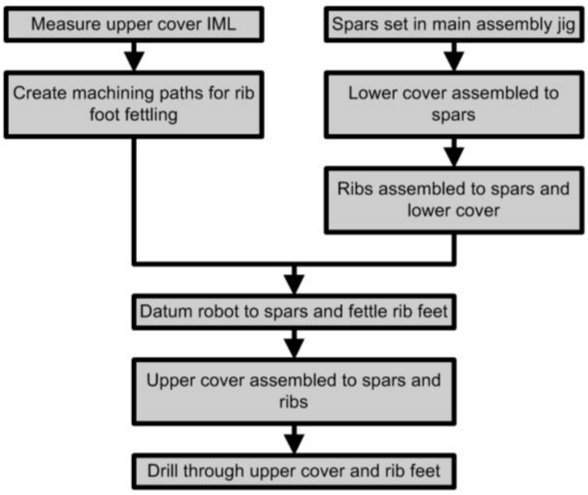

Figure 4: Assembly Sequence for Cover Interface Management

7.1. DATUM STRATEGY

Datums were required to transfer IML measurements of the cover onto the assembly to control rib foot fettling. The IML data consisted of approximately 1,200 three-dimensional coordinates. Additional complexity arose as the cover was expected to deform as it was clamped to the spars. This deformation was simplified by breaking the IML down into a number of rib interface zones (RIZ's) and assuming that as the cover deforms each RIZ will behave as an independent profile which rotates and translates as a rigid body, as shown in Figure 5. Dating is carried out in two phases, in the first phase the primary wing datum or *Wing Coordinate System* (WCS) is referenced. In the second phase of datuming measurements of the spar interface region, included in the measurements of each RIZ, are used to transform the data can be so that the cover maintains contact with the spars. The complete datuming and measurement process is shown in Figure 6.

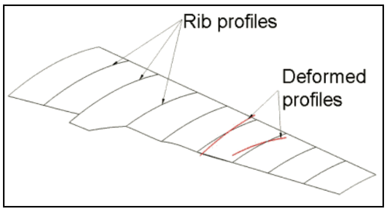

Figure 5: Rib Profiles Transformed as Rigid Bodies

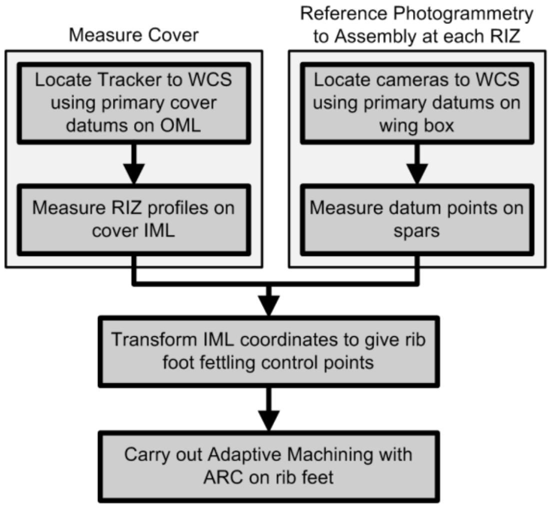

Figure 6: Datum and Measurement Process

The critical step in the datum process is the transformation of the IML coordinates to give rib foot fettling control points. This is where the relative heights of the points on the cover IML which will interface on the spars are compared with the corresponding points on the spars to determine how the cover will deform as it is clamped onto the spars. The information describing this deformation is then also used to transform each control point simulating the rigid body transformation of each RIZ.

For each RIZ (i) there is a reference point on the leading edge spar (L) and trailing edge spar (T), each of these points is measured on the cover IML (C) and on the spar (S). Each point has an x, y and z coordinate so that, for example, the x coordinate of the leading edge spar interface point on RIZ 1, as measured on the cover is denoted by L_{1CX}.

Each RIZ also has a number (j) of rib foot fettling control points (R), each of these points is measured on the cover IML (C) and transformed ready for fettling (F) so that the x coordinate of the second point on the first RIZ, as measured on the cover is denoted by R_{1C2X} or generally R_{iCjX}.

The x-direction distance of a given point R_{iCjX} from the trailing edge reference point belonging to the same RIZ is given by

$$x_{ij} = R_{iCjx} - T_{iCx} \quad (1)$$

The distance in the z-direction from the points measured on the cover IML and the corresponding points on the leading and trailing edge spars are denoted ΔL and ΔT respectively and given by

$$\Delta L_i = L_{Ciz} - L_{Siz} \quad (2)$$

$$\Delta T_i = T_{Ciz} - T_{Siz} \quad (3)$$

In order to reference a RIZ profile measured on the cover IML to the spar datums the coordinates must first be translated in the z-direction by ΔT and then rotated by the remaining angle (θ_{xi}) so that L_{icz} is equal to L_{isz} as shown in Figure 7 and given by

$$\theta_{xi} = \arctan\left(\frac{\Delta L_i - \Delta T_i}{L_{icx} - T_{icx}}\right) \quad (4)$$

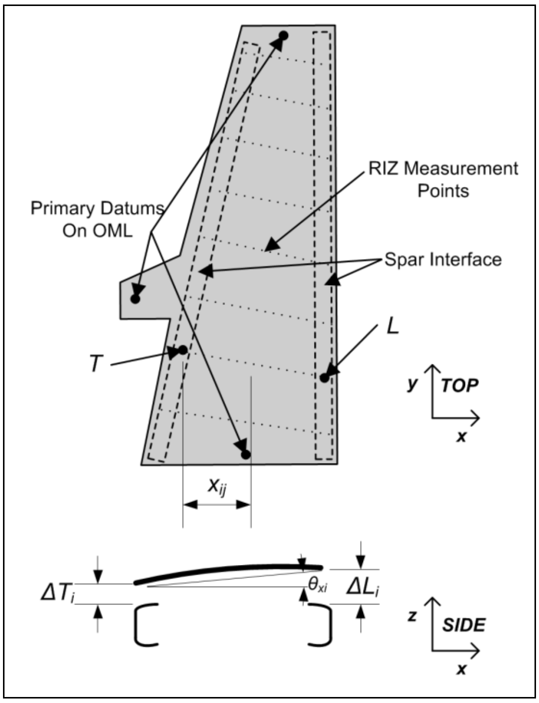

Figure 7: Control Point Transformation Parameters

Assuming that small angle approximations are valid translations in the x and y directions can be ignored and the z-coordinates of the transformed coordinates are therefore given by

$$R_{ifjz} = R_{iCjz} - \Delta T_i - X_{ij} \cdot \tan\theta_{xi} \quad (5)$$

7.2. THE ROBOTIC FETTLING PROCESS

Rib foot fettling was carried out using a standard 6-axis industrial robot to carry out machining using a novel combination of *Adaptive Robot Control* (ARC) and *adaptive machining*. ARC involves a robot moving to a control point in its program using its internal encoders, the position of the end effector being more accurately measured using photogrammetry [49] and this measurement being used to correct the position of the control point before the robot carries out an operation without further feedback from the photogrammetry system [46]. The positional correction stage of ARC is an iterative process repeated until the control point is within tolerance. Adaptive machining involves initial material removal or roughing cuts followed by measurement of the cut surfaces which is used to correct the cutting path for subsequent material removal [47].

ARC is normally used to carry out drilling where for each hole a single control point is corrected for position and surface normality before the drilling tool makes contact with the part. In the case of rib foot fettling approximately ten control points were required for each rib foot and the robot was then required to carry out continuous machining on a path through all of these points. The robot therefore moved through these points with the cutting tool detached from the end effector and positional feedback from the photogrammetry system applied to each in turn. The cutting tool was then attached before machining was carried out. This process was used to make the roughing cuts on the rib feet.

The actual cut surfaces on the rib feet were then measured using the same photogrammetry system as used for the ARC. The deviations from nominal were recorded. The ARC process was then used in the same way as described above to correct the path for the finishing cut but the deviations measured on the roughing cut were used to apply an additional correction. In this way the final cut was made using a combination of ARC and adaptive machining.

Tests were carried out to determine the accuracy of the process with the photogrammetry system referencing a local datum approximately 50 mm from the machined surface. This involved machining test pieces, which were subsequently measured on a coordinate measurement machine (CMM). Results indicated an accuracy of approximately 0.1 mm at a 95% confidence level. The actual rib foot fettling was carried out with datums located on the spar flanges and therefore an additional uncertainty of measurement affected the accuracy of the machining process. Measurement system tests were carried out with datum and instrument positions representative of the actual fettling process, a laser tracker was used as a reference standard with high accuracy measurements made using multilateration [50]. These showed that the when fettling rib feet close to the center of a rib relative to the spar flanges the uncertainty of measurement at a 95% confidence level is approximately 0.2 mm. The combined fettling process positional capability, given by the root of the sum of the squares of machining accuracy and measurement uncertainty, is 0.224 mm.

7.3. TOLERANCE ANALYSIS

An analytical model of the variation in the assembly process was created which considered the uncertainty in the measurement of the cover IML and the fettling process positional capability. The key characteristics of the assembly are the gaps at the rib-to-cover and spar-to-cover interfaces. Figure 8 illustrates the parameters in the analytical tolerance model. It is assumed that the cover is in contact with the spars and the ribs remain fixed to the spars throughout the process. The spar flanges define a nominal x-y plane from which the nominal scanned height of the cover IML (S_n) and the nominal position of rib foot after fettling (F_n) are defined. The uncertainties in S_n and F_n are given by US_n and UF_n respectively.

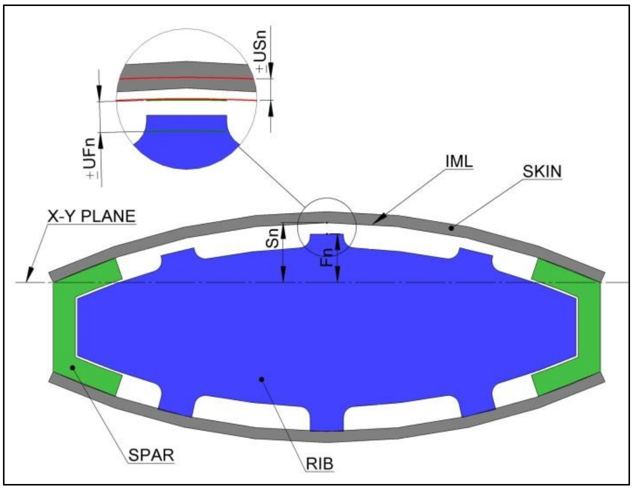

Figure 8 : Diagram of Wing Box Assembly

If the spars are higher than the ribs this would create gaps at the rib-to-cover interface and similarly if the ribs are higher than the spars this would create gaps at the spar-to-cover interface. Since the spar-to-cover gap is more tightly toleranced it was decided to specify the fettled position of the ribs to be lower than the expected cover position by an amount equal to the combined process variation so that the cover would always contact with the spars, therefore

$$F_n = S_n - \sqrt{US_n^2 + UF_n^2} - C \quad (6)$$

where C is the gap caused by the straight line approximation of the curved surface created by passes of an end-mill cutter

The maximum gap at the given confidence level would then be

$$G_{\max} = S_n - F_n + \sqrt{US_n^2 + UF_n^2} \quad (7)$$

Substituting (6) in (7) gives

$$G_{\max} = 2 \cdot \sqrt{US_n^2 + UF_n^2} + C \quad (8)$$

The uncertainty in the measurement of the cover IML US_n and the fettling process positional capability UF_n are the key process variabilities. The upper cover was measured using a laser tracker, the uncertainty of measurement could therefore be simulated using established techniques [51-53] and was found to be approximately 0.05 mm.

The constant gap caused by the end mill cutter making approximations of the curved surface of the cover can be calculated from the radius of the cover surface and the diameter of the cutter. If a 40 mm diameter cutter is used and the minimum radius of the IML is assumed to be 8 m then from geometry we can say that C will be 0.025 mm.

The combined fettling process positional capability is 0.224 mm as described above.

Applying equation (8) we can say that the maximum gap condition, at a 95% confidence level, is

$$G_{\max} = 2 \cdot \sqrt{0.05^2 + 0.224^2} + 0.025 \quad mm$$

$$= 0.48 \ mm$$

7.4. RIB FOOT FETTLING RESULTS AND CONCLUSIONS

The calculated maximum gap condition was just within the 0.5 mm specification. Post process measurements using slip gauges confirmed that the gap was maintained within specification. The largest source of variability is the uncertainty of measurement for the photogrammetry system, the process capability could therefore be improved by using a laser tracker to carry out the measurements used for adaptive machining to approximately 0.27 *mm*.

8 AN INTEGRATED APPROACH TO DIMENSIONAL VARIATION MANAGEMENT

Increased complexity of decision making processes and data management will be involved in using measurement assisted assembly techniques to bring about part-to-part assembly, low cost flexible tooling and automation, traceable quality assurance and control and the elimination of excess weight. This complexity will require an integrated approach which starts during the initial selection of structure designs and continues throughout the production process.

This integrated approach is illustrated in Figure 9. In this integrated dimensional variation management [22] approach there are two domains; the design and process planning domain where different structures and assembly processes are investigated within a 3D CAD based environment; and 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 for the product.

Step one is the first step within the design and process planning domain, it is where the structure design and build philosophy are selected, this step is detailed above in section 3 and Figure 1. Step two continues on from this to refine the structure design applying DfM principles. Step three then takes the final structure design and designs a detailed assembly process around it. At this stage it becomes possible to carry out accurate tolerance modelling including simulation of measurement uncertainty for MAA processes. Step four is the final stage in the design and process planning domain, this is where the algorithms are defined which process metrology data during production. This will include the integration of multi-sensor measurements and thermal compensation as well as using compensated measurements in decision rules regarding when fettling or shimming is required and when quality issues must be flagged to production managers. It also includes the algorithms used to control automated machinery performing predictive fettling and drilling operations.

Steps 5 to 7 are carried out during production within the manufacturing executable domain. This involves the algorithms developed in Step 4 running in real-time on automation systems to carry out quality assurance/control and to drive MAA processes.

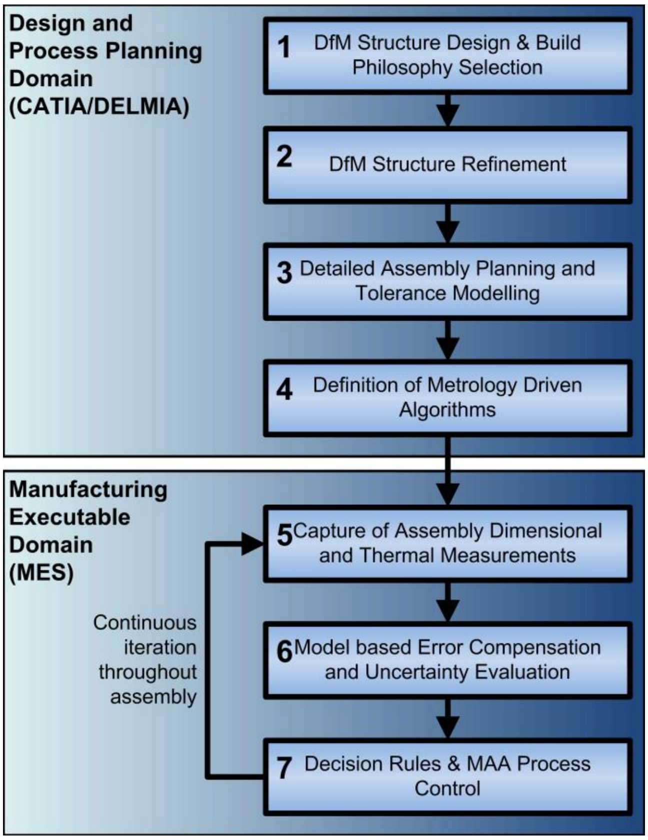

Figure 9 – Integrated Dimensional Variation Management

9 RESEARCH PRIORITIES

The solutions described above involve an increase in using metrology data to characterise components, partially built assemblies, tooling and enhance the capability of automation. If this increased level of measurement is to result in reduced cost then the acquisition of metrology data and its subsequent processing must be automated. Automated metrology networks consisting of either frameless optical instruments or metrology embedded within tooling will be required to carry out measurement. Environmental compensation techniques are necessary to allow the operation of automated measurement networks in real factory environments. Frameless networks are likely to include instruments such as laser trackers and photogrammetry cameras. 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.

An integrated dimensional variation management approach will also be required in order to design for manufacture within a metrology assisted assembly system, to reduce measurement uncertainty and to facilitate the complex data processing required for MAA. 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 modelling and compensation for large structures; and digital tools to enable simulation models developed during design and process planning to seamlessly develop into algorithms to drive manufacturing execution systems (MES). Such MES systems should be capable of incorporating data from disparate sites to allow predictive forming processes.

Figure 10 illustrates the way in which the various technologies discussed above are dependent on one another and can contribute to bringing about the objectives defined in the introduction. This roadmap also gives an approximate indication of the time frame over which these developments can be expected, assuming that sufficient research effort is applied in the areas identified. Key areas for research where additional effort is required are identified with a star.

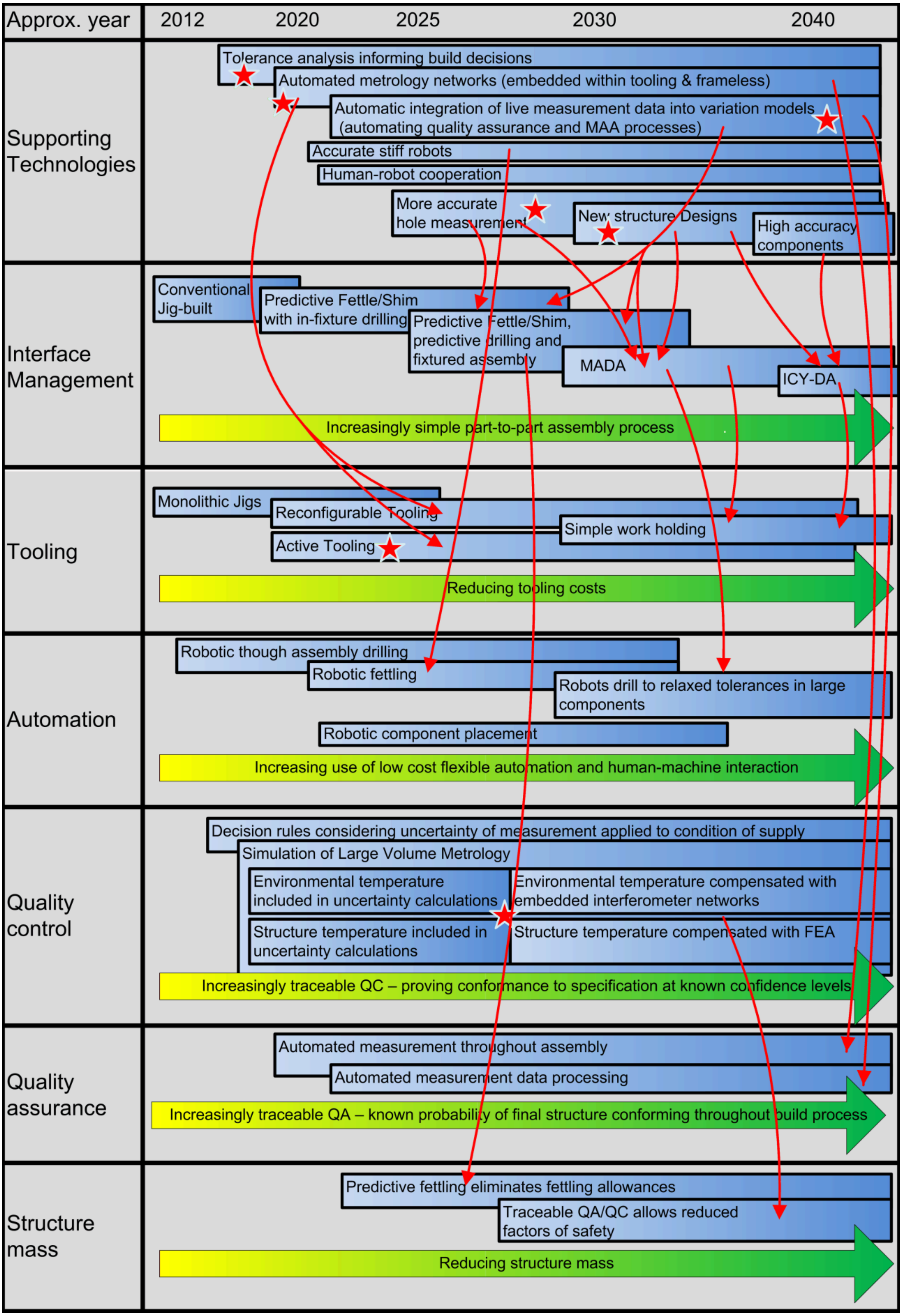

Figure 10 – Research Priorities Roadmap for MAA

CONCLUSIONS

The concept of MAA provides an integrated tool set of processes and methods that offers the potential to enable part-to-part assembly of complex aircraft structures using low cost flexible tooling and automation, while introducing traceable quality assurance and control, reducing structure weight, and improving the accuracy of aerodynamic profiles. The resulting reduction in the cost of manufacturing for civil aircraft would have a significant economic impact while the improvements in aircraft performance would reduce fuel burn and carbon emissions.

Part-to-part assembly will depend primarily on the development of predictive fettling and shimming processes. A range of low cost flexible tooling and automation systems will be required to suit different processes but these will depend on the emergence of pervasive metrology networks. These networks will also enable traceable quality assurance and control procedures. However, model based uncertainty estimation and error compensation will also be required, most significantly for thermal expansion of the emerging assembly and assembly tooling. Improved performance through reduced weight and improved aerodynamic performance will be realised through novel predictive processes described in this paper and the adoption of traceable quality assurance and control.

In order to bring about these significant changes in production capability research is required to develop automated metrology networks incorporating data fusion and thermal compensation algorithms as well as fundamentally new forms of metrology instruments enabling measurement that is embedded within tooling. Research for the development of new software tools for MAA are also required to support integrated dimensional variation management from design to production and deliver critical measurement planning functions.

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