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Large Volume Metrology Technologies for the Light Controlled Factory

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Abstract

In the Light Controlled Factory part-to-part assembly and reduced weight will be enabled through the use of predictive fitting processes; low cost high accuracy reconfigurable tooling will be made possible by active compensation; improved control will allow accurate robotic machining; and quality will be improved through the use of traceable uncertainty based quality control throughout the production system. A number of challenges must be overcome before this vision will be realized; 1) controlling industrial robots for accurate machining; 2) compensation of measurements for thermal expansion; 3) Compensation of measurements for refractive index changes; 4) development of Embedded Metrology Tooling for in-tooling measurement and active tooling compensation; and 5) development of Software for the Planning and Control of Integrated Metrology Networks based on Quality Control with Uncertainty Evaluation and control systems for predictive processes. This paper describes how these challenges are being addressed, in particular the central challenge of developing large volume measurement process models within an integrated dimensional variation management (IDVM) system.

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1. Introduction

The Light Controlled Factory project is a major research project running for 5 years starting in late 2013. It sets out to demonstrate how optical metrology systems, including those using laser, photogrammetry and while light projection, can be employed to overcome the challenges of large scale and high quality manufacturing. There is a particular emphasis on aircraft structure manufacturing.

Aircraft structures are currently assembled using tooling to control key dimensions. These heavy steel tooling structures are built on concrete foundations and are capital intensive as well as being very inflexible [1]. Manual fitting to control interface gaps and through assembly drilling is then carried out within the assembly tooling [2]. Achieving rapid assembly using interchangeable parts has not been possible due to demanding interface tolerances and large flexible components. Automation of drilling [3, 4] remains costly and inflexible due to the use of bespoke gantry based machines.

It is becoming increasingly important to improve these slow, costly and inflexible production methods due to ramp-up in production rates, increased use of composite structures with their inherent component variability issues and increased competition from low wage economies. At the same time improved performance is required due to carbon emission targets and increasing fuel costs. This will in part be achieved through weight reduction and the tightening of aerodynamic profile tolerances. The aims of increased production efficiency and improved product performance will be realized through progress on five objectives [5]:-

- **Part-to-part assembly:** An assembly process where all component forming is conducted pre-assembly allowing rapid one-way assembly [6]. 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 will make part-to-part assembly and traceable measurement more challenging.

2. Measurement Assisted Assembly

Increasingly data driven manufacturing and measurement assisted assembly (MAA) are enabling part-to-part assembly, low cost tools and automation, traceable quality assurance, reduced structure weight and improved aerodynamic form. MAA includes **Predictive processes** (fettling, shimming [7] and drilling) in which component measurements are used to adaptively form interfaces ensuring fit in assembly; **Assemble-Measure-Move (AMM)** [6] processes where a component is iteratively positioned, measured and re-positioned until within tolerance; **Active tooling** which adapts to feedback from dimensional and thermal measurements; and **Closed loop control** with feedback from external metrology systems to improve the accuracy of industrial robots.

Where it is not possible to achieve the determinate assembly of fully interchangeable parts, predictive fitting processes can provide an alternative route to part-to-part assembly. This involves carrying out three additional steps prior to assembly; 1) measuring components; 2) predicting how they will interface with each other; and 3) forming bespoke interfaces to achieve the required form and fit. Ultimately Measurement Assisted Determinate Assembly (MADA) could allow determinate assembly but will require aircraft structure design modifications and improved measurement capabilities [6]. Intermediate uses of predictive fitting processes can be readily adopted such as predictive fettling with in-assembly drilling [5]. Whole-Part Predictive Fettling (WPPF) will also enable reduced structure weight [5].

Reconfigurable tooling is widely used in other industries although in aerospace the tooling is used both to control the form of assemblies and as a verification gauge [8] making the less stable reconfigurable tooling difficult to adopt. Independent measurement is often not possible due poor visibility and the data being required for process correction before the structure is removed from the tooling. Active tooling could achieve a higher accuracy by compensating for its own dimensional drift and for thermal expansion of the assembly, but due to occlusions within tooling, as well as refractive index variation, current optical instruments cannot provide the required dimensional feedback. Embedded metrology tooling avoids these limitations by propagating optical measurements within the tooling structure [9], similar to the use of FSI in the Large Hadron Collider [10].

3. Large Volume Metrology Instrumentation

There are a wide range of different measurement instruments commercially available for sub-millimetre measurement at scales of 10's of meters. The most suitable instruments for craft based ad-hoc inspection which is currently common in aircraft production are spherical laser systems, such as laser trackers, at large scales and flexible arm CMM's at smaller scales and lower uncertainty. As production becomes increasingly lean and automated more automated and pervasive measurement will be required. iGPS is the only commercial system currently offering this type of factory wide infrastructure although the uncertainty in the 0.2 to 1 mm range is too high for many operations [11, 12]. Alternative measurement networks using photogrammetry may be developed to provide this capability.

Predictive processes will require a very low uncertainty of measurements for hole locations and surface profiles; to approximately 10 μm within 1 metre zones and to 50 μm within zones 10's of metres long. The state of the art Etalon laser tracker system achieves uncertainties of less than 10 μm over a 10 m length [13] proving the feasibility of this level of accuracy. Thermal variation currently means this cannot be achieved in a production environment and this instrument is not practical since features must be physically probed from multiple instrument stations. Photogrammetry uncertainties of 20 μm over a 1 m length and 110 μm over 10 m are claimed by the manufacturer [14] which is approaching the required accuracy. Direct photogrammetric measurement of holes is possible provided a sufficient contrast is achieved between the drilled component and the hole [15] while non-contact surface measurement can be achieved with laser target projection allowing an uncertainty of measurement of 50 μm over a 5 m length [16]. Another potential solution would be the use of a laser tracker to locate a localized non-contact measurement device, potentially handled by a robotic arm. While the combined uncertainty for a contact probing system might approach the 10 μm requirement [17], for a non-contact system it would be of the order of 60 μm [18].

Achieving the uncertainty of measurement required to match patterns of holes to accept interference fasteners and extending across large components is extremely challenging. None of the current measurement systems has the uncertainty to achieve this combined with the speed and ease of use required to integrate into a lean automated process.

3.1. Laser-based spherical coordinate measurement systems

Laser-based spherical coordinate measurement systems, such as laser trackers [19] and laser radar [20], combine a laser distance measurement with two angle measurements to give coordinate measurements in 3 dimensions. The instrument emits a laser, located on a gimbal. The laser is reflected back to the instrument allowing distance to be measured, laser trackers use a retroreflector while laser radar detects the light scattered off the object being measured.

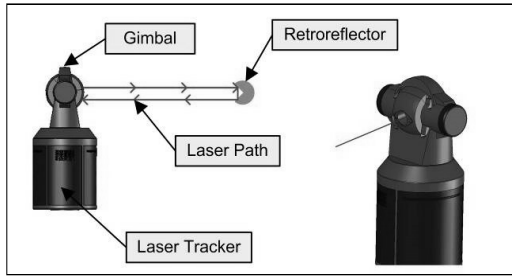


Fig. 1 – Laser Tracker Operation

Distance is either measured as a displacement from a known reference using a fringe counting interferometer (IFM) [21] or as an absolute distance measurement (ADM) using a number of techniques. IFM is more accurate and traceable but measurements must be taken without breaking the laser beam which is often not practical. IFM's also allow fully traceable coordinate measurements using multilateration where multiple displacements between coordinates are measured from multiple positions [22].

Claimed IFM uncertainties for a 10 m length range from 5 μm [18, 23] to 12 μm [24] although additional gimbal alignment errors will be present when tracking between coordinates for multilateration. Reduced uncertainty is possible by mechanically compensating for misalignment of bearings in the gimbal arrangement [25, 26] with such a system it is possible to achieve an uncertainty of less than 3 μm for a 10 m length [13]. In practice thermal effects limit the accuracy as described in

There are many ADM technologies, the simplest, time of flight for a pulse of laser light, is limited by timer uncertainty to a few mm [27]. Leica laser trackers use phase detection of a modulated polarization plane [28]. This compares the phase of a reference signal with that of a measurement signal similar to an IFM but using a modulated signal. The signal frequency is increased until the reference signal and the measurement signal are in-phase and then increased again until the next point where both signals are come back into phase so that

$$d = \frac{\lambda_1}{2} N_1 = \frac{\lambda_2}{2} N_2 \quad (1)$$

where d is the distance being measured, λ_1 and λ_2 are the two wave lengths when the signals are in-phase and N_1 and N_2 are the corresponding integer numbers of wavelengths over the length d .

Since the two points where the signals were in phase were successive

$$N_2 = N_1 + 1 \quad (2)$$

Substituting for the wave equation into Eqn 1 and rearranging gives

$$N_1 = \frac{2 \cdot d \cdot f_1}{c} \quad (3)$$

$$N_2 = \frac{2 \cdot d \cdot f_2}{c} \quad (4)$$

where c is the speed of light and f_1 and f_2 are the respective frequencies.

Substituting equations (3) and (4) into (2) gives

$$d = \frac{c}{2(f_2 - f_1)} \quad (5)$$

Claimed ADM uncertainties for a 10 m length range from 15 μm [23] to 28 μm [24]. ADM is not as instantaneous as IFM although the Leica Absolute Interferometer (AIFM) combines data from ADM and IFM systems to enable low uncertainty, dynamic measurement and ADM convenience [29].

Frequency Scanning Interferometry (FSI) is a cutting edge ADM which uses a tuneable laser so that multiple frequencies of the laser light its-self can be used to achieve ADM. This has been used at CERN with several hundred FSI's arranged in a geodetic grid to monitor shape changes of the particle tracker, this is similar to monitoring an aerospace assembly jig. The system was designed to function without any access or maintenance over a 10 year period and to cope with vibrations changing the optical path distance during ADM. The cost of the system was kept low by using only two lasers which were channelled using fibre optics to realise several hundred interferometers and achieved a precision of approximately 10 μm over a 6 m long by 1.2 m diameter volume. Another ADM technology, intensity modulation, has demonstrated a resolution of 1 μm at 5 m range [30].

Coherent Laser Radar is an ADM technology employing a frequency-modulated infrared laser producing a 100 GHz saw tooth signal with up-sweep and down-sweep comparison used to calculated distance [20]. It allows diffuse light reflected from the target to be imaged by the instrument and therefore does not require a retro-reflective target, greatly facilitating automation.

Coordinate measurements from a single station rely on both ranging and angular measurement with angle encoders typically dominating uncertainty. Measurement of a scale bar located perpendicular to the laser gives a good indication of the angular measurement system [31]; uncertainty a 10 m length at a range of 5 m ranges from 45 μm [18] to 66 μm [24] for laser tracker systems.

Centring, radius and form errors of spherically mounted retroreflectors (SMR's) are typically 6 μm , 2.5 μm and 1.5 μm respectively [17]. Drift nests, kinematic mounts used to repeatably locate SMR's, introduce further uncertainty of approximately 13 μm [32]. The combined uncertainty [33] due to target location is approximately 15 μm . If coordinates are measured with the SMR orientated in the same direction this will be reduced considerably. These effects are not modelled in current uncertainty evaluation systems such as Spatial Analyzer [34].

Additional measurements of SMR orientation enable six degrees of freedom (6dof) measurement with applications such as extended probes for measurement out of line-of-sight and feedback to automation systems. Polarization lenses at the

reflector can be used to enable rotation about the axis of the laser to be detected and photo detectors in the reflector can detect the remaining angles with uncertainties of ± 3 arc seconds [35]. Alternatively photogrammetry can be used to track targets around the SMR with an uncertainty of ± 36 arc seconds which equates to an additional 18 μm for every 100 mm between the probe tip and the SMR [18].

3.2. Photogrammetry

Photogrammetry uses cameras to detect the angles to targets and then triangulates the coordinates of the targets from multiple camera positions. This allows many targets to be imaged simultaneously and at high frequency. Common points must be identified on the images, achieving this on a featureless surface is virtually impossible and so it is often necessary to place targets. These may be physical artefacts possibly containing retro reflective targets or they may be part of a projected pattern.

Systems with two cameras or three planar cameras fixed at calibrated distances from each other enable simple triangulation calculations for high frequency real time coordinate measurement. More commonly individual cameras take images from many different positions requiring a bundle adjustment [36] to determine their relative positions and target coordinates.

3.3. Laser Scanners

A laser scanner is an active optical triangulation technique similar to a photogrammetry system with two cameras mounted a calibrated distance apart. The difference is that one of the cameras is replaced with a laser projecting a line at a known angle onto the object being measured. Each pixel imaged on the line by the camera give a coordinate measurement with one known angle for the projected line and two known angles from the position on the camera image plane. The laser may be rastered across the object with the camera imaging a frame at each stationary position of the laser to sequentially build up a grid of points on the object, or the entire scanner device may be moved over the object.

Localized scanners, designed moved over objects while another instrument tracks their position and orientation, typically have a field of view of less than 100 mm. They may be located by a conventional coordinate measurement machine (CMM), a multi-link arm or a frameless system such as photogrammetry. Uncertainties can be as low as 5 μm [37] although this is highly dependent of the optical properties of the object being measured and ambient light. Full field scanners raster to measure a complete surface from a static position. For example the Konica Minolta Range 7 line scanner has a range of between 450 and 800 mm with a field of view of between 79×99 mm and 267×334 mm with an uncertainty of ± 40 μm between two balls [38].

Small hand-held two dimensional line scanners which project a single static line are designed to measure features such as gaps, hole counter-sinks and fastener flushness. For example the GapGun can be used with different heads to give measurements ranging from a field of view of 7 mm with a resolution of 10 μm to a field of view of 80 mm with a

resolution of 120 μm [39]. The primary advantage of these devices is the low cost and ease of use.

A problem with scanning systems is that due to limited dynamic range of CCDs surfaces with different reflectance properties cannot be captured simultaneously. This can be dealt with by taking multiple images with different illumination levels, exposure or aperture [40] similar to High Dynamic Range Imaging (HDRI) used in photography [41]. Due to laser speckle effects the depth resolution of laser scanners is limited to around 1 part in 10 [42].

3.4. Fringe Projection

Fringe projection involves a number of different fringe patterns of sinusoidal light and dark bands being projected onto the object to be measured. Each pattern is imaged using a digital camera in order to identify coordinates of imaged pixels [43, 44]. The white light used is less susceptible to speckle effects than laser systems meaning that a depth resolution to 1 part in 105 is possible [45] and uncertainties of measurement of 1 part in 105 have been shown to be possible through demonstrations of precision at this level [46].

3.5. Indoor GPS

The Indoor GPS system (iGPS) uses a number of transmitters placed around the working volume to measure the angles to and coordinates of a single sensor. Communication from transmitter to sensor is one-way enabling an unlimited number of sensors to utilize a transmitter infrastructure; similar to NAVSTAR GPS [47].

Transmitters consist of a stationary body and a rotating head. The head rotates at approximately 3000 rpm sweeping two fanned laser beams throughout the working volume, while the stationary body delivers a strobe with a single pulse for every second revolution of the head. The fanned laser beams are inclined at 30 degrees to the horizontal and offset by 90 degrees to one another [48] as shown in Fig. 2. The sensor detects fanned laser beams as they sweep past and the strobe. Azimuth and elevation angles are calculated using the timing differences between pulses of light reaching the sensor. Each transmitter rotates at a slightly different speed enabling the sensor to differentiate between the signals from different transmitters [48].

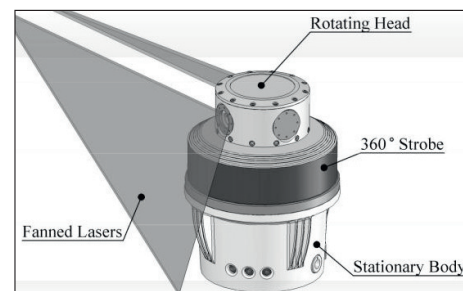


Fig. 2 - Main Components of iGPS Transmitter

If iGPS transmitters are installed in a factory they can support an unlimited number of sensors. Since the transmitters do not track the sensor no re-aiming is required if

line of sight is broken and sensors are able to detect signals from a wide range of angles, this means that a sensor can move around various line of sight obstructions losing and regaining connection to transmitters with relative ease.

3.6. Laser Projection

Laser projection rasters a laser point to project templates and instructions. These may be used to guide the layout of composites as shown in Fig 3, painting, fitting bracketry etc. In order to project an accurate profile onto a non-planar surface the projector requires a surface model of the object it is projecting onto.

Reference features are used to align this model with the actual part and an integrated laser line scanning system is used to locate these reference features.



Fig. 3 - Laser Projection used to Indicate Composite Layout Position (Care of LPT)

3.7. Gantry Type Coordinate Measurement Machines

Coordinate measurement machines (CMM's) have some advantages over optical instruments. They allow automated pre-programmed measurement of points on parts from multiple directions and at relatively low uncertainties. This makes them very useful for carrying out defined inspection sequences. The high cost and large physical size of CMM's capable of large scale measurements is a major disadvantage. Metris manufacture gantry CMM's with axes of up to 16 m x 6 m x 3 m and an accuracy of approximately 40 μ m for a 10 m length [49].

4. Research Challenges

It is described above how MAA can be used to; enable part-to-part assembly and reduced weight through the use of predictive fitting processes; enable low cost high accuracy reconfigurable tooling through active compensation; improve the accuracy of robotic machining through improved control; and improve quality through traceable uncertainty based quality control systems. In order to bring about this vision the major research challenges will be to develop:

1. Control of industrial robots for material removal
2. Compensation of measurements for thermal expansion
3. Compensation of measurements for refractive index changes in the measurement volume
4. Measurement systems embedded in tooling for assembly monitoring and active tooling compensation

5. Software to enable automated measurement networks

4.1. Control of Industrial Robots for Material Removal Processes

Accuracies of 0.2 mm to 0.02 mm required for drilling, fettling and component location operations cannot be achieved by current robots [50] without external metrology. Global referencing or Adaptive Robotic Control (ARC) enables holes to be drilled within ± 0.2 mm relative to datums a few meters away [51]. Scanning and vision based sensors mounted on the end effector can be useful to reference local features when drilling [52] or placing components [53] but cannot achieve the ± 0.02 mm accuracy required to match up hole patterns for interference fit fasteners. For this manual alignment can be mimicked using vision for initial alignment and then inserting tapered pins for final alignment with compliance provided by force feedback [54]. Currently real time closed loop control of dynamic operations such as fettling has not been achieved due to the inherent inaccuracy of the robot and vibrations induced by the machining process [55-57] which may be reduced using an ultra-high speed spindle [58].

LCF project will first aim to reduce high speed vibration; using accelerometers on the spindle to evaluate both passive and active vibration damping. Subsequently path following errors will then be compensated using a laser tracker.

4.2. Compensation of Measurements for Thermal Expansion of the Measurement

ISO 1 defines the reference temperature for all measurements as 20 °C and deviations from the reference temperature will introduce errors and measurement uncertainties in the measurement result [59]. This became ISO recommendation number 1 in 1951 [60], an indication of its importance. Fig 4 shows three different possible approaches to the reference temperature. In each case a pattern of holes is being drilled in a flange plate on a 1000 mm pitch circle diameter (PCD) by an industrial robot with external feedback. It is assumed that errors in the position of the holes are negligible and therefore the only errors are due to thermal expansion. Each of the two flange plates is drilled in a different factory, one with an ambient temperature of 22°C and the other with an ambient temperature of 18°C, they are then assembled in a third factory with an ambient temperature of 24°C.

- a) In the first case each flange plate is drilled at the local ambient temperature and the nominal dimension is used to guide the drilling operation. The holes are all drilled at exactly 1000 mm PCD, therefore when they are assembled at the increased temperature they have expanded by different amounts and the PCD's of the two components differ by 0.092 mm.
- b) In the second case the drilling areas are environmentally controlled so that drilling takes place at the reference temperature and the nominal dimension is then again used to guide the drilling operation. In this case since the two parts were at the same temperature when they

- were drilled they expand by the same amount and there is no miss-match between the components.
- c) In the final example each flange plate is drilled at the local ambient temperature but instead of the nominal

dimension being used the PCD is compensated for the current thermal expansion of the components. This means that when the two components are at the same temperature as each other they will match.

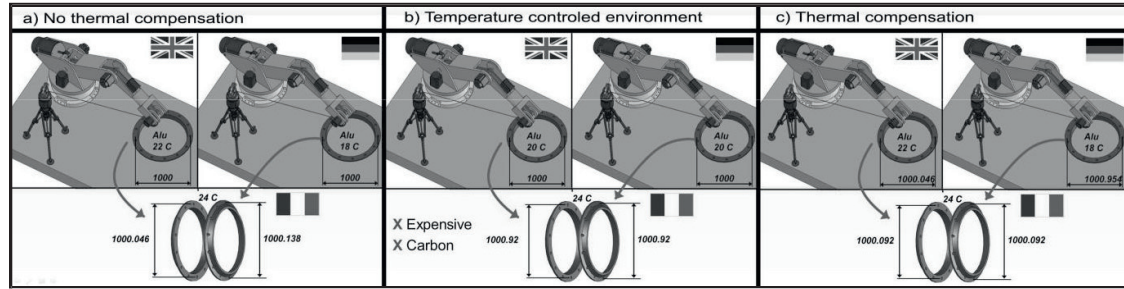


Fig. 4. Different Approaches to Thermal Compensation and Control

The light controlled factory project will develop thermal compensation methods as shown in Fig 4c. For simple structures uniform linear thermal expansion can be assumed and thermal compensation is simply a case of scaling measurements using the CTE of the component, in some cases with multiple temperature measurements and scaling zones. This ignores a number of error sources:

- **Thermal gradients:** Large components in typical factories have significant thermal gradients which causes bending and twisting.
- **Anisotropic Composites:** The CTE of composite materials is often anisotropic.
- **Gravity:** Large flexible components deform under self-weight with different support conditions during production.
- **Assembly Variation:** Variation in an assembly involves a six-degree-of-freedom propagation between components; thermal compensations of components must therefore be linked to more general assembly variation models.

Development of finite element model based thermal compensation will consider:

1. The density of temperature measurements required to provide accurate boundary conditions and whether low-density high-accuracy contact measurements can be combined with high-density low-accuracy non-contact measurements using data fusion.
2. How historical thermal and dimensional data can improve a compensation model using a data assimilation approach.
3. How methods can be scaled to complex aero structures.
4. How thermal compensation can be linked to assembly variation models to enable improved predictive fitting.

4.3. Compensating Measurements for Refractive Index Changes in the Measurement Volume

Optical measurements are affected by changes in the refractive index due to temperature, pressure, CO₂ level and humidity. For angular measurement refractive index gradients perpendicular to the beam path cause the light to bend with subsequent transverse errors [31]. Length measurements depend on a wavelength calculated by a weather station at the instrument. Changes in the refractive index along the beam

path will lead to radial errors. The fractional error in the radial direction is given by

$$e_R = \frac{\overline{\delta T}}{n(T_m)} \frac{\partial n}{\partial T} \quad (6)$$

Where $\overline{\delta T}$ is the difference between the average temperature over the optical path and the measured temperature, $n(T_m)$ is the estimated refractive index at the measured temperature and $\partial n / \partial T$ is the sensitivity of the refractive index to changes in temperature.

The transverse error is given by

$$\Delta x = n(z) \left. \frac{dx}{dz} \right|_{z_i} \int_{z_i}^{z_f} \frac{dz'}{n(z')} + \int_{z_i}^{z_f} \frac{1}{n(z')} \int_{z_i}^{z_f} \frac{\partial n}{\partial T} \frac{\partial T}{\partial x} dz dz' \quad (7)$$

where $dx/dz|_{z_i}$ is the initial slope of the laser, the limits z_i , z_f and z' are the initial, final and intermediate positions along the laser path respectively, $n(z')$ is the refractive index at an intermediate position along the laser path and $\partial T / \partial x$ is the temperature gradient in the x direction.

Even for a very stable environment with a temperature gradient of just 0.1°C/m the error over a 10 m length due to refractive index changes would be 5 µm while for a more typical 1°C/m the error would be 50 µm [31, 61]. Techniques are being developed to compensate these effects using multiple frequencies of light.

4.4. Software to enable automated measurement networks

Large volume metrology currently involves skilled and subjective measurement planning, operation and analysis to determine compliance with specifications, to control MAA processes and to compensate for thermal effects. Software tools are therefore required to:

- Aid instrument selection
- Determine achievable MAA tolerances as a tool for Design for Assembly (DfA) and assembly process planning
- Optimize measurement network design for user defined parameters such as minimizing uncertainty, minimizing process time or minimizing equipment cost

- Plan MAA processes and generate algorithms to be run by Manufacturing Execution Systems (MES)
- Provide optimized measurement results, accompanied by uncertainty values, in real time by fusing data from multiple instruments and compensating for thermal effects
- Provide modules to control MAA processes and provide quality metrics within established MES and with respect to the uncertainty of measurements.

Architecture for this Integrated Dimensional Variation Management (IDVM) involves two domains, illustrated in Fig 5 [62]. Within the design and process planning domain different structure designs and build philosophies can be evaluated in terms of achievable tolerances. Next detailed assembly planning is carried out with measurement networks optimized and the resulting uncertainties fed back into the tolerance models. Finally these detailed models are used as the basis for algorithms to control the Manufacturing Execution System (MES). These algorithms will enable data fusion from integration of multi-sensor measurements, thermal compensation, control of active tooling, application of decision rules to flag non-conformance and control of fettling or drilling operations.

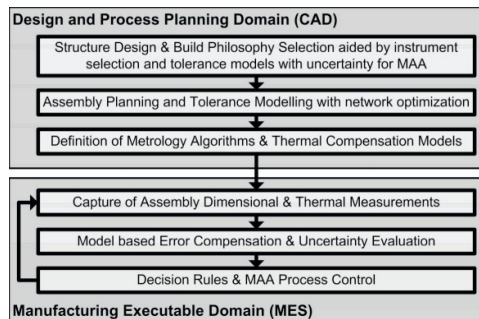


Fig. 5. Summary of Integrated Dimensional Variation Management

Established quality control (QC) methods such as Six Sigma [63] involve instrument capability, Gauge R&R studies [64] and conformance criteria which do not provide statistical confidence in conformance. The more rigorous approach to QC set out in the ISO GPS standards states that every measurement must be accompanied by an evaluation of its uncertainty [33] [65] and that conformance is only proven when measurement results fall within a conformance zone which takes account of this uncertainty [66]. IDVM will enable an ISO approach to QC to be adopted with thermal effects properly accounted for in uncertainty budgets.

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.

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