Computer Aided-Design-Manufacturing & Measurement Integration.

Coordinate Measurement System Committee
Albuquerque, New Mexico
August 13-17 2001

Authors

Boeing Commercial Airplanes
Michael C. Richey
Robert S. McIvor

New River Kinematics
Scott C. Sandwith

Abstract:

This paper describes the Computer Aided-Design-Manufacturing and Measurement Integration pilot development activities conducted by several organizations at The Boeing Company including; Tool Engineering, Tool Construction and Tooling Quality Assurance. The goals of this study were to integrate and evaluate 3-Dimensional measurement software, measurement hardware (Laser Trackers, PCMMs) and CATIA Digital Product Definition (DPD) datasets, into the build, measurement and inspection process.

A demonstration of the common instrument interface metrology platform was performed to locate a series of components onto an aircraft wing spar utilizing STEP geometry from the CATIA dataset and integrating multiple online portable 3D measurement systems. This project utilized computer-aided measurement systems; metrology software and an appropriately toleranced CAD model to assemble aircraft parts with minimal tooling

Introduction:

The test demonstrated efficient positioning of spar components within their tolerances using a compilation of proven measurement technologies (e.g., laser tracking interferometers and portable CMMs [5-9]). Measurements of the spars datum surfaces were made in each local area of interest to optimize the orientation of each component's key features relative to its CAD defined tolerances [2-3]. The graphical software platform animates each move of the components in real-time against its nominal CAD orientation in an easy to visualize manner [2]. Once the operator moves the parts key characteristics within the embedded CAD attributes the software signals the user (or external control) that it is in position. Measurements by additional online system(s) (e.g., tracker, Laser Radar, PCMM, or Real-time Videogrammetry [3,7-8]) are made to collect independent inspection and conformance data.

CATIA data, which served as the "Authority for Product Definition," provided the nominal criteria for the features to be measured which included surfaces, datum's, planes, axes, SOLID-E'S and Cartesian point coordinates [1]. An additional goal of this project was to shift the measurement focus from tool features to production part attributes thereby providing an opportunity to measure the 'as-built' production part in the field during the build process. This graphical build process was demonstrated without the aid of a traditional Floor Assembly Jig (FAJ). Each of the components was positioned relative to local key assembly features on the parts, e.g., datum surfaces, K-holes etc. These key features were measured with a real-time metrology system and then fit to their respective CATIA definitions. The assembly was located without the standard floor assembly tooling normally found with large assembly structures. The assembly was clamped to a floor post and wedged with wood blocks (no fixed tooling or complex fixture was needed).

This technology can eliminate the requirement for generating 2D drawings for parts and tools by reducing both the volume of engineering hours on a project and the inertia required for process change [1]. It increases product design and reliability by directly linking the 3D CAD definition and its tolerances to the assembly of the parts. The infrastructure and volume of data storage and configuration control is reduced [4]. When the factory is able to use the 3D data directly in a real-time graphics enabled metrology platform, the opportunity for drawing interpretation errors is reduced.

Background:

Balancing aircraft performance and design against manufacturing capability and configuration control requirements is a fundamental process within The Boeing Company. This balancing process defines the degree of success for an airplane program and the company as a whole. The effort and energy expended defining and refining these issues consumes significant resources from virtually every component of the company [1-2]. A key product of this enterprise wide effort is the 3D CAD definition of the components, sub-assemblies, and major assemblies including their respective tolerance definitions.

Currently, large-scale manufacturing expends a significant percentage of its resources to develop 3D CAD models for each part and assembly [1]. After developing the 3D models, the designers then break the 3D models into a series of 2D drawings and apply GD&T tolerances schemes and constraints on the 2D dimensioned drawings. This process defines the 2D drawing as the configuration control and "authority for manufacturing".

This process generates a significant duplication of effort. GD&T tolerances assigned in 2D drawings are then evaluated in the 3D model, yielding a complex web of dependencies. Changes and maintenance of the 2D drawings and the effects on the manufacturing planning and processes are considerable [1].

Enabling the manufacturing and quality organizations with a system that can work directly with the nominal 3D CAD definitions, using 3D metrology hardware and software can reduce the development and maintenance of this infrastructure [2].

Overview of 3D-Measurement Pilot

Building airplane components and assemblies directly from the CAD definition with 3D metrology systems can be accomplished with four primary components.

- **CATIA Model with embedded, Tolerancing:** 3D CAD "Authority for Manufacturing" entities, components, and assemblies with their associated tolerance attributes and constraints.
- **DataTransfer:** STEP dataset of complete production assembly.
- **Measurement Systems:** Real-time 3D measurement systems with open interfaces controlled by trained operators.
- **Measurement Assembly:** A software platform that integrates items 1 and 2 with the ability to optimize and analyze measurements (from multiple online systems) of the parts to their CAD definitions in real-time. The analysis includes real-time reports of the deltas between the CAD entity and the measured entity.

CAD Modeling and Tolerancing

The orientation of each component relative to the assembly is defined and controlled by the CAD dataset. The position and orientation tolerances between components are defined by annotating the relative relationship between the entities forming the components. The annotation can be as simple as distance envelopes or as complex as Geometric Dimension and Tolerancing (GD&T) [10] or Functional Dimensioning Tolerancing (FDT).

GD&T is typically applied to 2D perspectives of parts while FDT is a unified functional tolerancing scheme. The goal of FDT is to determine the dimensions and tolerance in product design by providing a methodology to simultaneously integrate the product functional requirements against the manufacturing constraints and metrology conditions.

Figure 1 shows the scope of processes that the FDT technology attempts to unify into a cohesive strategy.

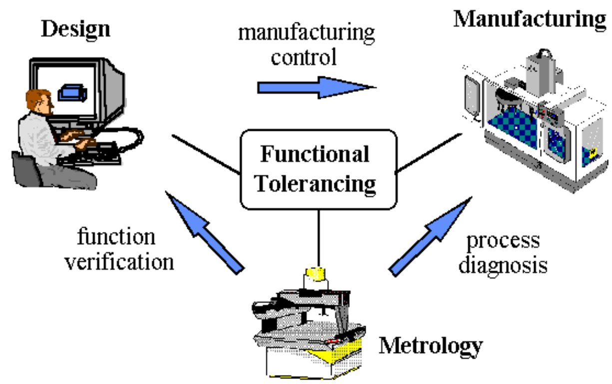

Figure 1: FDT Process Scope Diagram

Note: The CATIA FDT application is currently limited to detail level components due to constraints within the Product Data Management (PDM) platform.

Data Transfer:

Once the components and assemblies are designed and toleranced, the CAD model of the assembly is needed in a compatible format such as STEP (STandard for the Exchange of Product) or IGES (International Graphics Exchange Specification). The format used for this project was STEP.

Measurement Systems:

Within the manufacturing environment The Boeing Company currently uses a number of types of computer-aided measurement systems including laser trackers and portable coordinate measurement systems (PCMMs)[4,9]. The traditional role of these instruments in aircraft manufacturing has been to construct close tolerance tooling fixtures from 2D drawings.

A down side to the current implementation of our measurement systems has been the difference in the operating software. An operator trained on one type of laser tracker may not be able to operate a different type of laser tracker [3]. The ability to analyze data using the PCMMs native software gave no assurance that a similar type of analysis could be accomplished in a different PCMM's software. And finally, each software package varies in its ability to accurately import or export CAD data [2].

Key to the success of this project was the interface of all the measurement hardware through a single metrology software platform. See Figure 2.

The metrology software provided a common interface for data simultaneously acquired from a number of different instruments [3]. The user interface between like instruments (e.g. different brands of trackers) was identical, reducing training requirements and improving hardware utilization. The software provides a common real-time graphical interface between the measured and modeled data.

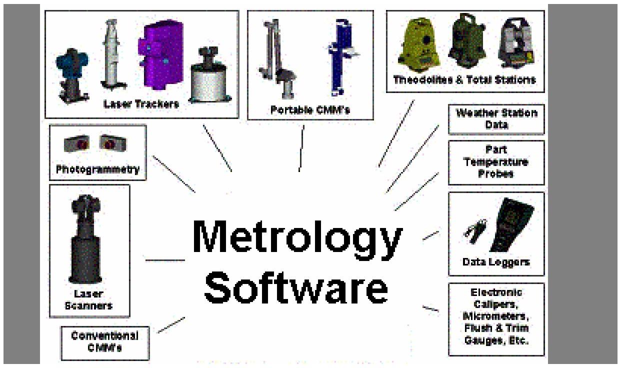

Figure 2: Integration of multiple measurement systems with the metrology software.

Measurement and Assembly:

The measurement software's graphical user interface shows the user the location of the actual component relative to the CAD model of the component and its respective sub-assemblies. The real-time visualization of the part against the nominal location allows operators to easily make adjustments to component location and therefore produce assemblies that consistently meet precise functional specifications [3]. Depending on requirements, the metrology software continuously collects measurements from the online measurement hardware and uses the data to display a virtual image of the component's location and orientation. As the user moves the real component to its nominal position and orientation the metrology software will show the virtual component moving against the backdrop of the larger structure of the total assembly. As the component begins to move within the tolerances defined by the CAD model (or user); the system changes the color of visible features in a distinctive pattern (i.e., blinking or changing colors) as it approaches the modeled nominal location. The user knows the virtual component was located within tolerance when the attribute is not blinking or changing colors.

Other benefits of the software platform included its ability to cooperatively use multiple types of measurement systems simultaneously. The object oriented distributed TCP/IP interface technology supports as many online systems as necessary. The platform's distributed computing architecture enables efficient measurement system network configuration as well as supports remote process control and monitoring [3].

In this project a PCMM and two laser trackers (from different manufacturers) were used. The assembly process demonstrated the use of these instruments to set stiffeners and hinge fittings on a spar. One laser tracker was positioned inboard on the "dry" side of the spar, the other tracker inboard on the "wet" side of the spar and the PCMM outboard of the two trackers, as shown in Figure 3

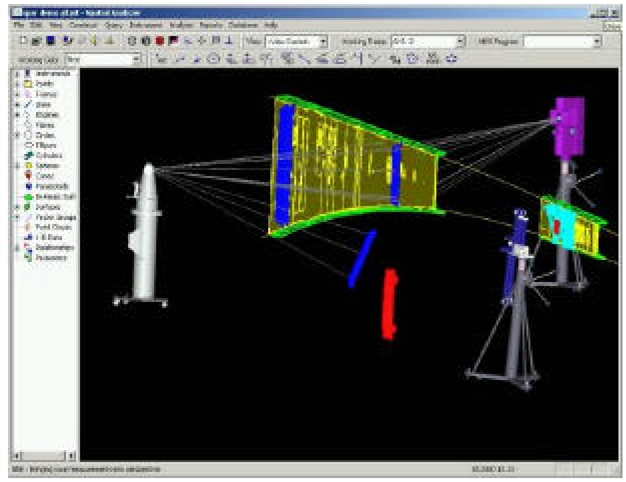

Figure 3: Wing Spar Assembly Layout

The "wet" side tracker was used to measure the reference features on the production part. The "dry" side tracker was oriented to the production part reference system using common points between the "wet" and "dry" side trackers. The PCMM location was established by transforming measurements of reference features on the spar surrounding the hinge-line feature. This local coordinate system was desired because it simplified setting the hinge-line feature. It should be noted that in a variation of this process, the PCMM could be oriented into the same coordinate system as the two laser trackers. But in this particular demonstration, the inboard and outboard reference systems of the production part are different; therefore the trackers and PCMM were used in different coordinate systems.

Once the appropriate coordinate systems were established, the "dry" side tracker set a stiffener while; the PCMM was simultaneously, setting the hinge-line assembly.

Figure 4 shows the hinge-line fitting being located in a traditional FAJ while Figure 5 shows the same fitting being set directly from the CATIA nominal geometry.

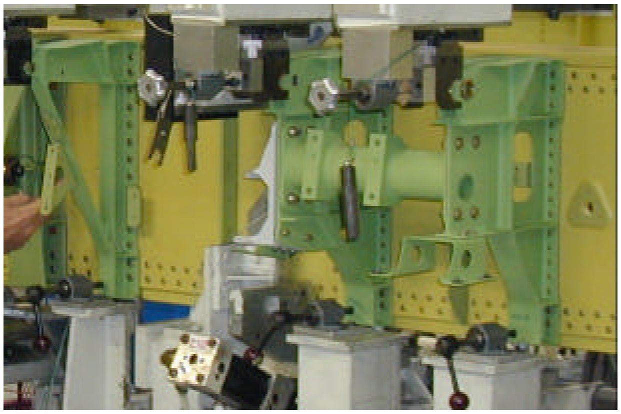

Figure 4: Image of the spoiler hinge fitting

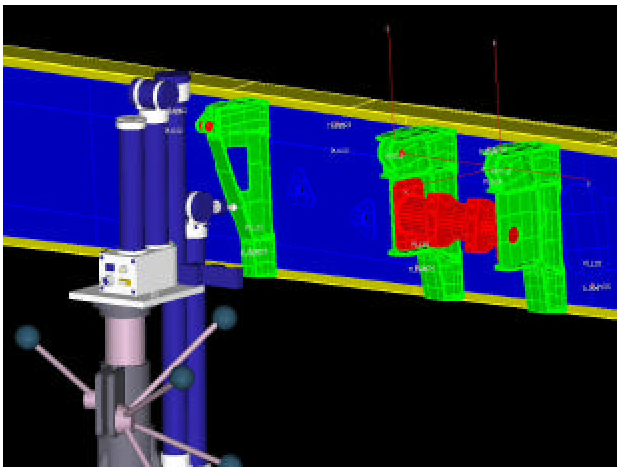

Figure 5: Graphical representation of the spoiler hinge fitting with the PCMM

Figure 6 shows the metrology software being used to assemble components on the spar against the design geometry. The spar components were positioned within tolerance using a combination of proven measurement technologies (e.g., laser tracking interferometers and portable CMMs). Measurements of the spar datum surfaces were made in each local area of interest to allow the software to produce feedback to the user that optimizes the orientation of each component's key features relative to its CAD defined tolerances [7].

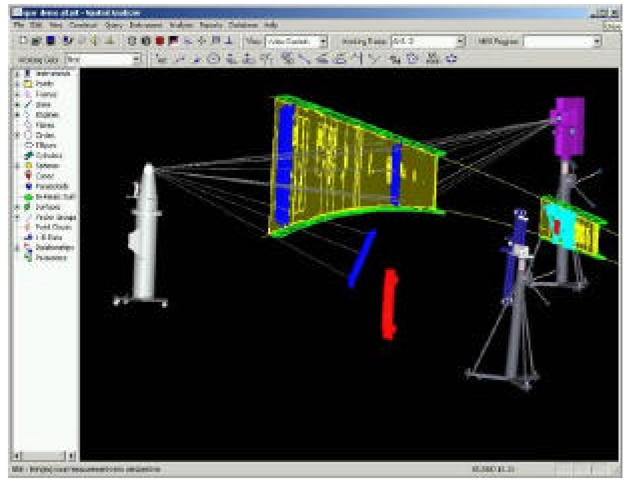

Figure 6: Graphical representation of the wing stiffeners and ribs assembly with the trackers

The assembly process is typically automated by a pre-packaged measurement plan for an operator with prompting dialogs and Go/No-Go automated analysis [4].

Process Developments:

A number of process developments were identified during the study.

1) The first step to automate an assembly process is to release 3D CATIA datasets as the authority for manufacturing.

   a) The dataset should include:

      i) Released CATIA 3D models of the primary SOLID-E components and the assembly attributes.

      ii) STEP (STandard for the Exchange of Product) export of the CATIA model

Note: The STEP standard uses mechanisms referred to as Application Protocols (AP) to support specific technologies. The AP designated to support FDT and GD&T is known as AP219. AP219 has not been formally released, as it is still a working draft.

      iii) 3D FD&T embedded attributed CAD mode (defining the fit, form and function of the assembly and their tolerances).

   b) Tooling (e.g., FAJ, DJ, etc.) and tool control documents (i.e., Sheet 800 drawing, tool routine, conformance reports, etc.)

   c) Part and tool planning documentation

      i) Process events and QA acceptance process checklist

   ii) Assembly time study, downstream affects

d) The team of disciplines should include at a minimum.

   i) Product Design Engineering

   ii) Tool Design

   iii) Production Planning

   iv) Quality Assurance Engineering

   v) Measurement System Technicians

2) Acquiring 3D measurement equipment, software, holding fixtures, and assembling a team of people representing each of the functional disciplines listed above.

Benefits:

The Computer Aided-Design-Manufacturing and Measurement Integration technology eliminates the requirement for generating 2D drawings for parts and tools by reducing both the volume of engineering hours on a project and the inertia required for process change while it increases design and product reliability. Additional benefits are listed below.

1) Product quality improvement with reduced cycle time and defects.
2) Reduce Design and product Quality costs by capturing the manufacturing index plan and sequences in the theoretical CAD data.
3) By-pass the 2D drawing release process by using the "Authority for Manufacturing" CAD data and FDT.
4) Direct use of the full production part assembly tolerances.
5) Integration of "Key Characteristics" from the production part into the measurement, inspection and build plans.
6) Verification, inspection and rework in the field (AOG) with the design data.
7) Enables database analysis tools to generate historical standard reports to support SPC/HVC improvement processes.
8) Alignment to evolving CAD 3-D measurement modeling processes, e.g., Enoiva, Virtual Product Manager, CATIA V5, FDT.

Conclusion:

The Computer Aided-Design-Manufacturing and Measurement Integration technology was demonstrated using the common instrument interfaces available within the SpatialAnalyzer graphical metrology platform.

The project located a series of spar components onto a production assembly from the CATIA geometry using multiple online portable 3D measurement systems. The process uses the nominal 3D CAD definitions with tolerance constraints for assembly control and verification.

Each of the components was positioned relative to local key assembly features on the parts, e.g., datum surfaces, K-holes etc. These key features were measured with the optimal online system and then fit to their respective CATIA definitions. This orientation technique enables the process to use simple, inexpensive holding fixtures. The reduction or elimination of entire families of tools and their maintenance could be realized using CAD data to directly control assembly processes.

The technology can eliminate the requirement for generating 2D drawings for parts and tools by reducing both the volume of engineering hours on a project and the inertia required for process change while it increases design and product reliability.

Recent developments in CAD software such as SOLID-E "Authority for product definition" 3D Only, and ENOVIA VPM (Virtual Product Manager) integrate design to manufacturing architecture, moving CAD data to the machine bed or factory floor. Incorporating 3D-Measurement software technology into our design and manufacturing process will for the first time, bridge the gap between the CAD model and our factory manufacturing/build applications.

The challenge is in overcoming constraints within our computing architecture and existing product development processes and encourages the integration of new products that facilitate cost reduction and support innovation.

Acknowledgements:

The authors wish to acknowledge the exceptional engineering support by the Brunson Instrument Co. and New River Kinematics. Specifically, Rick Cole, Kirk Franklin, Mark Wilmont, and Matt Settle of Brunson worked to organize the system components. Bob Salerno, Joe Calkins, and Bruce Thomas of NRK, introduced capabilities that enable the successful application of this process development in Assembly Technology.

A number of people from Boeing were key resources in this effort to integrate CAD as the control media for airplane assembly process. Gary Dreessen supported the export to the STEP format requirements and Christine Lynch was instrumental in planning the test and bringing the right resources together to accomplish the project goals.

References:

[1] Richey, M. and Nichols, S., 1998, Title, SME Conference Bellevue, WA

[2] Sandwith, S. C., 1998, Integration of Large-Scale 3-D Optical Metrology with CAD, SME Graphical Technology Exchange.

[3] Salerno, R., PhD, Calkins, J., 2000, Open Architecture for Portable Metrology Equipment, Metrology Automation Association, Open Architecture Workshop. May 2-3, 2000

[4] Muske, S., Salisbury, D., Salerno, R., Ph.D., Calkins, J., 747 Data Management System Development and Implementation, 1999 CMSC Conference and 2000 Boeing Large Scale Metrology Conference, Long Beach, CA

[5] Sandwith, S., Predmore, R., 2001, Real-time 5-Micron Uncertainty with Laser Tracking Interferometer Systems using Weighted Trilateration, 2001 Boeing Large Scale Metrology Seminar

[6] Sandwith, S. C., 1992. Gageless Tool Building with Computer Aided Theodolites, SME Composite Tooling Conference.

[7] Hubler, D., Salerno, R., Ph.D., Calkins, J., McLean, T., 2000, Using Real-Time, 6D Object Tracking to Assemble Large Aerospace Components, 2000 CMSC Conference Detroit, Michigan

[8] Palmateer, J. W., 1992, Lidar-Angular Measurement System for Simulating "Real Time" Photogrammetry, XVII Congress ASPRS/ACSM, Aug. 1992.

[9] Greenwood, T. A., 1995, Tracking Interferometers and Macro-Metrology in the Aerospace Industry, Society of Manufacturing Engineers, Laser Gauging Conference, December 1995

[10] Dimensioning and Tolerancing ASME Y14.5 Standard

Contact the Authors:

The Boeing Company

Michael C. Richey michael.c.richey@boeing.com
Learning Education and Development LEAD CATIA Instructor.

Robert S. McIvor robert.s.mcivor@boeing.com

Tool Maker - 777 Tool Construction, Team Leader – Puget Sound Laser Tracker User Group

New River Kinematics

Scott Sandwith scott@kinematics.com

A Software Developer for SpatialAnalyzer, Manager of NRK-West Office, and Large Scale Optical Metrology Consultant.