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Automated Metrology Solution to Reduce Downtime and De-Skill Tooling Recertification

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ABSTRACT

Wing and fuselage aircraft structures require large precise tools for assembly. These large jigs require periodic re-certification to validate jig accuracy, yet metrology tasks involved may take the tool out of service for a week or more and typically require highly specialized personnel. Increasing the time between re-certifications adds the risk of making out-of-tolerance assemblies. How can we reduce jig re-certification down time without increasing the risk of using out-of-tolerance tooling? An alternative, successfully tested in a prototype tool, is to bring automated metrology tools to bear. Specifically, laser tracker measurements can be automated through a combination of off-the-shelf & custom software, careful line-of-sight planning, and permanent embedded targets. Retro-reflectors are placed at critical points throughout the jig. Inaccessible (out of reach) tool areas are addressed through the use of low cost, permanent, shielded repeatability targets. Simple locators enable adequate location of the tracker for each position, while automated tools within off-the-shelf software such as Spatial Analyzer provide a vehicle for very rapid measurements. Custom software guides the non-expert through the use of the metrology system so that the periodic "quick checks" are de-skilled, low cost, and fast.

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INTRODUCTION

Aircraft manufacturers are constantly being challenged to improve quality, productivity and reduce costs in an effort to be more competitive in the global market. Many companies look to reducing manufacturing costs by reducing their tooling requirements. An area that has significant potential for cost savings is the process of performing tooling recertifications. Typically, an assembly tool will be removed from production from a few days to several weeks, while specialized technicians measure key features on the tools that establish the position of critical components on the assemblies in the tool. The ability to significantly reduce the amount of time a tool is out of production can improve production flow times and potentially eliminate the need for duplicate tools used to accommodate impacts caused by tooling recertifications.

Beyond the need to maintain tool up time is the desirability of more frequent checks in an effort to improve tool quality and thus improve both part quality and productivity (by reducing out of tolerance parts and consequent rework). In the conventional tooling scheme it is possible to damage a tool immediately after a recertification but continue using the tool until the next recertification, with all the assemblies made during that interval being consequently out of tolerance, and causing assembly difficulties or necessitating rework.

A combination of off the shelf technologies opens the door to a methodology that significantly reduces tool down time and also enables a "deskilled" approach to tool verification. These technologies include laser trackers, low cost "repeatability" targets and metrology software with automation features, the sum of which shall be referred to as "Automated Metrology System" or AMS, for convenience.

The project began with the aircraft manufacturer and the metrology team establishing time goals for both a partial jig verification "PJV" and a comprehensive jig verification "CJV" for a wing assembly tool. Allowable jig down time for the PJV is 60 minutes, and 8 hours for the CJV. A rigid time goal was not set for the total jig recertification "TJR" because of the large number of factors involved (e.g. time to rework damaged tooling).

An additional goal is that this be a production process run by operators and not by engineers or metrologists. An appropriate set of hardware and software was combined and or developed to meet these goals. Targets were placed on a set of appropriate structures to approximate a tool, and the system was implemented in this test environment. These tests demonstrated that the goals were achievable and practical, and laid the groundwork for a future implementation.

METHOD OVERVIEW

A simplified method overview is given for the PJV process. The actual process is more robust and more complex, since it must handle the occasional requirement for a repeated measurement, blocked points, etc., but for the sake of understandability these issues are omitted here.

The following essential elements comprise the validation system:

- Permanent "repeatability" targets are placed around the tool, especially at critical locations
- A laser tracker for measurements
- A custom tracker stand to enable repeatable (to within 25mm) placement of the laser tracker
- Tracker stand pickup points embedded in the floor
- Metrology software
- Macro program to execute measurement routine
- A custom software interface to aid in de-skilling the process

Simplified Process:

- Stage laser tracker and tools just outside tool
- Check tracker calibration
- Clear the wing from the jig
- Roll tracker and stand into first station location
- Place a limited number of temporary targets
- Initiate orientation program;
    - the tracker seeks, finds, and measures three targets
    - the program best fits to the known targets and orients the station
    - the metrology software now "knows" where it is and where to find other points
- Initiate measurement routine
    - Tracker seeks and measures all permanent and any temporary targets
- Initiate analysis routine
    - Analysis macro best fits the data set to the nominals
    - Measured data is compared to actuals
    - Report is generated with a pass/fail determination
- Operator vacates metrology gear from jig

The CJV process is nearly identical, but with the addition of the placement of many temporary targets. The TJR process involves the placement of flags (removable details) and other tooling and inspection tools adequate to enable measurement of 100% of the tooling points. It also requires the repair and resetting of tools. Automated Metrology System (AMS) can significantly reduce the measurement and rechecking time for the TJR process but does not impact the flag setting, inspection tool placement or repair and doweling operations.

SYSTEM ELEMENT DETAILS

While most the elements of the system are off the shelf, they merit some detail discussion.

Targeting Concepts

There are two targeting concepts that are appropriate for AMS verification: permanently installed targets and temporary or "replaceable" targets. The objectives for targeting the wing jig are to maximize accuracy, minimize cost, maximize visibility, reduce placement time and ensure target survivability. The two concepts present differing benefits and limitations.

The following table provides a good overview of the contrast in approaches between the two target concepts:

To meet the 60 minute goal of a PJV requires that as many of the time-consuming aspects of a laser tracker survey be minimized. This warrants consideration of having laser tracker targets embedded in the tool permanently. The time to place and aim 100 or more SMRs or prisms on a 30m long jig at a height above the factory floor of at least 4 meters could consume the entire measurement window of 1 hour. However, it is expensive to place SMRs on a tool permanently, especially when there are going to be multiple duplicate tools in both a left hand and right hand

Target Concept	Cost (estimate)	Placement Time	Visibility	Damage Risk
Permanent	$200/target	0 minutes/target	Very limited	High
Replaceable	$600/target	1 minute/target	High	Low

* Replaceable targets can be moved between instrument positions and tools to reduce the overall total number required.

configuration that will require targets. SMRs are also exposed to factory dirt and grease and are not easy to keep clean.

The team explored the two targeting alternatives and compiled the following summary information:

1. **Permanent Targeting** - The permanent targeting approach all but eliminates the time to place targets on the jig prior to measuring. This is crucial to meeting the significant time constraint for the PJV routine. There are two target types that could be used for permanent targeting: the ½ in SMR and the 3/8 in. Solid Prism. Either targeting option is intended to minimize the overall cost by keeping the target size relatively small, creating a protected mounting position to limit exposure to factory dirt and physical damage and to optimize visibility by placing the targets in an area in a clear line of sight to the laser tracker position.

Figure 1. Laser Tracker Target for Comparison

The benefits to using a ½ inch SMR are that it does not require accurate aiming and the physical position is very accurate and repeatable due to spherical shell. The limitations are the cost of each target ($600), susceptibility to damage of mirrored faces, difficulty in cleaning and larger size than the prism option. The benefits of using the 3/8 in. prism are that it is lower cost ($200) and smaller in size. The limitations are that its accuracy is highly dependent on accurate aiming back at the laser tracker (within ½ a degree of normal to laser tracker beam), non-repeatable mounting due to a lack of a mounting shell and the prism face will need to be kept clean. Solid targets are cleanable with acetone and a soft cloth.

2. **Temporary Targeting** - The use of temporary targeting is most viable when there is sufficient time to place targets prior to measuring them. For a PJV there is little or no time to place targets. However for a CJV enough time exists to allow factory personnel to place the targets in pre-defined locations on each jig interface. The goal would be to have at least 3 targets on each critical feature. The targets would need to be initially aimed at a specific tracker location but would be manually adjustable if those tracker locations should change. To mount the temporary targets on a jig interface or detail requires a target nest or adapter to accurately and repeatedly position the SMR. These locations need to be carefully selected for optimal visibility, proper detection of jig interface movement and minimal interference to tool function and operation.

Below are examples of temporary targets on two primary types of jig interfaces:

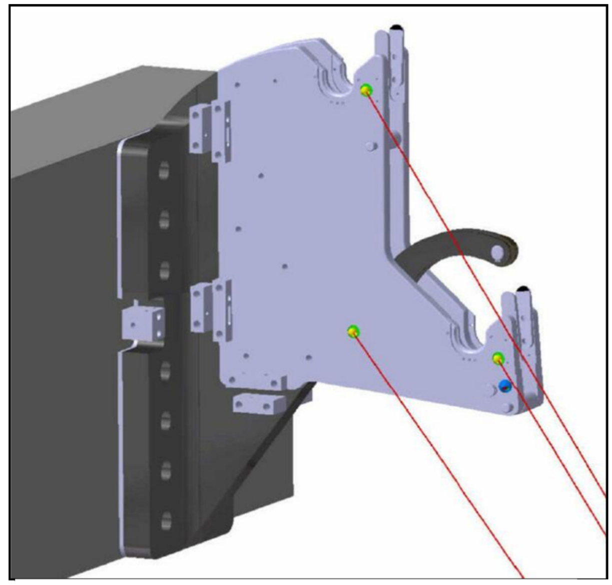

Figure 2. Jig - Flag Interface

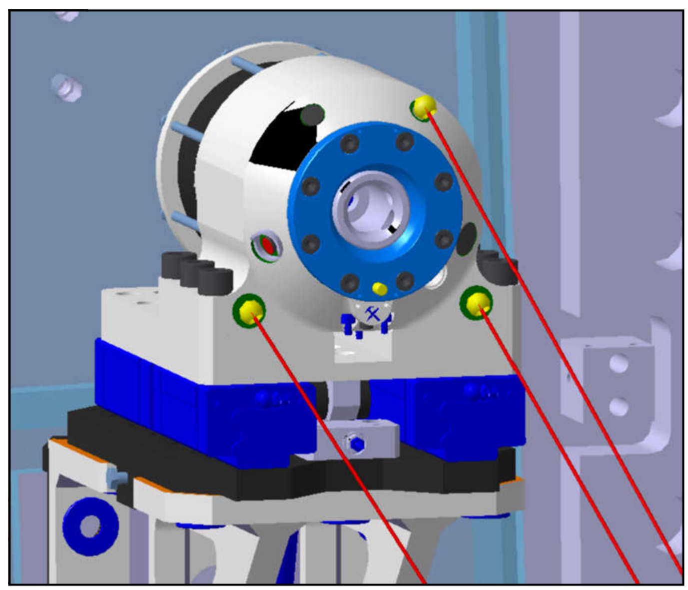

Figure 3. Ball Clamp Interface

An additional consideration for temporary or replaceable targeting is the efficient placement and aiming of each target. Concepts from using man-lifts to get an operator up to the target positions to the idea of using a target pole to reach the target positions from the factory floor have been considered. Ultimately, speed is going to be a prime consideration. If the target placement uses up a majority of the measurement window, there is little time for data collection and re-measuring of missed or rejected points.

Target protection

Some form of protection for permanently installed targeting is a key component to ensuring the targets stay clean and undamaged. Conceptually, the method of protection, be it a cover or cap or lens, needs to be inexpensive, removable, low profile and adjustable. The image below depicts a graphical rendering of a target cover. During the Automated Measurement System study, many different types of covers were investigated. Both solid prisms and open air, SMR targets would need to be protected.

Prior to testing it was thought that if dust covers were not provided, the targets would need to be cleaned or at the very minimum dusted off prior to measurement. In practice, mirrors that were pointed downward remained dust free after six months in our shop floor environment - where operations such as welding and grinding took place frequently. This experience gave us confidence that a partial cover, such as that shown below, would provide adequate protection for retro-reflectors placed in a wing tool.

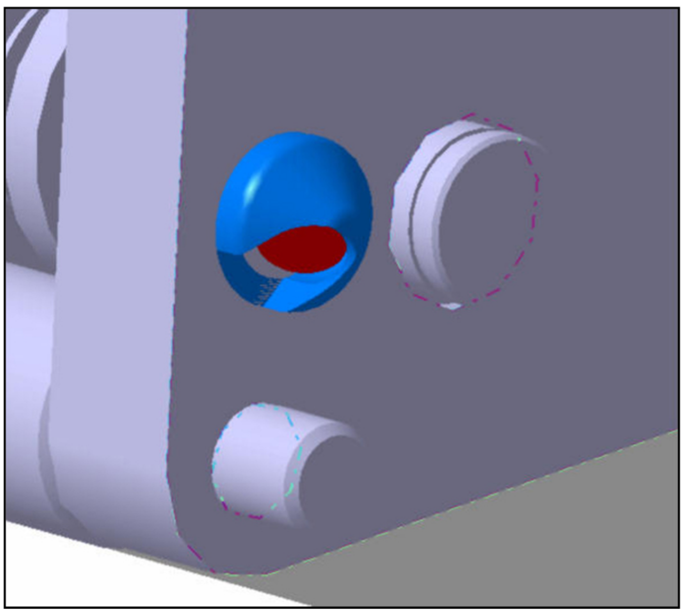

Figure 4. Laser Tracker Target Cover Concept

Target testing

Of the two target types being considered for AMS, the open air SMR is well characterized for both accuracy and repeatability. However, the solid prism target is known to have greater errors than the open air target, especially when the solid prism is angled relative to the laser tracker beam. To quantify these errors, testing the solid prism was necessary.

The EI team acquired several 3/8 inch solid prism target samples with the 1550 nanometer (nm) anti-reflective coating (required for use with the FARO tracker). Tests were performed on both the solid prism and the open air SMR to provide a direct point of comparison. Two key tests were performed: center point repeatability as incidence angle increases and repeatability over the expected range of use.

The testing was performed in a prototype tool using a laser tracker and several targets placed on a fixed column approximately 5 meters from the instrument. Measurements were taken of 3 SMRs and 3 solid prisms in a similar orientation relative to the instrument, starting at a 0 degree angle of incidence. These values were used as the baseline data. Then the instrument was moved in 1 degree increments along the X axis (centerline) of the tool so that the incidence angle increased relative to the targets with each instrument move. Each time the laser tracker was moved, 4 "control" targets were measured to realign the tracker to the same coordinate system to allow direct comparison of the data.

The results of the incidence angle testing are shown in the graph below:

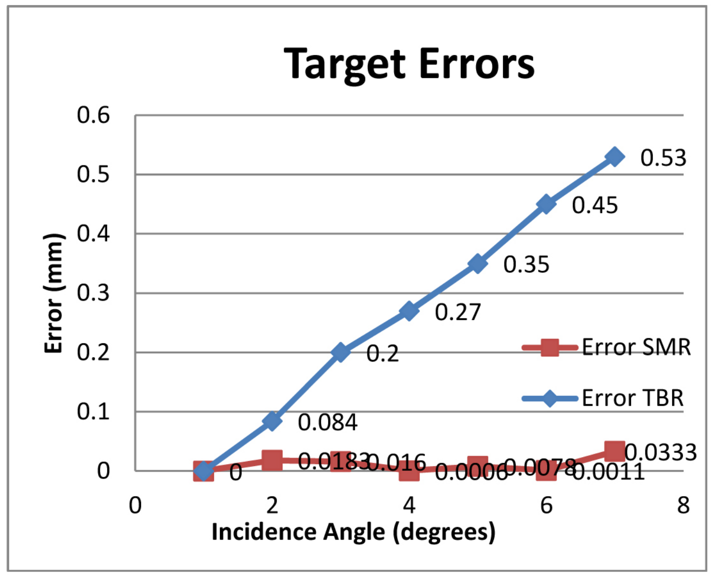

Figure 5. SMR vs Solid Prism

From the graph it is evident that the open air SMRs have little or no error increase caused by an increase in the angular offset from normal to the target face as indicated by the red line in the graph. However, the solid prism shows significant changes in the target position as the incidence angle increases. These errors quickly reach unacceptable levels after approximately 2 degrees of incidence angle. This indicates that to use the solid prisms requires the targets be aimed very accurately at the laser tracker or conversely that the laser tracker alignment be highly repeatable relative to the fixed solid prisms. The location of the laser tracker must be repeatable to within 1 inch to keep the incidence angle to the solid prisms within acceptable levels.

The second test for the solid prism was to determine if the target was repeatable at the maximum range it will be measured from in the production wing jig. This distance has been determined to be approximately 18 meters. A solid prism was measured multiple times at various ranges from 1 meter out to 20 meters. The target repeatability at close range in all three axes (x,y,z) was ± 0.003 mm. This is excellent repeatability and is competitive to the open air SMR, if not slightly better.

NOTE: The solid prism target was also checked for tracking out to 35 meters and it tracked fluidly without losing the beam. No actual tracking will be necessary for STM, but the test results are still useful for target evaluation.

LINE OF SIGHT PLANNING

Line of sight (LOS) analysis is necessary to determine the number of laser tracker stations required and to optimize target locations. Each additional station adds set up time, so minimizing the number of stations is important.

In practice, LOS analysis is tedious and time consuming, but it was essential for properly locating targets and stations.

AUTOMATED METROLOGY SYSTEM (AMS)

One of the primary goals of the Automated Metrology System is to simplify the entire process so that a non-metrology technician could operate the system. In support of this goal, the EI team has utilized three software tools to automate the data acquisition and data analysis portions of the AMS process. The graphical user interface was created using Visual Basic and provides the operator with simple screen commands to drive the AMS routine. The automated measurement routine was created using NRK Spatial Analyzer's Measurement Plan. The analysis of the collected measurements is primarily performed using Microsoft Excel. Each element in the automation is covered in greater detail below.

Graphical user interface (GUI)

The graphical user interface (GUI) is a key component of the AMS program. The interface provides operator instructions for both metrology and non-metrology tasks. Non-metrology steps would include document control, job ticket selection, uploading data to file server. The metrology related task would direct the shop floor level user to initiate the measurement sequence, placing targets, moving the laser tracker and directs the user to perform each step toward completing a Level 1 or Level 2 survey.

The NRK Spatial Analyzer (SA) Measurement Plan (MP) is coded to automate the measurements but does not provide a simplified interface that allows an operator to select a button on a screen to initiate a specific action. This is accomplished via a Visual Basic.Net program that provides buttons on a computer screen that offer options for starting, stopping and controlling how the measurement program operates. The data acquisition, data analysis and report generation are automated and the operator has only a few specific commands that can be executed to control the AMS process.

The image below is the prototype interface for the shop floor user. The interface allows the operator to enter his/her name, select job files, confirm laser tracker is compensated and then check off a series of tasks prior to running data collection. When all the windows show green, the operator is ready to go to the next window.

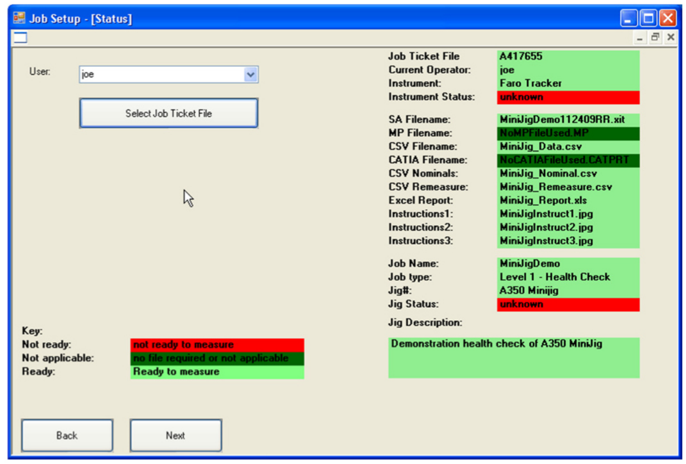

Figure 6. GUI Opening Screen

Once all the key components are in place, including laser tracker and targets, the program prompts the operator to check off each aspect of the tool preparation prior to initiating the data collection sequence. The image below shows what the GUI looks like to an operator after the targets have been uncovered, control point targets have been placed, and the tool is clear of personnel.

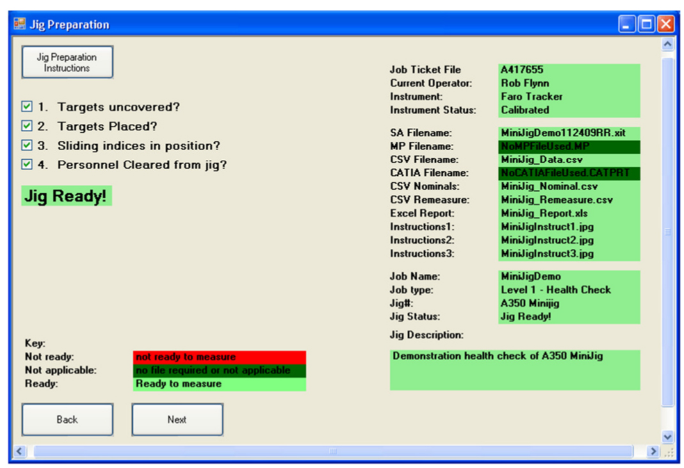

Figure 7. GUI Ready to Measure

The right hand of the screen shows the "all green" and indicates to the operator that the tool is ready for data collection

The automated measurement process

For the automated measurement phase, there are three primary components to be automated: initial positioning of the laser tracker at predefined locations, the accurate alignment of the instrument to the tool reference system and the automated measurement of all the reference points and optical tooling points.

The alignment is initially accomplished using the physical alignment of the laser tracker stand using 3 V-blocks precisely located at the required laser tracker locations within the tool. An initial concept was developed using V-blocks embedded in the center of the prototype tool at Electroimpact. The images on the following page show the V-block and adapter prior to installation and after installation with a leg of the laser tracker stand placed in the V-block. This solution works exceptionally well for quickly placing the stand on the shop floor and providing the necessary alignment to permit automatic aiming at known point locations.

Figure 8. V-block Mounting Point (componenents)

Figure 9. V-block Mounting Point (installed)

To improve upon this rough alignment, a cluster of three "AIM" points are measured. A best fit alignment to these points automatically aligns the laser tracker to the tool reference system accurately enough that all control points on the tool are within the spiral search range of the tracker. The image below shows the configuration of the AIM points on a column in the tool.

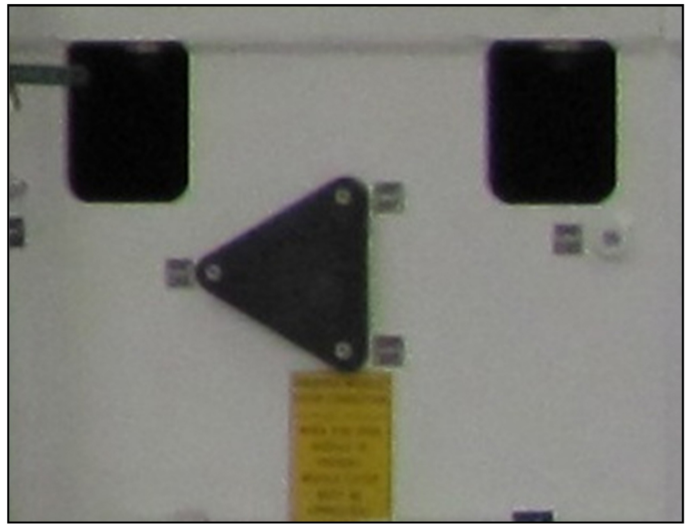

Figure 10. AIM points installed

Finally, the control points are surveyed to improve the location of the instrument in the tool reference system using a best fit transformation which will allow highly accurate pointing to the target features on each detail to be measured.

The entire process is automated via the "Automated Metrology System Routine". The specific steps are defined in a Spatial Analyzer software "Measurement Plan" and simplify the measurement routine to guide a "non metrologist" through the data acquisition and alignment steps without extensive training.

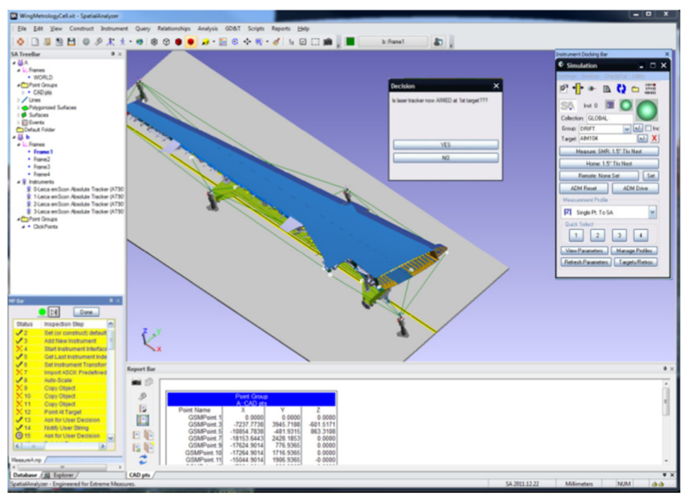

Figure 11. Custom Spatial Analyzer Measurement Plan

Once the accurate alignment of the laser tracker is accomplished using reference points on the tool, a nominal group of points is measured. Once these points are measured, the measured values are compared to their nominal values and a table of deltas is created. For any points that are not measured or the actual value exceeds the nominal value by a specified amount, the points are re-measured. This ensures the measurement process has sufficient redundancy to catch errors and to validate point measurement problems.

Data analysis

As part of the process, data collected from the laser tracker is passed to an analysis routine run in Microsoft Excel or Spatial Analyzer that computes the differences between the measured positions and the nominal positions of points on each critical feature. These results are logged to a results file and also passed back to the measurement program to drive a verification routine of points that are missed or exceed the tolerance from previous measurements.

The working files and reports are stored on the instrument PC until they can be transferred to a central database. Below is an example of the Excel spreadsheet populated by the process. This analysis can also be performed completely within SA but in this case was more robust to calculate deviations in Excel.

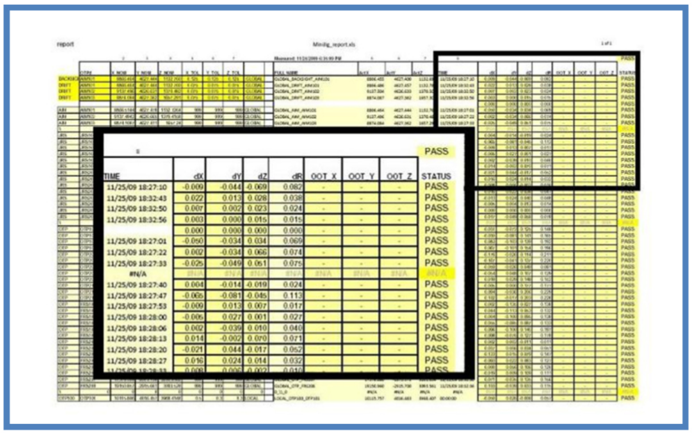

Figure 12. Measurement Report

The Measurement Plan launches the data analysis process, passes the measured data and waits to receive a successful completion notification from the data analysis before continuing. The spreadsheet contains the measured data, nominal data, computed differences between measured and nominal points, tolerances, weighting schemes for coordinate transformations in both global and local coordinate frames, time stamps for each point, out of tolerance magnitudes and a pass/fail condition for each point.

The analysis is written to identify any points that exceed tolerances set in the worksheet or that are missed as "Failed" and returned to the SA data collection routine for confirmation measurements. If no points are missed or out of tolerance, the program returns a "PASS" condition with a green window as shown below.

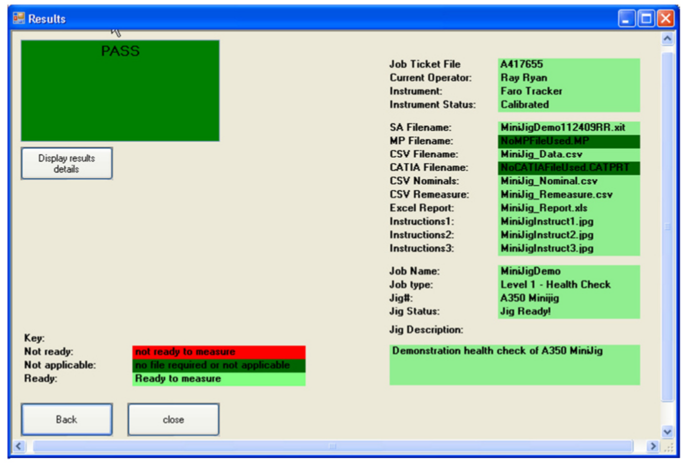

Figure 13. Successful Completion Window

AMS TIME STUDY

The prototype tool provided the EI team with the opportunity to time each phase of the AMS routine. The time study is based on the prototype automation routine and includes steps for equipment staging, target placement, data collection, data analysis, and report generation. The table below provides times for each phase of the tool measurement.

Test Fixture Automated Metrology System Step	Step Time (min:sec)	Elapsed Time (min:sec)
Laser tracker placement in V-blocks from staging area	5:00	5:00
Place targets in control points	3:30	8:30
Measure (3) Aim Points, Initial Best Fit Alignment, Backsight Check	1:00	9:30
Auto-Measuring (14) Reference Points, 2nd Best Fit Alignment	1:34	11:04
Auto-Measuring (26) Feature Points on column tops and beams	1:31	12:35
Automatic Drift Check on (3) Aim Points	0:20	12:55
Data Analysis Routine (Compare to Nominals, Report, Remeasure)	0.05	13:00
Auto-Remeasure of Missed or Rejected Points (Sample = 10 pts)	1:05	14:05

The time study provides sufficient data to indicate that the measurement time is going to be the smallest contribution to the STM process. From the perspective of PJV on a wing jig, the staging of the equipment, the targeting of any reference or control points and the removal of those same targets after the automatic measurement routine are going to require the majority of the 1 hour window.

SUMMARY/CONCLUSIONS

Initially, the idea of measuring an entire wing jig for a large commercial airplane in less than 8 hours, let alone performing a quick health check in less than 1 hour, seemed unattainable. However, as each of the tasks was evaluated for methods of simplifying the most time consuming elements, the probability of meeting the time goals increased. Upon completion of the Automated Metrology System study, it is evident that not only can the time goals be achieved, but there are additional opportunities to develop and improve the proposed methods to reduce the time and improve the amount and quality of the data further.

The results of the study provide information to make the following conclusions:

- Time requirements for Level 1 and Level 2 Automated Metrology System are achievable
- Viable targeting schemes exist to accurately and permanently target wing jig features
- COTS software solutions are available for implementing the Automated Metrology System
- Laser trackers are the best technology for performing Automated Metrology System
- Automated Metrology System measurements can be performed effectively with non-metrology personnel

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DEFINITIONS/ABBREVIATIONS

CJV - Comprehensive jig verification

PJV - Partial jig verification

ERS - Extended Reference System

FRS - Foundation Reference System

JRS - Jig Reference System

SMR - Sphere Mounted Retroreflector (aka Corner Cube)

AMS - Automated Metrology System

TJR - Total jig recertification

LOS - Line of Sight