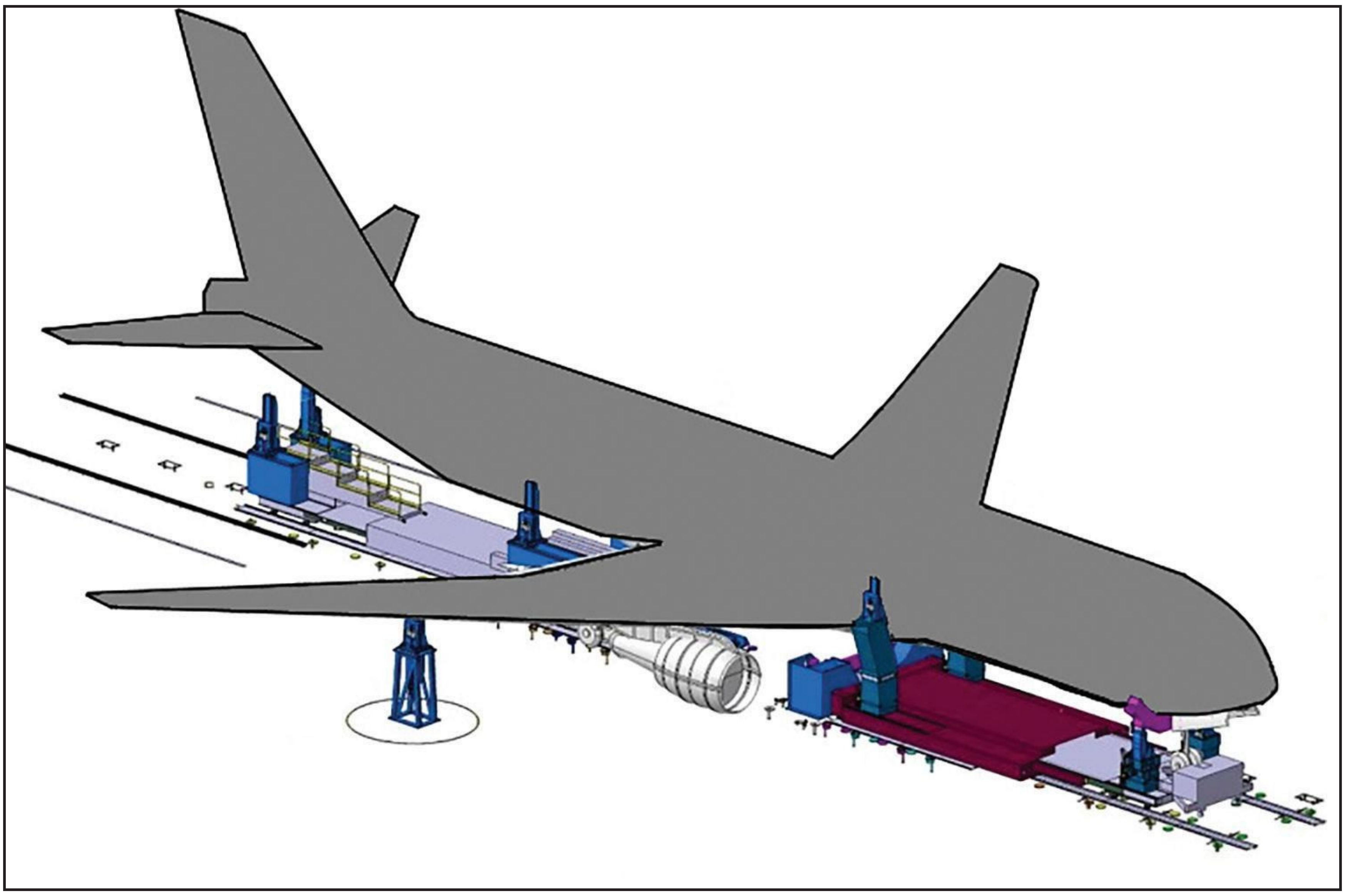


Case Study of a Fuselage Join Automation

by Rob Flynn, Nathan McRae, and Spencer Thompson, Electroimpact

A large jet fuselage consists of forward, center, and aft sections which must be joined together. The join process calls for a rough move to a "stage" position, automated measurements, and calculation of a transformation matrix to yield a move to an accurate "pre-join" position from which the manual join process is started. After the manual join is complete the fuselage sections are measured again, and the final locations recorded. Because the process of measurement, transformation calculation, and data transfer to the programmable logic computer (PLC) is an involved series of events, the customer chose to automate it and thereby ensure a repeatable and reliable result. In this article we examine the solution, look at some of the challenges faced, review the results, and consider some lessons learned.

INTRODUCTION

Large aircraft assembly tasks include the joining of the fuselage sections. Although these sections are very large, fit between parts is tight; therefore, the assembly motion must be very precise. Automated metrology enables this process. In this production process case study, forward and aft sections are joined to the center (non-moving) section, as seen in figure 1. The automated metrology system accomplishes two tasks. First, it moves the moving section to an exact pre-join location; second, after the system is manually joined, it measures the final moving section location. The challenge is increased somewhat because there are two different aircraft models that the system must handle.

The former solution for join assembly required considerable operator knowledge and experience to use, did not provide consistent results, and sometimes took a long time to complete the join. The new system addresses these problems and provides post-join data as well.

NOMENCLATURE

- **Best fit:** More properly, "least-squares best fit," best-fit techniques are used to align a measured set of points (or other features) to the nominal values. Some error always exists, which is spread across all the points evenly using the least-squares algorithm.
- **CTE**: Coefficient of thermal expansion, which is a measure of the expansion of a material as temperature changes
- **LOS**: Line of sight
- **OTP**: Optical tooling point; a target holder placed on an aircraft or on tooling to aid in measurement
- **PLC:** Programmable logic computer
- **Reference systems** (e.g., ERS, FRS, JRS): Fixed points in a system which are used to build the system details. Also known

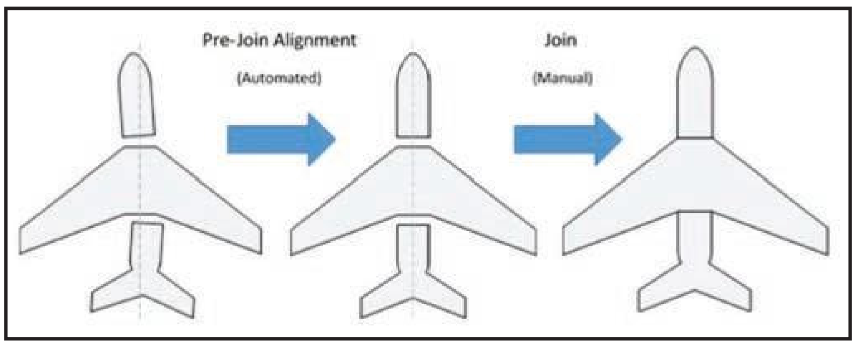


Figure 1. *Overview of join process*

Figure 2. *Complete positioner system during test phase*

as a "control network," these are usually very carefully valued through using multiple station shoots. A JRS is a jig reference system, meaning points on the jig or fixture structure. An FRS is a foundation reference system, with points in the foundation. An ERS is an enhanced reference system and may have points in both the foundation and on a fixture or jig.

- **SMR**: Sphere-mounted retroreflector; a precision target mirror in spherical form used for laser tracker measurements. A BMR is a ball-mounted retroreflector.
- **SA**: SpatialAnalyzer, a commonly used program for laser tracker work in the aerospace industry, from Hexagon Manufacturing Intelligence of North Kingstown, RI.
- **Tooling:** Used to hold aircraft parts in the correct location for assembly; the phrases "tooling," "tool," "jig," and "fixture" may be used interchangeably.

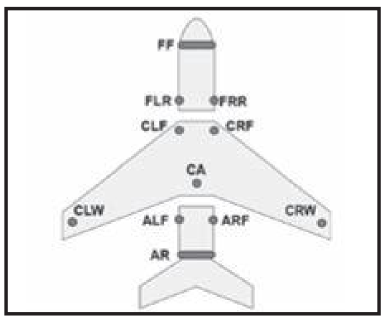


Figure 3. *Positioners for each aircraft section*

DESCRIPTION OF THE JOIN SYSTEM

The join system consists of a mechanical subsystem, a PLC-based control subsystem, and a metrology subsystem. A photo of the complete system during testing can be seen in figure 2.

Figure 4. *This aft positioner uses a design common to all, providing sub .001-in. repeatability via absolute encoders*

Mechanical subsystem

The mechanical system consists of two zones, the center/forward zone, and the aft zone. The join system is composed of 11 different positioners. Each aircraft is composed of the center section (held static during the join process) and two moving sections (forward and aft). Each moving section is supported by two standard positioners and a cradle. The cradle is located at the front of the forward tool and the rear of the aft tool. The layout of the eleven positioners can be seen in figure 3. The positioners in each zone move together to create a rigid body motion. (Note that the center is moved to a home position and stays static thereafter).

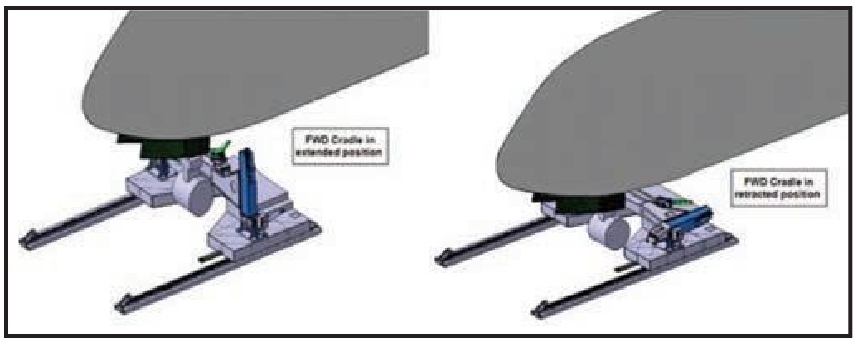


Figure 5. *Model of FWD cradle in folded and retracted configurations*

Figure 6. *Forward cradle— 1) floating pads allow for roll; 2) cradle driven linearly in X, Y, and Z*

Figure 4 shows one of the positioners used in the system. Each positioner provides motion in the *X*, *Y*, and *Z* motion. Incorporated into each jack is a load cell that gives the operators force feedback. The forward positioner folds down to allow the aircraft to easily be removed from the system and rolled away. For this particular job, the customer has two separate aircraft configurations that have a 120-in. difference in length, as seen in figure 5. This system can travel and position the jacks in the correct position for each specified aircraft configuration. This is enabled by long linear rails that allow the positioners the required travel. Part commonality across the system is achieved by incorporating a universal positioner design that is modified as little as possible between all non-cradle positions.

Shown in figure 6 is one of the positioning systems cradles. These unique positioners still have the standard three axes of motion where the contact pads are driven on a *Y* axis. The rest of the cradle is moving as a single unit in *X* and *Z*. This design is highly compliant, which helps to avoid putting high loads into the fuselage as it is moved. All the forward positioners, including the cradle, fold down or retract into a configuration which allows the aircraft to be unloaded from the tool.

Controls subsystem

The controls of the join system consist of a single SIMATIC S7-1500 series PLC from Siemens (Munich, Germany) with motion

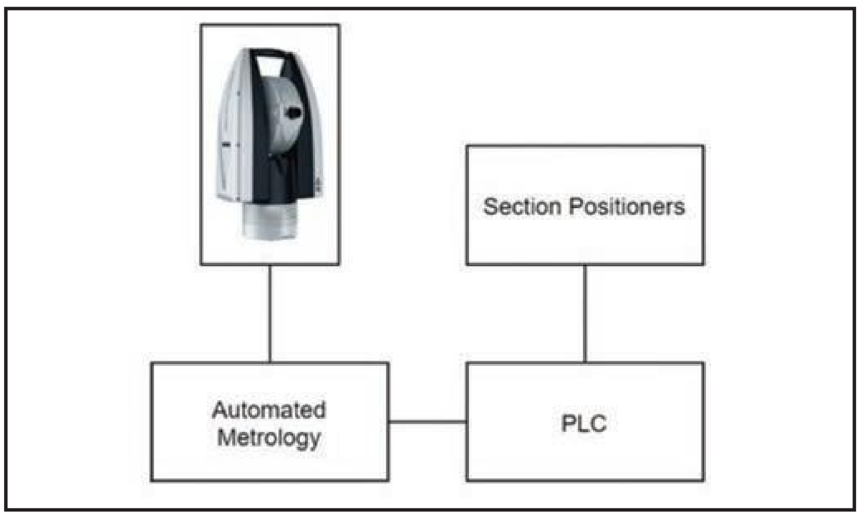


Figure 7. *Controls/metrology overview*

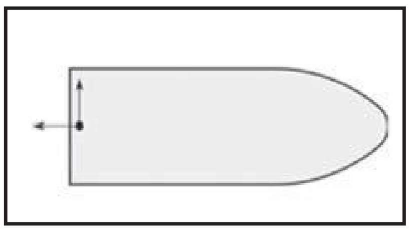


Figure 8. *Airplane section as a rigid body*

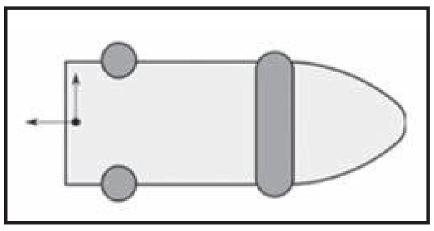


Figure 9. *Section with positioners*

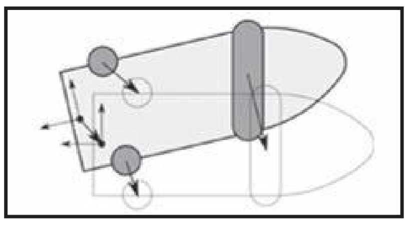


Figure 10. *Rigid-body motion of the section*

control of all positioners. The PLC performs many functions, but for the purposes of automated metrology it is primarily responsible for motion control and kinematics calculations. A schematic overview of the system can be seen in figure 7.

For all part moves the entire airplane section must be moved as a rigid body to avoid stressing or deforming the part, as seen in figure 8. (Individual positioners may be moved independently only if no part is loaded.)

So, to move the section as a whole, each positioner's motion must be calculated separately via the section's kinematics model, as seen in figures 9 and 10.

Similarly, the individual positioner values are run backwards through the kinematics to obtain the section position in the controller's coordinate system. In other words, by knowing the position of each of the three positioner tool points, it is possible to calculate the position of the section. Before the section is moved via the automated metrology system, the initial position is calculated this way, as seen in the schematic in figure 11. The calculated position of the section is compared to the measured position of the section by Operation Commander (OpCom) software from Electroimpact (Mukilteo, WA), and used to calculate the desired position of the section in the controller's coordinate system.

Metrology subsystem

The metrology subsystem, as seen in the schematic in figure 12, supplies the measurements and the calculations with respect to those measurements. The heart of the metrology subsystem is the laser tracker, which provides the measurements key to correct orientation of the fuselage sections. A single laser tracker sits in the middle of the center fuselage section and measures key points on the seat tracks of the center section, and then the forward and aft sections. Once the system "knows" where the sections are it can then calculate where to move the forward and aft sections to match the center. The metrology system passes the new position data to the PLC and the operator executes the move.

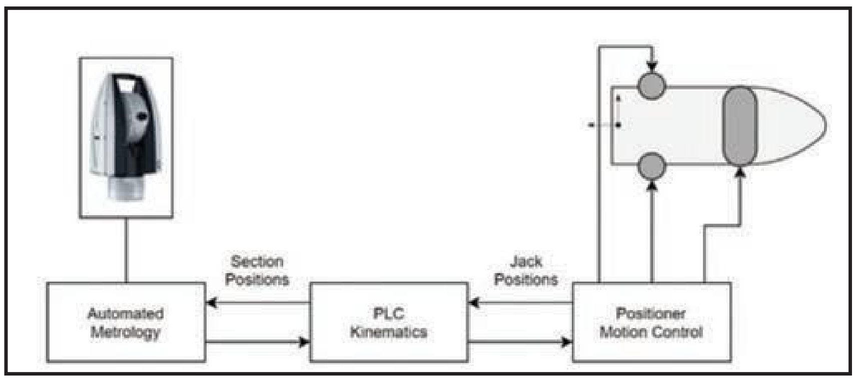


Figure 11. *Controls/metrology system diagram*

Hardware

Much of the hardware is typical for a metrology operation, but there are a few noteworthy items. The tracker stand, for example, is designed to mount directly to the seat track, thus providing an accurate starting location as well as a solid mount, as seen in figures 13 and 14.

To protect the SMRs during manual operations, seat-track mounted kick protectors are used to reduce the chance of SMR damage. Flags coming out the top also make them easier to avoid.

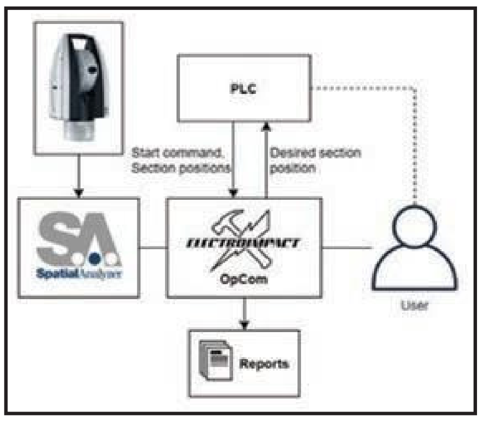


Figure 12. *Metrology overview*

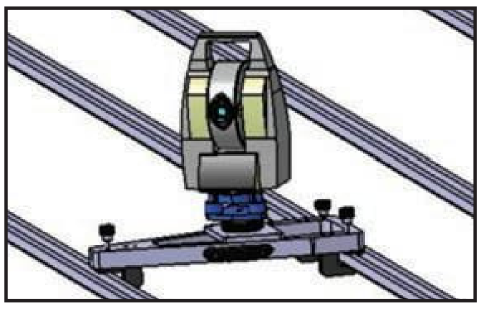


Figure 13. *Tracker on specialized tracker stand on aircraft seat tracks*

Figure 14. *Leica tracker on a custom seat track mount*

Metrology hardware

- Tape measure (for locating laser tracker mount and scalebar)
- Leica Absolute Tracker AT930 (Hexagon Manufacturing Intelligence, North Kingstown, RI)
- Custom laser tracker seat-track mount
- Approx. 20 7/8-in. SMRs
- Seat-track tooling
- Scalebar
- Lights
- Extension cords
- Ethernet cable
- Target flags
- SMR kick protectors

Software

The complete software system consists of several distinct components. SA metrology software is used to run the laser tracker and collect the data. OpCom is used as the human-machine interface (HMI) for the PC. A job-specific OpCom workflow (an extended script written in MS Excel) was written specifically for the pre-join task and dictates everything in the process from the instrument health checks to the number and location of SMRs. One of

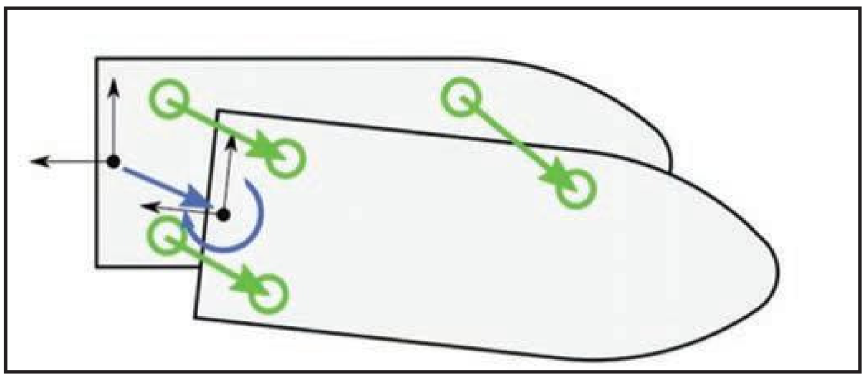


Figure 15. *Plan view of a frame-to-frame move*

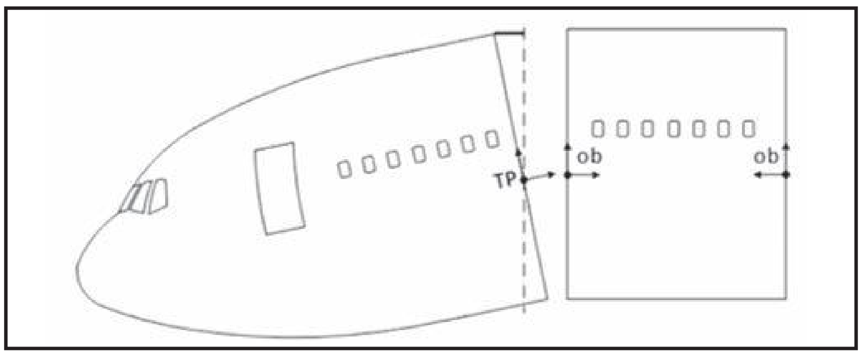


Figure 16. *Key frames*

the key tools of the process is the "frame" (i.e., the coordinate frame or "ordinate system").

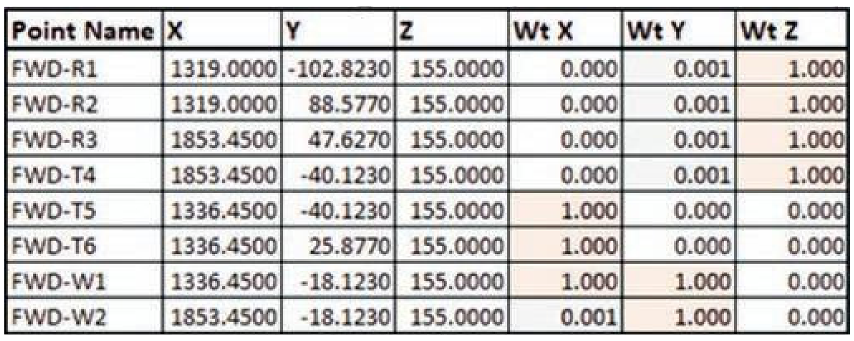
Use of frames in joins

Consider an aircraft center fuselage section with 10 key points representing its location, and a matching forward section with another eight key points. The CAD data tells us where the forward section's eight points should be relative to the center section's 10 points. How does this become six-degree-of-freedom (6DOF) data that the CNC can use to move the section? We have used coordinate frames to address this need, as seen in figure 15.

How do we calculate the desired section position? The first step is to choose the frame of reference for the center section during the forward join. It is convenient to pick a frame with an origin at the center of the fuselage about the height of the seat tracks and at the forward end of the center section. We define a frame here called Ob. We can draw this object in CAD and assign it a location in our aircraft coordinate system. Ob has positive *X* pointed towards the front of the aircraft and positive *Z* up, as seen in figure 16. (Note that there is a corresponding Ob on the back of the center section which we use for the aft join).

We know the CAD (or theoretical) value of each of the 10 key points in the center section in aircraft coordinates, so we can translate those values to Ob coordinates. Now we can take our measured 10 points and "best-fit" them to the CAD values. This gives us a frame which represents the forward section as we have measured it in space.

The next step is to best-fit a frame we call TP to the forward section just as we did for the center. When the aircraft is assembled these two frames (TP and Ob) will be in exactly the same location and have the same orientation. Therefore, our goal is to calculate the move necessary to go from where the forward section is now to where it should be. The calculation produces a transformation matrix. Using the transformation matrix, we then calculate the new position of the forward section (this will also be a matrix).



Point Name	X	Y	Z	Wt X	Wt Y	Wt Z
FWD-R1	1319.0000	-102.8230	155.0000	0.000	0.001	1.000
FWD-R2	1319.0000	88.5770	155.0000	0.000	0.001	1.000
FWD-R3	1853.4500	47.6270	155.0000	0.000	0.001	1.000
FWD-T4	1853.4500	-40.1230	155.0000	0.000	0.001	1.000
FWD-T5	1336.4500	-40.1230	155.0000	1.000	0.000	0.000
FWD-T6	1336.4500	25.8770	155.0000	1.000	0.000	0.000
FWD-W1	1336.4500	-18.1230	155.0000	1.000	1.000	0.000
FWD-W2	1853.4500	-18.1230	155.0000	0.001	1.000	0.000

Figure 17. *Example weighting table*

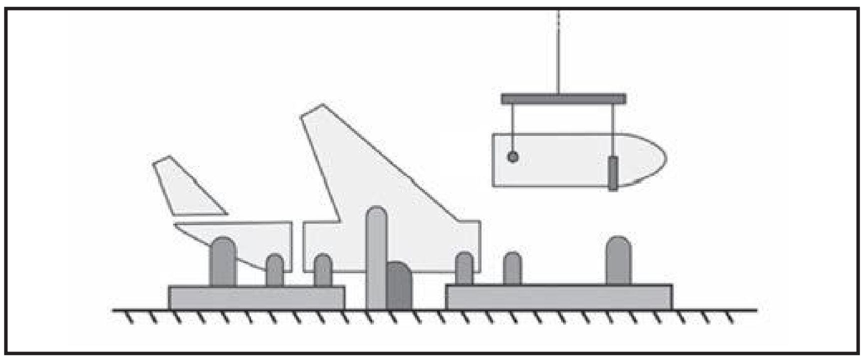


Figure 18. *Section loading*

We mentioned "best-fit," referring to the "least squares best-fit" process, which can be a very simple best fit or a "weighted" best fit. For a "weighted" fit, each *X*, *Y* and *Z* element of each point will have its own weighting between 0 and 1, where 0 does not count and 1 is 100% weighting. See the table in figure 17 for details.

Selective weighting enables the engineer to align certain features when necessary. On the other hand, it is more complicated than a simple best fit, so it is a bit harder to understand. Also, it may be more sensitive to individual point-measurement errors. In the example dataset, the entire *Y* weighting falls on just two points (FWD-W1 and FWD-W2) so if there is a *Y* measurement error in one of those two points, then half that error will go directly into the assembly. In a simple (non-weighted) best fit, the *Y* error for a single point is washed out against the other seven points, so the assembly sees only 1/8th of the error.

THE JOIN PROCESS

Like other automation projects, this one has its peculiarities. One is that access to the inside of the fuselage is very poor once the sections are craned into position. Because of this, the customer may chose to pre-load each section with the appropriate equipment, as seen in figure 18.

Center section prep

- Lock down laser tracker mount to seat tracks in correct location
- Place laser tracker on mount
- Connect extension cords and power up (note that a minimum warmup period is required, so warmup is begun prior to craning the section into position)
- Place lights for illuminating inside of fuselage
- Place scalebar
- Place SMR nests, SMR kick protectors, and SMR flags
- Place SMRs
- Check line of sight (LOS) from tracker to each SMR to verify SMR orientation and obstacle-free LOS

Forward section prep

- Place SMR nests, SMR kick protectors, and SMR flags
- Place SMRs
- Check LOS from tracker position to each SMR to verify SMR orientation and obstacle-free LOS. This can be done with a hand-held laser pointer. The tracker position is marked on the floor of the tooling platform adjacent to the forward section, and the laser pointer is held by hand at the approximate height of the tracker and pointed at each SMR

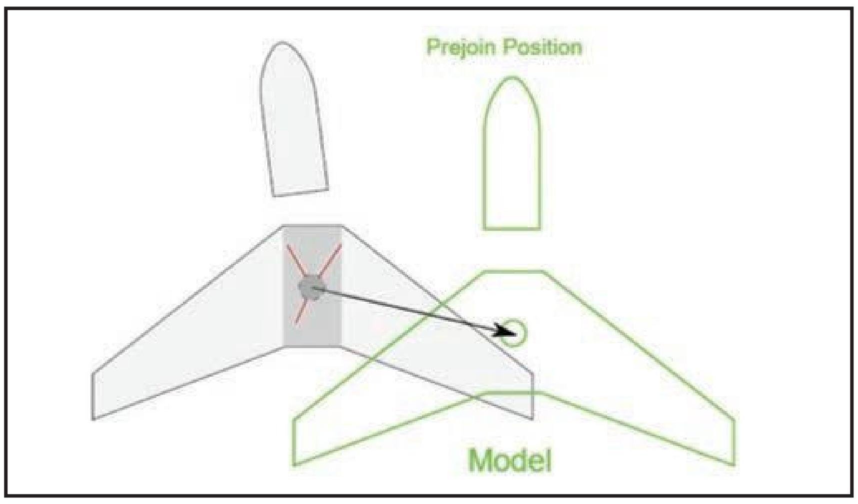


Figure 19. Orient tracker in model

.Section loads

- Crane center section into join assembly station, as seen in figure 18
- Power up laser tracker and lights (note that the laser tracker is running on battery power during the crane move to eliminate any down time due to tracker warmup requirements)
- Crane forward section into join assembly station
- Power up lights
- Move forward section to the "stage" position (about 14 in. away from fully joined position)

Operation commander workflow

- Startup
    - Execute the tracker backsight check
    - Execute the tracker scalebar check
    - Measure the two drift points
- Center section points
    - Measure the first three points
    - Orient the laser tracker, as seen in figure 19
    - Measure all center section points
    - Re-orient using all points
    - Check fit quality
- Forward section points
    - Measure all forward section points
    - Check fit quality
    - Determine current forward section position as understood by the PLC
- Calculate move
    - Calculate transformation matrix to move forward section from current location to desired location, as seen in figure 20
    - Mathematically apply the transformation matrix to the current forward section position as understood by the CNC to yield the new forward section position.
    - Pass the new forward section position to the PLC
- Execute move to pre-join position (about 14 in. away from fully joined position, as seen in figure 21)
    - Using the hand-held pendant, accept the data from the PC
    - Execute the move. Partial moves may be made and then continued, which is important for join processes that typically require frequent collision checks. (Note that the "move" begins and ends with $X \cong -14$ in; therefore, the "move" is actually a minute position and orientation correction to bring the forward section into alignment with the center section.)
- Manual join
    - Customer manually drives the forward section into position, and makes any required adjustments based on other criteria not exposed to the metrology join system.
- Post-join
    - Measure center and moving section as in pre-join workflow to verify join position, as seen in figure 22

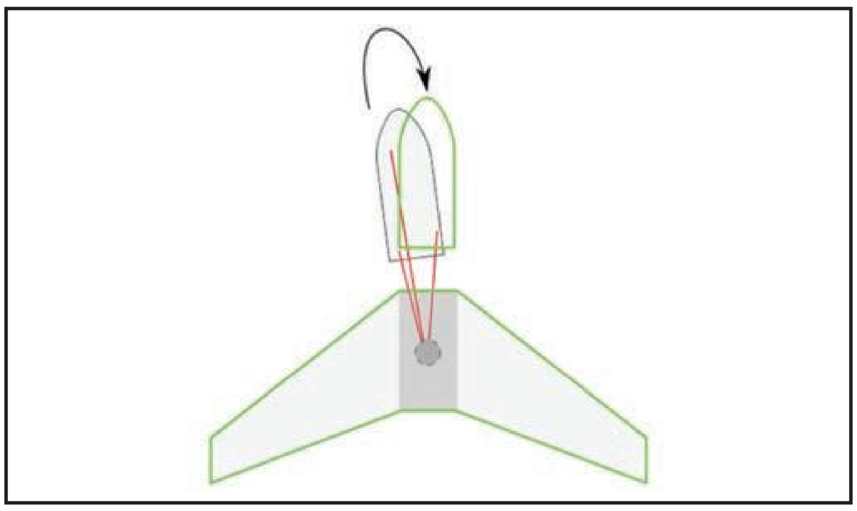


Figure 20. Calculate alignment move

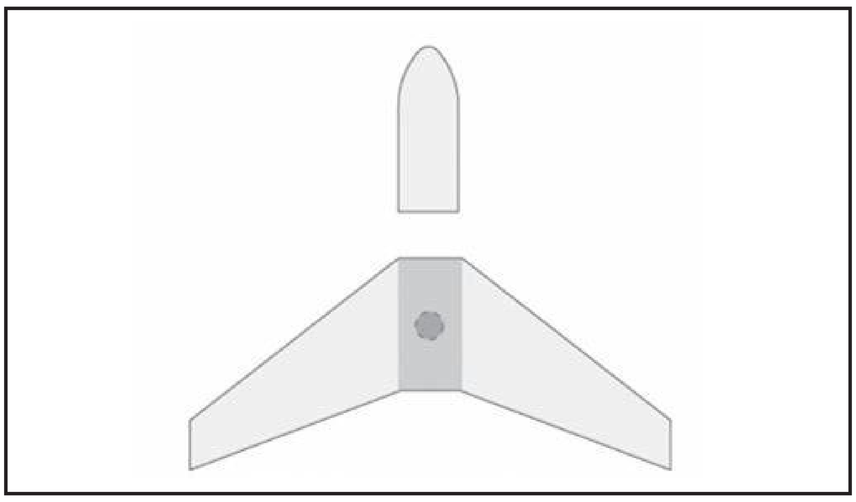


Figure 21. Section now aligned

CHALLENGES AND SOLUTIONS

On one level, running a laser tracker is simple: You place targets in appropriate places with a clear LOS, and then you measure them. The reality is usually more complex and there always seem to be some unusual requirements. This project was no different.

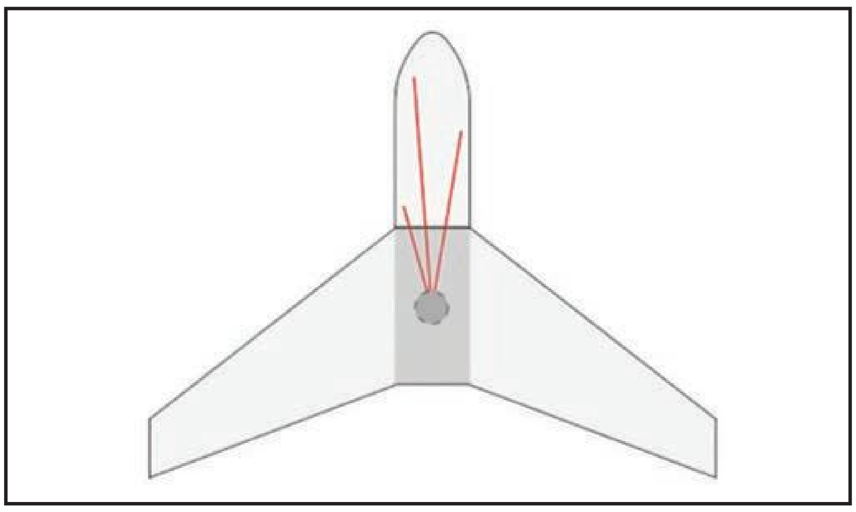


Figure 22. Re-measure join to verify alignment

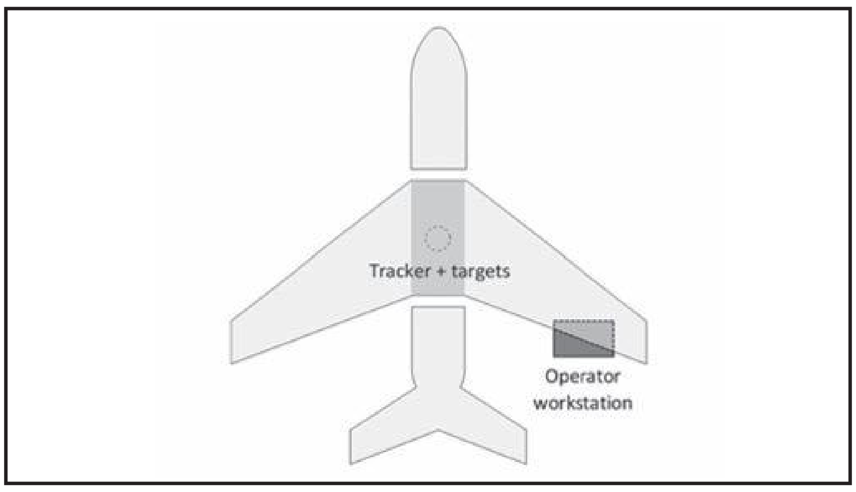


Figure 23. Join cell layout

Separated workstation

As previously mentioned, the tracker is located inside of the center section fuselage. On the other hand, the operator workstation is located on the outside of the fuselage underneath the right-side wing, as seen in figure 23. This led to some unforeseen issues. Initially there was no lighting inside of the fuselage. When using an automatic group measurement, we sometimes had point measurement failures. Without lighting inside the fuselage, the integrated tracker camera was useless as a diagnostic tool to determine the cause of failure. Adding the temporary lighting earlier in the build process resolved this.

Obstacles inside the aircraft

Because the inside of each section of the fuselage is a working area, the mechanics often accidently leave obstacles in the LOS of the targets. Objects like ladders, mats, and even the visual flags (added by the customer to help make the targets easier to identify) blocked some of the targets. LOS obstacles cannot be addressed by software, but we did add functionality to the workflow to handle such issues more smoothly and easily allow re-measurement of any missed points. The customer focused on improving housekeeping discipline to keep obstacles out of the way of the metrology process.

Using power lock modes effectively

Throughout the automated metrology process, we utilize the AT-930's built-in PowerLock functionality. PowerLock simplifies point acquisition, especially when exact point locations are not known (as is the case during initial orientation). In simulation and in preliminary testing the system worked well with PowerLock engaged. However, once we began measurement inside our first fuselage, we ran across the issue of PowerLock occasionally grabbing the incorrect optical tooling point (OTP, also known as a "target"). Some of this issue stemmed from OTPs being close to each other and within viewing angle of the onboard camera. An exaggerated example of this can be seen in figure 24.

Figure 24. Exaggerated PowerLock failure

Given these issues, we turned to using different locking modes on the tracker in different cases. For our initial three-point alignment where the tracker location is not perfectly known, PowerLock is used to automatically grab onto the points. But for the case of our group measurements, we turned PowerLock off and switched to spiral search with a 1.5-in. radius to mitigate the chances of grabbing an incorrect point. By switching measurement search modes, we drastically reduced mismeasured points.

Access to in-production aircraft is always limited, so we came up with a full-scale testing model inside of one of our buildings to mimic the inside of the aircraft. This enabled us to test the new changes we made and created a better testing scenario than our simulation mode inside of OpCom and SA. With the aid of the full-scale test environment we were able to prove out our changes.

Grappling with these sometimes-subtle errors taught us the importance of duplicating the actual point distribution accurately and at scale, and gave us an appreciation for the value of such at-scale models for debugging. It also underscored the necessity to thoroughly understand the functionality of instrument software features such as PowerLock.

In the exaggerated case shown, we commanded the tracker to aim at the point "A1," but PowerLock grabbed onto "A2." The points are roughly in line with each other but about 20 ft apart. This mockup somewhat represents the challenges faced inside of the fuselage when points were close to each other.

SA weighted points error

For all best fits that are used to accurately transform the moving sections of the aircraft we use a weighted best-fit method. We were surprised several times by software anomalies related to this point weighting. First, a software bug caused confusion by inconsistently applying weights (quickly fixed for future releases of the software). Second, we discovered an undocumented feature of SA—weighting only applies in the frame in which the weights were imported/created. This was unexpected, but after consideration we realized that weights are direction-specific, and thus may reasonably be tied to a given coordinate frame. These issues cost us some hours of head-scratching. This sort of problem may not be preventable, but it is more of a warning to be ready to investigate unusual or unexpected developments, and to allow time for exhaustive testing and rigorous scrutiny of the results.

Ideal orientation points

Each operation requires orientation of the tracker by shooting three points. For this application the three points were pre-defined (not user-selectable). Some of these orientation points had other points in the field of view. Because the initial orientation is accomplished by merely orienting the tracker handle towards the rear of the aircraft, rather than through a more precise technique, the initial orientation is sometimes off enough that the operator gets confused about which point to pick.

It may not always be possible, but ideally the initial three orientation points would have no nearby points at all. This approach avoids the possibility of picking the wrong initial point. In some cases it might be worthwhile to add orientation points solely for this purpose. The cost of an extra point may well be worth the reduction in errors made by a careless, tired, or inexperienced operator.

We also realized that other improvements can easily be made such as making alignment marks on the tracker mount and stand, or even better, leaving the tracker mount permanently on the stand.

Poor access to aircraft and the challenge of aiming SMRs

On most metrology jobs there is good access to the laser tracker and targets. That is not the case here, where the inside of the fuselage is off-limits. This means all targeting as well as the scalebar and the laser tracker itself must be pre-loaded before the three sections are flown onto the join tooling. How is this done?

First, the laser tracker is placed in the center section and powered up via carefully routed extension cord. (The tracker has backup power via the Hexagon battery pack, which keeps the tracker warmed up while being craned into position on the join tooling.) The custom tracker stand locks into designated spots on the seat tracks and the tracker locks onto the stand. Tracker orientation is established by simply pointing the tracker handle to the rear of the aircraft. This rough orientation is sufficient to enable the camera to see the appropriate target immediately, which simplifies the initial three-point measurement for orientation.

The Ethernet cable is routed with the extension cord. The scalebar is locked into a designated place with a special mount. All of the SMRs and target protectors are placed and aimed towards the tracker. After all items are in place the tracker is manually aimed at each of the SMRs to guarantee that the SMR orientation is correct. This completes the center section preparation.

The forward and aft sections are more challenging because they are staged far from the center section and cannot rely on tracker aiming to verify SMR orientation. Instead, after the SMRs are loaded, a mechanic takes a hand-held laser pointer to a designated spot on the decking adjacent to the section and, holding it at the laser tracker height, aims it at each of the SMRs in turn, verifying that SMR pointing is correct.

This simple process greatly decreases the occurrence of misaimed SMRs during the next stage and enables the smooth measurement of the sections.

LESSONS LEARNED

Common language via better drawings

A common language is always important and in metrology the key feature is the origin. We failed to do a good job communicating internally about our coordinate frame origins, and this misstep cost us confusion and engineering hours. With multiple coordinate frames in our key files and two different aircraft models to contend with, proper communication is essential—as is the proper display of data. A best practice, then, is to create a very clear scale diagram of the structure including all reference frames and key points with their 3D values. With this in hand, the validity of the tracker and data configuration can rapidly be verified, avoiding a host of problems.

A future goal is to implement importation of data structures accompanied by very lightweight aircraft graphical structural models as well as a lightweight model of the tooling. Graphical tooling models, if used correctly, can make certain types of errors obvious, and would be a welcome addition.

Using a reference solution

We have learned this lesson before, but it was underscored again on this project: It is important to have a “reference” solution for your system. In other words, a dataset and known solution must be developed such that it is possible to run through the entire program and generate a matrix solution that can be checked against the reference solution to verify that all is being calculated and executed correctly. Many subtle errors are possible for this type of system and a good reference solution would reveal them. Implementing a reference solution is difficult, and a future enhancement of OpCom is aimed at making this process easier.

Diagnostic report essential

Another lesson we have learned before was repeated: A diagnostics report is a very useful and important tool. In addition to the standard customer reports we produce a “diagnostic” report which is informal, not submitted to the customer, and which is not polished, but which is continually expanded throughout the project to give as many windows into the data as possible. Ideally, a good diagnostic report provides insight into any type of error that occurs during the process.

Improving test cases

One area we can improve in is that of identifying particular special cases. For example, the workflow functioned flawlessly for one fuselage but showed reporting errors on the next. The cause turned out to be an error which caused the point order to change. A more exhaustive identification and simulation of various test cases would have revealed this sort of bug.

JOIN QUALITY

Join quality is one of the principal measures of success. Although we are not free to divulge join statistics, we did conclude that the system is able to achieve very good join quality. The metrology process produced results that were at the limit of tracker accuracy and the join alignment during join moves was excellent.

SUMMARY

The rigidity and positioning consistency of the system helps the operators perform the manual join with more confidence. They no longer must rely on intuition and extensive experience with floppy, inconsistent jacks.

Using automated metrology allows the join to be performed with consistent relative positioning of the sections to be joined. By having a consistent alignment set and checked by automated metrology, problems due to misalignment are eliminated.

Consistent alignment also helps highlight variation of incoming parts. In the previous system, it was unclear if problems in the join process were due to the tooling used for the join, or due to the incoming parts.

The fact that the metrology process is automated has two key benefits. First, the operator running the process does not need training for the details of each step of the process or for the underlying tools used (such as SA). They only need training in the high-level behavior of the system and in operation of the system interface. Second, automation consistently generates data on the process results. If the process is run manually, then the operator can omit details that may not seems important at the time or forget to save any data at all. Automation creates complete, consistent reports that lend themselves well to analysis.

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