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Unique Material Handling and Automated Metrology Systems Provides Backbone of Accurate Final Assembly Line for Business Jet

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Figure 1Global 7000 Business Jet. Photo credit: Robert Backus.

Abstract

The customer's assembly philosophy demanded a fully integrated flexible pulse line for their Final Assembly Line (FAL) to assemble their new business jets. Major challenges included devising a new material handling system, developing capable positioners and achieving accurate joins while accommodating two different aircraft variants (requiring a "flexible" system). An additional requirement was that the system be easily relocated to allow for future growth and reorganization.

Crane based material handling presents certain collision and handover risks, and also present a logistics challenge as cranes can become overworked. Automated guided vehicles can be used to move large parts such as wings, but the resulting sweep path becomes a major operational limitation. The customer did not like the trade-offs for either of these approaches. A unique conveyance system (ATLAS) based on in-floor rails was developed to offer a solution that provides highly controlled, low risk and accurate moves that allow workers and tools to remain in the assembly area. Positioners were developed, some of which include a driven passive axis (DP axis), useful in certain conditions for driving positioners in their passive axis.

Accurate and rapid joins required an advanced metrology solution. Integrating this automated metrology based positioning system posed a challenge. The accuracy requirement meant that the system had to measure and accommodate slight differences between the incoming parts i.e., be an "adaptive" system. A Human Machine Interface (HMI) was developed to enable de-skilled automated metrology and to communicate with the metrology and PLC systems. The HMI presents a virtual task checklist and restricts the user from deviating from the order of operations or omitting any tasks. Established tolerances must be achieved before proceeding to the next task. A robust architecture allows failed tasks to be re-attempted without re-starting the join process, resulting in a forgiving and flexible process. Integrated supervisor-override privileges make it possible to execute alignment adjustments if dictated by engineering or circumstance.

Introduction

The airframe builder was faced with the challenge of developing a Final Assembly Line for their new business jet. The scope of work included; a) wing to wing join for a butt-line zero join of a 105' wing, b) wing to fuselage join, c) forward and aft fuselage to center fuselage joins and d) flight controls rigging measurement. Two aircraft variants were to be supported. This new program allowed them to start with a clean slate, so they sought a solution which could leverage current technologies to address problems they had seen in their legacy aircraft assembly systems. One of the first challenges to resolve was the question of material handling. An examination of proposals based on cranes and AGVs led the team to seek alternate solutions, and gradually the Aircraft Transportation Linear Actuation System (ATLAS) was developed. This provided an improvement over the more risky crane moves yet without the huge floor sweep problem posed by AGVs.

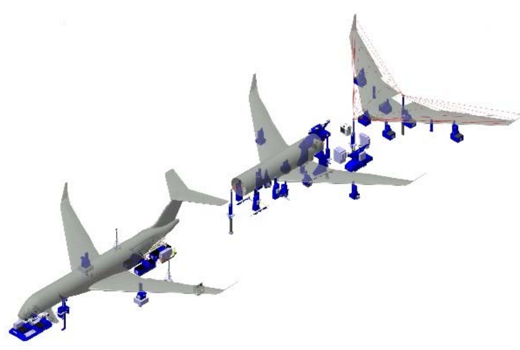

Figure 2 Business Jet FAL

While the Final Assembly Line material handling system evolved, development went forward on the system positioners for the join work centers. Each required some unique positioner features, among them the requirement for a drivable yet floatable axis to prevent over-constraining the aircraft parts during joins.

The structural joining was accomplished in three separate cells. First, the wing-halves were joined; next, the center fuselage was married to the wing; and lastly, the forward fuselage and empennage sections were joined. The ATLAS was used to convey the main component through the three cells.

Figure 3 Positions support and locate wing in the LGT020 workcenter. Photo credit: Robert Backus.

Figure 4 Wing to fuselage join laser trackers are hidden behind surrounding equipment. Photo credit: Robert Backus.

Figure 5 Forward fuselage join is achieved via feedback from tracker mounted inside the fuselage. Photo credit: Robert Backus.

Material Handling

The material handling solution for the wings and the center fuselage section was driven by the high degree of accuracy required for the Automated Positioning System (APS), the requirement to leave handling features out of the wing design for weight savings, the limited wing footprint available for material handling, and the production need for fast conveyance.

Cranes

The initial design concept utilized cranes for all material handling. Unlike ground-based handling solutions, cranes are able to convey the handled components above the ground-based APS. This advantage puts the handled components' swept paths well above any ground based tooling and equipment. However, the joined wing-fuselage assembly pushed the capacity envelope of the building crane system. This crane-based solution became costly, took up a large storage footprint, had an elevated risk of component damage, and threatened to impact production rate. For these reasons, a ground-based handling solution was sought.

AGVs

The ground-based handling solution started out with the industry norm of AGVs. The concept that was developed used 2 AGVs operating in tandem to pickup on a wing cradle. The wings provided the interface to the AGVs as the structure was moved from the first cell to the second, and from the second cell to the third.

Due to the sensitive nature of the components, a structural tie between the 2 AGVs was preferred although not mandated. This tie would prevent the possibility of inadvertent side-shifting or misalignment and allow components to be conveyed safely at a higher height. Additionally, it would serve as a means of allowing the AGVs to communicate with each-other over ProfiNet (an industrial Ethernet network). This ProfiNet connection was critical for maintaining synchronous motion between the 2 AGVs.

Issues with the tie became apparent when the drive paths both into and out of the cells were analyzed. Accommodating the tie would require significant additional stroke into each positioner on the APS as the whole system would have to be higher. These negative impacts that the structural tie drove into the APS were significant, and compromised the tolerances that could be held during the structural joining.

Because of these limitations, the structural tie was abandoned and the option of using 2 AGVs without the tie was explored. This method was impractical because the required stability of the conveyed component was unattainable at the height required to clear the positioners.

ATLAS

With the handling constraints now well defined, the team determined that a machine was needed which would support the handled components with a slim footprint, provide an automated guidance solution similar to AGVs, work in all three positions, provide sufficient stability, and support the handled components without requiring additional handling fittings. It became apparent that such a system would need a moment connection to the floor in order to fit within the space envelope derived from the APS locations. For these reasons, the ATLAS was placed on a linear bearing-rail bed, allowing it to react the predicted side-loads. Each tower uses two servo motors; one for driving forward or aft, and one for moving the handled component up or down. Absolute encoders provide the positioning feedback that the PLC relies on to keep the two towers synchronized.

Figure 6 ATLAS moves the wing-fuselage section to the next workcenter. Center of mass is surprisingly far back in the assembly. Photo credit: Robert Backus.

The ATLAS is highly integrated with the APS; allowing a tightly controlled handover process with system checks to prevent mishandling. All paths are automated and the PLC checks the state of a cell before it is allowed to enter. Operators go through a sequence on the HMI (human machine interface). During each stage of this sequence, the PLC is looking for each sub-system to be in the correct state. For instance, during the handover from a cell onto ATLAS, both ATLAS and the APS are monitoring the handled component's load. During this transition, CG checks are performed to prevent an operator from moving an unbalanced load.

By using measurable states to control the moves, the ATLAS provides part protection that is unmatched by crane-based systems. Line moves are also accomplished much quicker (15 minutes, start-to-finish) than were achieved with the crane-based process to move a similar component. The narrow profile with a moment connection to the floor allow for high lift while maintaining stability.

Figure 7: ATLAS with flush to floor interface.

Automated Positioning System

To support the metrology system, precisely coordinated multi-axis positioners were required to support and manipulate the aircraft components. It was the task of these positioners to hold components in known locations within the factory space and to enable movement of components in an accurate and repeatable fashion.

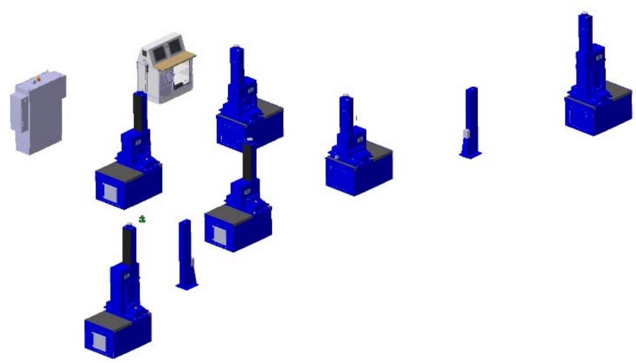

Figure 8: APS layout for wing-to-wing join work center.

Overview

The APS was designed with several key characteristics in mind: (1) safety, (2) positional accuracy and repeatability, (3) compact stroke, and (4) system portability.

Safety—the first aspect of safety was that of personnel. The APS was handling components with personnel above, below, and within the structures. As such, safety was of utmost importance. Rigorous design and testing standards were followed comparable to those used on similar equipment in the automotive industry. For example, dynamic proof load testing of every vertical axis at 150% of rated load, redundant safety nuts on ball screw drives, and redundant braking systems.

Figure 9: Proof loading setup.

The second aspect of safety was that of the components. Location and quantity of positioners was driven by the structural requirements of the aircraft components. In some instances, safe handling meant over-constrained conditions in which an erroneous move of any single positioner could result in damage: The maximum number of support points on any single component was six (6) and the maximum number of support points in an as-joined configuration was twelve (12). For this reason, it was imperative that the positioners work in precise coordination and all movements be monitored by redundant means for the purpose of error checking. A combination of force, position, and power cross-checks were implemented to ensure the safety of parts and personnel throughout the build process.

Figure 10: Single positioner module of the APS.

Positional accuracy and repeatability—while the integrated metrology system enhanced the accuracy of the positioners, to achieve the required build tolerances, a highly accurate and capable base system was needed first. To achieve this, the system used precision ball screw drives and each axis was fitted with precision linear encoders, all drive components were preloaded to eliminate any backlash, the structure was optimized for stiffness, and the machining and manufacturing process was carefully considered during the design. A box structure with linear bearings was utilized for the vertical ram. This box design provided for a more predictable and rigid behavior throughout the stroke, cleaner and better protected packaging of the linear encoders and load transducers, and also eliminated many of the challenges associated with more traditional cylindrical rams (e.g. bushings, seals, tight manufacturing tolerances, wear on sliding elements, etc.). Testing was performed by dial indicator and the requirement of bi-directional repeatability to +/- 0.002" was easily met and exceeded.

Compact stroke—the APS was challenged with the need to accommodate a variety of scenarios: receiving parts from a crane, manipulating parts during join operations, retracting for ATLAS part conveyance, and meeting the work center access heights required by the customer all while trying to keep the structure above grade to minimize impacts to the foundation. Across the three work centers (i.e. wing-to-wing join, wing-to-fuselage join, and forward and aft fuselage join), the FAL had twenty-seven (27) vertical axes not including those of the ATLAS. Three (3) of these axes were higher capacity jacks used in the final work center for lifting the entire joined aircraft structure and installing the landing gear. The other twenty-four (24) axes were the principle axes of the APS and posed the unique challenges driving the requirement for a very compact stroke.

With such a large quantity of axes in the system, commonality was key to creating a robust, easily maintainable design. Thus, the design needed to be modular to adapt to the various positions with a minimum number of unique parts. As a result, the design was heavily driven by the minimum compressed height for any given location and the maximum extended height for any given location. The ratio of extended to compressed height achieved by the APS was

1.6 while maintaining a redundant shaft brake directly on the drive screw, and a redundant safety nut. This ratio could have been minimally improved by altering the location of the load cells; however, it would have come at the cost of reduced performance and more costly, less readily-available load cells.

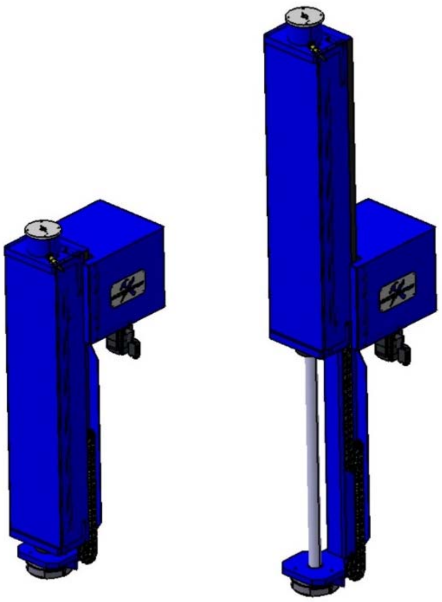

Figure 11: Example compressed and extended heights of APS vertical axis

This design was successfully implemented in all locations. Standoff spacers were used where a higher nominal mounting height was required. Where stroke requirements varied, only three (3) components were required to be unique.

System portability and the "reconfigurable factory"— A new growing demand in aerospace workcenters is system portability – the ability to relocate the workcenter to a different part of the factory to meet demands of production. Portable system elements enables a reconfigurable factory, whereby production can adjust factory layout and flow to meet changing demands. Portability was addressed in design, in this case. Each positioner within the APS was designed, more-or-less, as a standalone unit. This allowed for the bulk of the mechanical install to be done exceptionally quickly. Each positioner utilized a "cup and cone" indexing arrangement for positioning and securing into place. The stiff standalone base structure meant that no rail leveling or base grouting was required in the factory setting. Prior to major hardware arriving onsite, the mating cone features were post-installed into the concrete slab and tracker set. Installation of the positioners themselves was simply a matter of setting them onto the cones and bolting them down followed by a tracker "homing" process to rapidly commission the system. While this type of modular design requires a heavier structure to meet performance and stiffness requirements, the benefits are well worth the tradeoff. Key benefits include: Faster install times, minimal foundation impact, improved system portability, and expanded maintenance options. With this type of modular system, having a complete spare unit available for the event of a breakdown is a real option allowing for offline repairs that do not hold up the production flow.

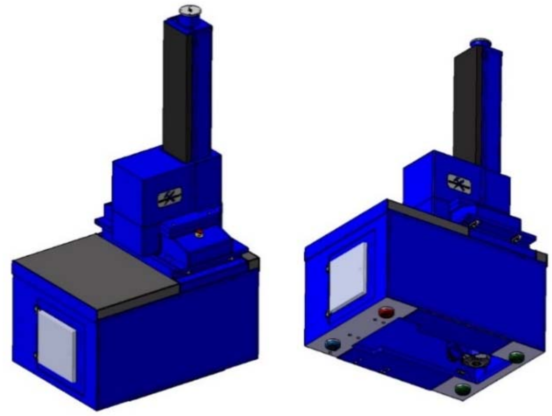

Figure 12: Single positioner module of the APS. Foundation cup/cone interface (right).

Unique Characteristics

DP axes (Driven-Passive)—Passive horizontal axes within the APS were unique in that the controller had the ability to choose when the axes were passive and when they were driven. Initially, the desire for this functionality was for reasons of convenience and safety. For instance, during a crane load of a wing onto the APS, there is no risk of an operator forgetting to manually center a passive axis--and thereby creating a temptation to quickly adjust something beneath a suspended load. Rather, the controller can command the system to a position and all axes are automated including the "passive" axes. Ultimately, having the flexibility to choose when to drive or float an axis allowed the ability to join parts in a more relaxed state. When purely floating an axis and relying on the stiffness of the aircraft structure to 'float' the axis along during join moves, varying degrees of part spring were seen depending upon the location and type of component being handled. With secondary feedback on all axes, it was easy to see that this behavior was occurring since the passive axes would not quite arrive at the locations computed using rigid-body transformations. In these instances, having the ability to control the floating locations allowed for elimination of part spring. While the differences were subtle, this made the difference between joins that were very, very close and joins that were perfect.

Tooling interface—for instances where the component needed to be constrained using more than three (3) handling balls (e.g. center fuselage), a unique scenario existed. As typically done, two balls owned the component positioning and clocking, respectively, and the others floated to accommodate. Where this became unique is that all handling balls needed to be able to react lateral load during the join process and the features were well out of reach of an operator. To address this, a custom ball lock unit was designed that could be floated or released. The unit was spring actuated and pneumatically released. By changing one (1) component in the assembly, the same unit could be used as a positioning, a clocking, or a floating location. Additional functionality built into the unit included ball sensing to detect if a handling ball is present, and a locking unit to retain the ball.

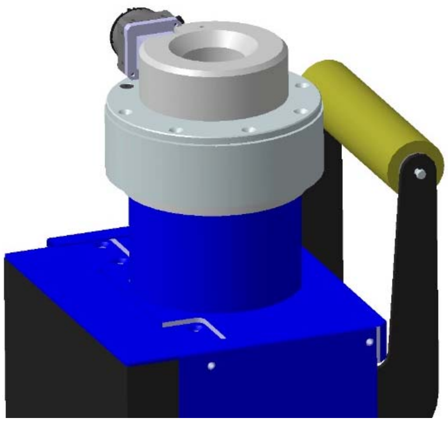

Figure 13: Custom handling ball receiver. Lateral float with lockout. Ball sensing and retaining. Spring actuated and pneumatically released in a tight package.

Automated Metrology

Highly repeatable positioners are of limited use without powerful measurement tools that enable system accuracy. To be effective in a factory environment these tools must also be automated. The system must also insure that no tasks are overlooked. Both of these requirements are achieved by the HMI.

Overview

The backbone of the system are Leica AT402 laser trackers run via Spatial Analyzer (off-the-shelf metrology software), providing reliable and accurate measurements. Because of challenging lines of sight (LOS) each system requires multiple laser trackers, 2 for the wing to wing join, 3 for wing to fuse join and 3 for fuselage to fuselage joins.

HMI "Operation Commander"

Since the operations executed by the operators, laser trackers and Spatial Analyzer combine to form a complex set of tasks it become attractive to have a software solution which would provide visual aids and instructions to help the operator track and execute jobs in a correct sequence. This programming development -- dubbed "Operation Commander" or "OpCom"—allows programming of workflows via a list of tasks and arguments in a Microsoft Excel spreadsheet.

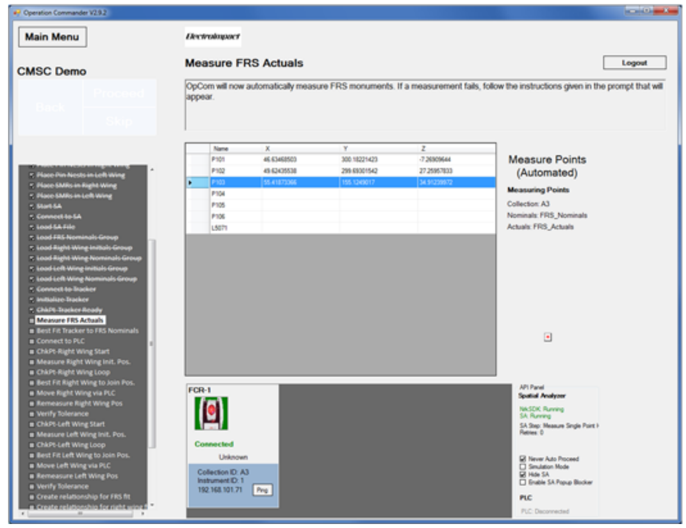

Figure 14: The HMI provides visual feedback and instructions to the operator.

OpCom provides a list of tasks on the left side of the window. Each is checked off as the operator progress through the list.

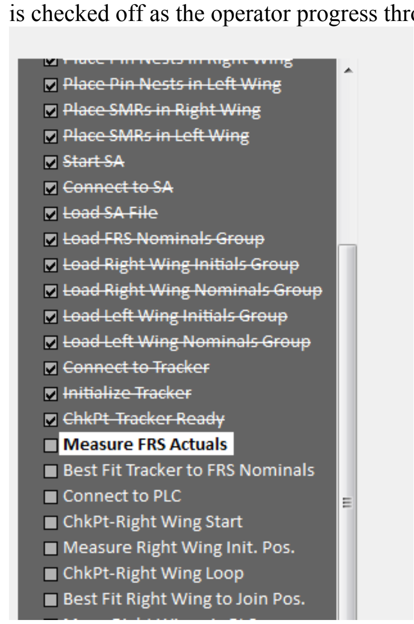

Figure 15: The task list is displayed on the HMI

In essence, the task list provides some "guardrails" against operator error and insures process integrity:

- Essential steps cannot be skipped.
- Instrument integrity checks can be automated. For example, the foundation reference system is automatically measured and best fit; the process cannot proceed if the best-fit criteria are not met.
- Process integrity checks can be automated. For example, drift checks are automatically taken and must be passed for the process to continue.
- All operators must follow the same sequence; skipping ahead is disallowed by the system.

- Engineering part-fit criteria must be met. Measurements outside the criteria are flagged and the process is halted until an engineering or quality over-ride is provided.

Such automation guarantees uniformity and quality in process and acts as a check against inaccurate joins. Meanwhile, integrated security prevents unauthorized changes to the programmed workflow. At the same time, the use of user and group password overrides, such as supervisor, engineering, quality, etc., allow process flexibility for unusual situations.

Other features

Other features simplify the system programmer's task for developing a workflow. For example integrated looping allows easy implementation of a move-measure-move cycle which is very useful in "high-force" join conditions (joins with tight part fits requiring components to be pushed together with force). Communication with Spatial Analyzer allows tracker control, while communications with the system controller enables transfer of transformation matrices to the controller for accurate positioner moves.

Automated reporting

No metrology process is complete without reporting. Automated data export to Microsoft Excel provides comprehensive and real-time process feedback.

LGT040 WING TO FUSE P

A/C# Test **Date:** 3/2/2016 T

	A. MEASURED CENTER FUSE CIPS				B. MEASURED WING CIPS (-6")			
	X	Y	Z		X	Y	Z	
MA1	-35.026	71.097	330.495	WA1	-38.145	47.659	729.152	
MA2	34.953	71.121	330.490	WA2	38.132	47.659	729.154	
MA3	-35.018	71.042	530.505	WA3	-38.139	58.899	539.657	
MA4	34.996	71.046	530.520	WA4	38.139	58.901	539.658	
MA5	-34.948	71.097	846.521	MID WA12	-0.007		729.153	MID V
MA6	35.085	71.103	846.487	MID WA34	0.000	58.900		MID V
MK3	-49.506	84.147	545.037					
MK4	49.506	84.183	545.028					
MC1	-38.145	50.660	729.166					
MC2	38.145	50.660	729.134					

CENTER FUSE DATUM CHECK

MID MK34	.0000		
MID MC12	.0000		729.1500
MC1		50.6600	
MC2		50.6600	

IF ANY RED CONDITIONS OCCUR IN THE DATUM DEFINITION VERIFY AND RESUBMIT THE DATA. (TOLERANCE=.0005)

NOTE1: The purpose of this report is to validate the position of the wing relative to the fuse at -6". Re to the fuselage.

NOTE2: The datum frame for the above datasets should be MJ, MK, ML

NOTE3: The section C. WING NOMINAL CIP is provided with -6" nominal coordinates

Report Template Version: 02/03/2016

Figure 16 Excel is used as the engine for the automated reporting.

Enabling more sophisticated joins

The various features of OpCom combine to simplify the programmer's task of creating more complex and sophisticated joins. In the examples here, it enable adaptive tooling, flexible tooling, and aided in implementing solutions to some interesting join problems.

Adaptive and Flexible

Traditional "hard" tooling fixes the parts to be joined in a given position time after time. This has the advantage of simplicity, but traditional hard tooling cannot offer flexibility – the accommodation of multiple variants – or adaptability – the ability to modify the assembly based on the slight variations found from part to part.

The accuracy demands for the joins mean that the metrology system must measure the incoming parts, evaluate them and adjust the join configuration slightly to optimize the form of the resultant assembly. This adaptability feature of a join cell enhanced with automated metrology offers subtle but important improvements in the accuracy of the assembly.

Joining with vector bars

The aft fuselage join process offers a special challenge in that features critical to the join are found on both the interior and exterior of the aircraft. To meet this, a tracker was placed in the center of the fuselage on a special stand, while two trackers were placed externally on either side of the rear of the aircraft.

Figure 17 The left hand tracker is shown sighting to vector bars in the windows. Photo credit: Robert Backus.

A key to this solution is to be able to tie together the interior and exterior laser trackers. This was done through the use of "vector bars", also known as "hidden point rods". In this case, the vector bar is a precision made artifact with three targets, each in line and at a set distance apart. One laser tracker measures two points and infers the location of the third. (The capability to make such inferences is a built-in feature of Spatial Analyzer).

Figure 18 Vector bars used for aft fuselage joins.

In the example case here, the vector bars were placed so as to protrude through the empty windows of the aircraft such that the inner laser tracker could see two points on each bar while the exterior trackers could see the third point. The trackers on the exterior of the aircraft were tied together via a foundation reference system (control network) in the floor. The resultant ensemble provided a reliable and accurate system for providing critical fuselage join feedback.

Figure 19 A custom stand is used to mount the tracker on the a/c seat track rails.

De-skilling operations through the HMI

The aft fuselage join operation highlights a successful feature of the HMI, which is that it very significantly "de-skills" complex metrology operations. An operation which would typically only be undertaken by experienced metrologists is easily carried out in the production environment by users with a minimal amount of training, and with complete consistency of process.

Summary/Conclusions

Re-locatable positioners with passive axes, a unique material handling system and an unusual automated metrology software HMI integrate to provide a flexible, accurate and effective final assembly line system.

References-ALL

1. Flynn, Robert X. and Horky, Schuyler Q., "Improving Quality of Aircraft Structural Joins Via Adaptive Tooling and a Flexible HMI," *Journal of the CMSC*, Vol 10, No. 1, Spring 2015.

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Definitions/Abbreviations

HMI	**Human-machine interface – software to enable direct human control of a machine or process.**
LOS	**Lines of Sight.**
SA	**Spatial Analyzer – metrology software used to control laser trackers and gather and analyze data.**