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Gaugeless Tooling

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ABSTRACT

At The Boeing Company, the advent of a Determinant Assembly (DA) program and the subsequent production of accurate fuselage subpanels created a need to be able to position subpanels accurately and repeatably during fuselage assembly. The tool engineering organization of The Boeing Company and Advanced Integration Technology, Inc. (AIT) as the prime contractor, are developing and installing automated positioning and alignment systems throughout major 747 fuselage assembly areas which enable DA techniques. The benefits of this assembly approach and this automated precision tooling are flexibility, assembly accuracy, ease of assembly and associated speed, reduced downtime for tool maintenance, and improved shop-floor ergonomics.

INTRODUCTION

When Boeing decided to apply determinant assembly methods to construction of major fuselage sections of the 747 aircraft, it needed to find alternative tooling technology to support the unique requirements. Boeing has worked with Advanced Integration Technology, Inc. to adapt automated precision positioning to the assembly process. As background, this paper will first describe the benefits Boeing hopes to realize by implementing determinant assembly. It will then give a technical description of individual components and the system used to support the DA process along with a description of how the system is used. Finally, it will compare conventional tooling methods with the methods employed in the Fuselage Assembly Improvement Team (FAIT) program, highlighting the many benefits of the newer techniques.

BACKGROUND

BENEFITS OF DETERMINANT ASSEMBLY - Recently, Boeing has adopted a determinant assembly (DA) philosophy for use in 747 major fuselage assembly. The essence of the DA philosophy is that indexing one part or assembly to another yields three primary benefits over indexing the two parts or assemblies to a tool: improved accuracy; increased flexibility; and reduced cost.

First, accuracy of the part-to-part relationship is improved because the tolerance chain is typically shorter and each individual tolerance is smaller in magnitude than tool-based indexing systems. Also, tool tolerances are usually biased and fixed while part-to-part indexing tolerances are randomly distributed and centered around the mean. This fact allows the manufacturing engineer to take advantage of statistical tolerance combinations for determinant assembly which typically are not available for tool based assembly processes.

Second, DA is more flexible because changes to assemblies can often be accomplished by modifying the feature locations in the part NC program. This is contrasted to conventional assembly tooling where a physical component of an assembly fixture must be relocated or a new index fabricated and installed on the assembly fixture.

Third, DA yields cost advantages in several ways. As previously mentioned, engineering change costs are typically lower. For similar reasons, non-recurring tooling costs are significantly lower for DA because many of the typical parts of the assembly fixture are precluded by part-to-part indexing. The biggest cost savings is recurring and is a result of the superior fit of parts and assemblies built using the DA process. Not only is less assembly rework required using DA, but basic direct and indirect factory labor is also significantly lower for these closer tolerance assemblies. As a result, the customer receives a higher quality product at a lower cost within a better delivery schedule.

IMPLEMENTING DETERMINANT ASSEMBLY - Determinant assembly is accomplished by integrating part indexes into the product definition process. Digitally designed subassemblies and assemblies with DA features are used to create NC programs used in the machining of these features into the part. In 1995, Boeing and Northrop Grumman commenced a re-engineering program for the majority of the Northrop Grumman-supplied fuselage panels including the creation of CATIA data sets with DA features. Northrop, along with its suppliers, completely revamped its 747 manufacturing and tooling plan to take advantage of the determinant assembly enhanced digital product definition. To maximize the leverage obtained from this investment in quality, Boeing committed to building completely new Major Assembly Jigs in its Everett facility based on the DA philosophy.

It is important to note, that some portions of the fuselage were outside the scope of the Northrop Grumman effort. In these areas, Boeing needed a method to bridge the gap between the determinant assembly index systems and the conventional tooling based index systems. In order to bridge the gap, planar laser systems similar to those provided by AIT for other recent Boeing airplane programs were required. The planar laser technology allows high accuracy integration of conventionally built assemblies and determinantly built assemblies. The resultant tooling is a combination of gaugeless (determinant assembly) and virtual (planar laser) tooling. Figure 1 summarizes the objectives, tooling requirements, implemented solutions, and benefits of the FAIT program.

Figure 1: Drivers and Requirements for FAIT Tooling

Manufacturing Objectives: Accuracy, Flexibility, Lower Cost

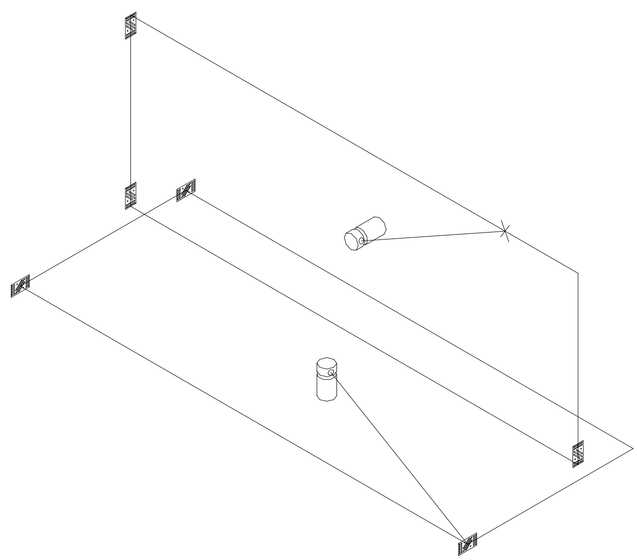
	DETERMINANT ASSEMBLY	CONVENTIONAL ASSEMBLY	
Assembly Technique	Snap Together Parts Part-to-Part Indexing	Parts-to-Tool Indexing	
Tooling Characterization	Gaugeless Tooling	Hard Tooling	Soft Tooling
Tooling Requirements	Free Form Manipulation	Indexing	Indexing
Benefits	Precision, Speed, Flexibility (versus non-automated tooling)		Less Constraining Less Routining (vs. hard tooling)
FAIT Program Solution	Precision Automated Motion		Laser Measurement

TECHNICAL DESCRIPTION OF AUTOMATED GAUGELESS TOOLING AND LASER INDEXING

To fully understand the benefits of automated gaugeless tooling and laser indexing, it is important to understand their technical aspects. The following is a brief technical description of the pieces and parts that comprise the tooling along with the control system that makes it all work.

PLANAR LASER SYSTEM - In a laser indexing system, airplane features are located using laser measurement feedback instead of hard tooling. At Boeing, a rotating laser continuously sweeps 360 degrees and strikes targets located in a plane. A retroreflective pattern on each target face returns a pulse signal to a photodiode receiver in the laser head. The pulse signal varies based on where the laser strikes the target face. By processing this return signal, the laser can determine where the target is in space relative to its “zero” or centerline position.

Figure 2: Laser Reference System



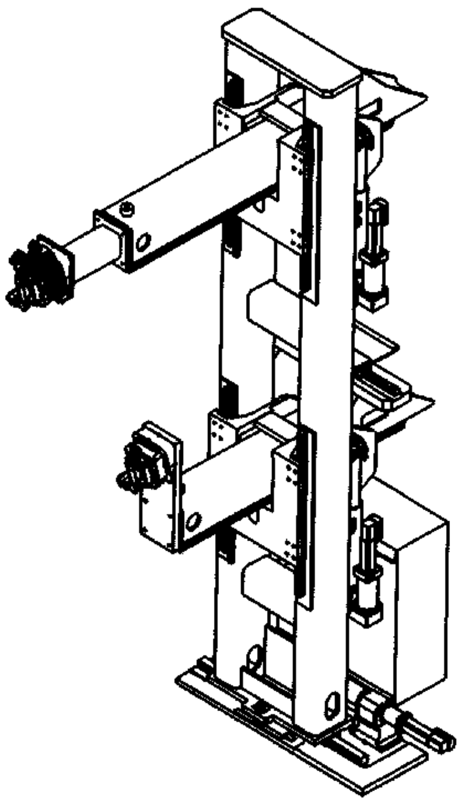
Two to three laser Cartesian planes are used as references during assembly. In order to establish and index these laser planes prior to build, the laser sweeps monument targets located on tool structure and processes the return signals. The laser then actuates tilt and roll mechanisms in its rotating head until it strikes all targets at their centerlines. This buck-in process occurs each time the tool is prepared for use. During construction, these monument targets are precisely located on the tool’s primary structure using an independent computer-aided measurement system. Thereafter, they are periodically routined for location.

Targets are mounted into skin coordination holes and seat tracks on the airplane floor structure such that they are located nominally in the plane defined by the laser. The amount by which the target is not coplanar during assembly is detected or measured by the laser. This value is scaled and displayed on all graphical user interfaces (GUI) as an engineering value which is “up/down”, “fwd/aft” or “in/out” from the nominal location.

These values are used by the operator in determining how to manipulate each panel.

SIDE PANEL MANIPULATORS AND POGOS - Fuselage side panels are craned into the fixture and attached to panel manipulators via body fittings. Each panel manipulator is composed of a column structure which is actuated in station and protruding arms which are actuated in waterline and buttockline. Each of the moving axes is controlled by closed loop servo control, and each arm assembly is equipped with an end effector that attaches to the Perishable Miscellaneous Tool (PMIT), a throwaway shipping lug. Multiple panel manipulators arms attach to each side panel. End effectors on the arms provide a combination of positive indexing to the panel and compliance to prevent stressing during manipulation.

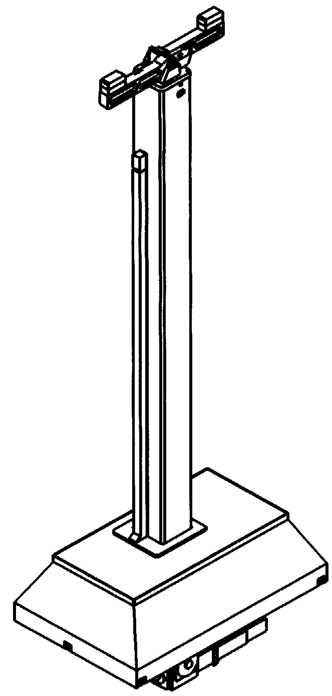
Figure 3: Side Panel Manipulator



Similarly, keel panels are craned into the fixture and supported by pogos (the fuselage section is built upside-down). Each pogo is composed of an X-Y table which supports tube steel Z-actuator column structure. The top of the Z-actuator is equipped with a collapsible end effector which indexes to floor beams. Since multiple pogos support each panel, many of the X-Y-Z axes float to provide compliance and the remaining axes are controlled by closed loop servo control.

Once each panel is in place and the crane is free, the pogos or panel manipulators move the panel to a staged position. The pogos' and panel manipulators' movements are controlled by the real-time controller upon commands from the operator console GUI or the joystick.

Figure 4: Pogo



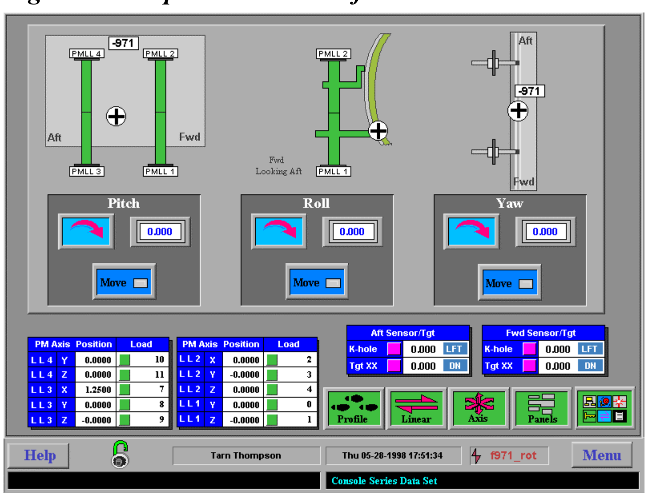
DISTRIBUTED CONTROL SYSTEM - The distributed control system is composed of an operator console which performs cell-level control, Real-time Controllers (RTCs) which perform low level motion and I/O control, digital joysticks which allow local free-form panel manipulation, graphical pendants for remote mobile viewing of all process data, and precision servo motors which allow sub-mil manipulation. These components comprise the distributed control system which is the key to supporting the unique requirements of the FAIT program, namely the capability to move panels precisely and predictably in an intuitive fashion.

<u>Control Architecture</u> - All of the panel motion is actuated by precision servo motors. The servo motors are controlled by high-speed servo motion controllers or real-time controllers (RTC). The real-time controller is an open architecture, industrial PC-based platform with multiple DSP motion control cards. Each RTC controls between 10-50 axes of motion. High-level orchestration is performed by the operator console which communicates to the RTCs over a dedicated ethernet sub-network. This high-level control is required to coordinate over 110 axes of servo motion in a single assembly cell or system. The operator console also provides a graphical user interface through which operators can actuate panel translations or rotations of known magnitude.

Servo Motion Control - Precision, brushless DC servo motors with integral feedback drive each of the manipulating axes. The servos are controlled digitally over an industry-standard SERCOS fiber optic bus network. This architecture results in improved noise immunity and lower total wiring which leads to lower maintenance costs. Servo loop resolution to 1/4095th of a motor revolution allows the pogos and panel manipulators to be positioned in sub-mil increments.

Graphical User Interface - The operator interface is made intuitive by graphical representations of the panels as shown in Figure 5. To move a panel, the operator simply toggles the arrow until it points in the desired direction, enters a numeric move value in thousandths of an inch, and touches the Move button. The control system then calculates the move profile for each axis involved in the move and parses the move commands to the appropriate RTCs. The RTCs then perform multi-axis motion control including monitoring position feedback, limit switch status, load cell readings, and all other analog and digital I/O. All of this control is performed in real-time without operator intervention. This interface precludes the user from having to calculate or guess appropriate move distances for each axis.

Figure 5: Graphical User Interface - Panel Move Screen



Digital Joystick - Since the assembly process involves aligning several coordination holes, it is beneficial to be able to move panels in a free-form fashion. In other words, if an operator is trying to align holes that he can see, there is a need to be able to steer the panels into position using visual feedback to determine the distance to be moved. To this end, the system incorporates a joystick which provides open loop positional control. To select a panel to move, the user pushes a button on the joystick which scrolls through a list of the aircraft panels on the LCD.

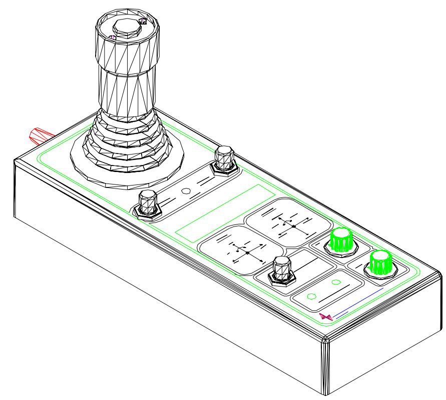


Figure 6: Portable Digital Joystick

When the name of the desired panel appears on the LCD, the operator selects either linear or rotation mode to determine which type of motion is actuated. Deflection of the joystick in any of three directions then actuates a station, waterline or buttline move or, in the case of rotation mode, yaw, pitch and roll.

Since the holes must be aligned very accurately, the operator must be able to move the panels consistently and predictably with the joystick. A jog mode provides this capability. When a rotary switch on the joystick indicates jog mode, deflection of the joystick past 50% of its stroke in any direction produces a discrete move of known magnitude. The joystick can actuate an identical move only after it is returned to its center position and deflected past its midpoint again. This produces a fine bumping of the panel into position. The magnitude of the jog move is configured by the system administrator through the operator interface.

Real-Time Load Measurement - In order to ensure that sub-assemblies are not stressed during movement, load cells are integrated into the load path of every driven axis. The load cell outputs are wired directly to the high-speed RTC which reads loads every 10 ms. The protection provided by the load cell is two-tiered: First, the load values are scaled and displayed on the operator interface, and icons are color coded to indicate the magnitude of the load. This interface provides the operator with a visual indication of the load condition of all axes. Second, the system can automatically stop movement when loads reach a predetermined value or zone. The load at which movement is halted along with the color coding range values can be altered at any time by a system administrator through the graphical user interface.

Remote GUI Pendant - A lightweight portable PC can be toted into and about the airplane structure during alignment. The pendant remotely shows the same data as the operator console. This allows the operator to see loads, axis position, and target data while using the joystick to align coordination holes in panels. This pendant is connected to the same dedicated ethernet sub-network, therefore, there is no latency in the data transmittal.

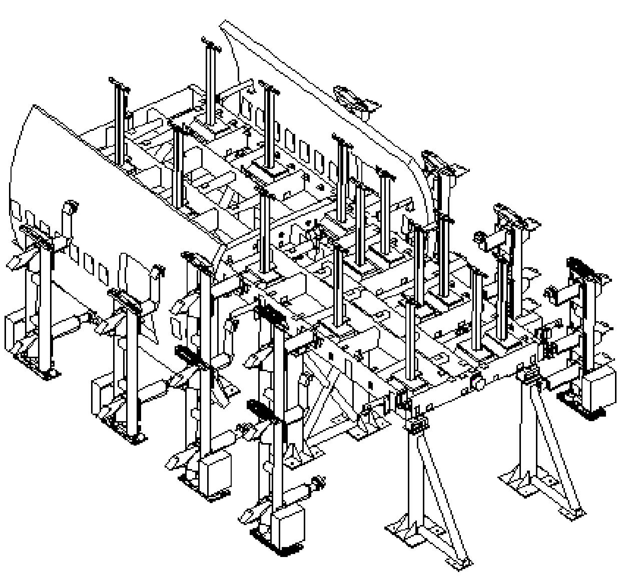
Part Programming - Once the system is put into production, mechanics will learn the best way to move panels together in the alignment process. The software gives the shop floor the ability to capture these routines and run them automatically. Through the graphical user interface, the user can record and save motion macros for future use. The operator can also edit the move profiles step-by-step to make small alterations.

Data Archival - After the fastening is complete, but before the completed assembly is removed from the tool, the system inserts final as-built data into a remote plant-wide database for future analysis. This database server archives data records for each airplane manufactured in this tool.

HOW THE SYSTEM IS USED - Before parts are loaded into the tool, the operator initiates a buck-in of the lasers through the operator console GUI. Upon completion of the buck-in, the floor grid assembly is loaded into the tool and indexed to the seat tracks and floor beams. Side panels are loaded onto the panel manipulators and the laser targets are installed into skin coordination holes. The keel panel is then loaded onto the cargo floor supports (pogos) and laser targets are installed in the buttock line and station alignment holes. The operator then initiates a pre-programmed automatic move which sends the side panels to a rough set position. The operator then transfers control from the operator console to the remote pendant/joystick to-fine position the panels.

The first step in the fine-positioning process is the alignment of the keel panel for buttock line and station using the laser targets to establish the relationship to the floor structure. Next, using the joystick, the operator positions each side panel until its waterline laser targets are set nominally to the floor structure and the panel-to-panel lap splice coordination holes are aligned with the keel panel. At the completion of the alignment process, power Clecos are inserted in the coordination holes and the underlying lap stringer. Pins mounted on a slide assembly are inserted into selected frame k-holes. The position of the slide assembly is sensed by a linear transducer whose output is read by the control system to verify panel buttline positioning at the floor structure interface. Once the load mechanic has verified that all laser targets, load cells, and linear transducers are within tolerance, he contacts Quality Assurance. Quality Assurance then reviews the measurement data and electronically buys off the load using the GUI screen designed for this purpose. The as-built assembly data is then automatically sent to a plant-wide database server for use in process improvement activities.

Figure 7: Tool Overview



BENEFITS OF AUTOMATED GAUGELESS TOOLING AND LASER MEASUREMENT

PRECISION AND REPEATABILITY VS. NON-AUTOMATED TOOLING - The process requirement of aligning multiple tight tolerance coordination holes creates a tooling requirement for precise movement of subassemblies. With conventional pneumatic or mechanical cranking mechanisms, precise and repeatable movement is not attainable. With servo controlled positioning, input drive shaft position can be controlled to 1/4095th of a revolution. On the manipulator output, this resolution translates into sub-mil movement. This precision allows the panel coordination holes to be aligned in a controlled manner.

The assembly process also includes drilling holes through mating sub-assemblies, subsequent separation for debur, and realignment of the drilled holes. With conventional manual manipulation, the process of realigning holes is laborious and time consuming. With automated tooling, the location of the subassemblies during drilling is stored electronically and invoked when the debur operation is complete. Similarly, the location can be repeated to the sub-mil level.

ASSEMBLY SPEED VS. NON-AUTOMATED TOOLING Traditionally assembly tooling employs multiple independent mechanical actuators attached to a single structure. To manipulate the structure, the actuators are driven sequentially in an effort to achieve the desired assembly movement. This process involves several intermediate steps and panel positions on the way to the ultimate location. The mechanic must try to account for the geometry of the panel and the arrangement of the actuators when trying to move the assembly from location and attitude A to location and attitude B. Since this process is iterative for each side panel, it is time consuming and requires a great deal of aptitude on the part of the mechanic.

With automated tooling, the operator can initiate panel-based movement which requires no knowledge of individual axis movement requirements. After the user configures the graphic, and enters a numeric value, the control system calculates move profiles for each axis and synchronizes their execution. This automated control removes the iterations by allowing the user to move the panel in a know increment.

Similarly, the digital joystick can be used to move the panel in a predictable path. The RTC accepts the joystick input and coordinates all axis movement associated with the selected panel. When the panel reaches the desired location, the user releases the joystick which stops movement.

FLEXIBILITY VS. HARD TOOLING - Normally, tooling is designed and built for the purpose of building a single or small set of similar parts. Switching production between parts involves time-consuming manual reconfiguring of the tool. Further, introduction of a new assembly into the tool (an assembly for which the tool was not originally designed), requires modification of the existing tool. This modification is costly because it requires rework of the tool and production downtime in which to perform the modifications.

Automated tooling overcomes these limitations. By storing unique electronic data sets for each assembly or model, the system is capable of producing a large family of similar parts. For instance, freighter model panels are physically different than passenger model panels. Consequently, panel pick-up points, manipulator locations at nominal, assembly motion paths and load thresholds are different. To accommodate these differences, upon introduction of a new model or variant, the system is taught locations which characterize the unique panel and assembly process. Similarly, load thresholds can be entered through the GUI that accurately represent the typical loads associated with that panel. The position and load data along with the name of the model or variant are stored in the operator console computer. When parts are craned into the tool for assembly, the user enters the model through the GUI, and the data sets are distributed to the controllers.

The processes of introducing a new variant or reconfiguring the fixture between existing variants is far less disruptive to production than conventional hard tooling. This is increasingly important in a lean manufacturing environment.

LESS CONSTRAINING VS. HARD TOOLING - Traditionally, end gates and mid gates along with other hard indexing features have been used as datum to build fuselage assemblies. Aircraft parts are indexed to these datum by contact with the index feature. This contact results in friction which inhibits the free manipulation of the aircraft structure. Further, if the index feature is the zero datum, it allows movement of the assembly only to one side of the datum. If parts are being best fit, the freedom to move to either side of the datum is not available. The datum becomes a constraint to the assembly process.

Laser indexing employs virtual datum established by sweeping lasers. Parts are manipulated freely in three axes by servo driven panel manipulators, positioners, and pogos. Real-time measurements of targets on the airplane structure indicate the assemblies' relative position to the datum. Panels are free to move to either side of the reference plane and can be moved without interference from the jig making assembly easier.

DECREASED ROUTINING VS. HARD TOOLING - Hard tooling requires regular routining to verify that indexes are located properly in the tool reference system. Such routining includes several index points on the jig structure usually all of which cannot be viewed from a single vantage point. Consequently, routining requires several instrument set-ups. Since the tool routine must be performed on the tool, it robs valuable flow time from production. With laser indexing, the quantity of index points to routine is reduced and only monument targets require periodic routining. Additionally, since much of the indexing is provided by lasers and linear transducers, the validation can be done in the form of calibration and certification. This off-tool verification does not interrupt production activities.

SUPERIOR ACCESS AND ERGONOMICS VS. HARD TOOLING - Since the laser replaces large, complex jig structure which is typically required to provide indexes in multiple planes at long distances, the assembly being built is more accessible to the mechanics and inspectors. This accessibility results in improved ergonomics, work flow and quality of workmanship.

CONCLUSIONS

Technology is allowing the Boeing Fuselage Assembly Team (FAIT) to accomplish their manufacturing objectives of accuracy, flexibility, and cost effectiveness. Primarily, precision fuselage panel motion control actuated through an intuitive GUI and/or joystick supports the unique requirements of determinant assembly, namely the alignment of skin coordination holes in the panels. Additional benefits of this enabling technology are ease of assembly and associated speed, and manufacturing flexibility.

The laser measurement technology used to allow the high accuracy integration of conventionally built assemblies and determinantly built assemblies in the fixture yields side benefits as well. The replacement of hard tooling with laser indexing frees up critical shop-floor space, decreases tool routine requirements, and eliminates part constraints during assembly. The respective benefits are better shop floor ergonomics, fewer interruptions to production for tool maintenance, and assembly ease.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

Routine - Calibration of tool to ensure it is within tooling tolerance.

FAIT - Fuselage Assembly Improvement Team

GUI - Graphical User Interface

I/O - Control System Electrical Inputs and Outputs

LCD - Liquid Crystal Display

PMIT - Perishable Miscellaneous Tool

RTC - Real-time Controller

SERCOS - SErial Real-time COmmunications System