Automated Positioning and Alignment Systems

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ABSTRACT

To eliminate some of the problems associated with the conventional process of locating and positioning large airframe subassemblies, Advanced Integration Technology, Inc. (AIT) began working with aircraft manufacturers in the late 1980s to design automated positioning and alignment systems. These tools differ from conventional jigs in two regards. First, they rely on an automated positioning control system to simultaneously coordinate the motion of multiple mechanical actuators to smoothly and accurately manipulate aircraft parts in a known fashion. Second, laser measurement subsystems are used to locate parts and control aircraft geometry. The combination of these technologies yields benefits such as lower non-recurring and recurring costs as well as better quality, lower cycle time, and improved production flexibility. Over the last decade, AIT has installed dozens of such systems making many improvements along the way.

This paper presents automated positioning and alignment systems as a viable alternative to the traditional locating and positioning of aircraft parts and assemblies, and provides a technical description of such systems.

INTRODUCTION

As an overview, this paper will describe the conventional process of locating and positioning large airframe subassemblies together with a description of an automated system. It will then give a technical description of an automated positioning and alignment system and discuss the system's operation and capabilities. Finally, it will compare the conventional process of locating and positioning large airframe subassemblies with the automated process, highlighting the automated system's advantages.

OVERVIEW

PART POSITIONING

The process of mating and joining large airframe subassemblies has historically been accomplished using multiple mechanical actuators that are attached to the airframe structures. These mechanical actuators are sequentially driven by such means as hand cranks or pneumatic motors to effect the desired assembly or part motion.

Since each mechanical actuator in this conventional system is an independent, stand-alone device, factory personnel are tasked with the coordination of these actuators to move the assembly. This is accomplished by multiple personnel each moving a single actuator while communicating with others. Since the movement of multiple actuators cannot be truly coordinated and because the part's movement may be along a complex path, the assembly motion can be inaccurate and unpredictable. Additionally, actuators can potentially counteract each other, thus imparting unwanted forces to aircraft structure.

Unlike the conventional process, automated positioning relies on a control system to simultaneously coordinate the motion of multiple mechanical actuators to smoothly, accurately and predictably manipulate airplane parts in a known fashion. The supervisory control of a high-speed controller translates assembly-level user commands into individual actuator distance and speed profiles. The user commands are issued via either a graphical user interface which shows the subassembly pictorially, or a joystick which allows the user to "fly" the subassembly. Under this control scenario, the user can command a fuselage section, fuselage superpanel, wing assembly or any other aircraft assembly to move in any of three linear or three rotational paths without knowing precisely how each mechanical actuator must move.

PART INDEXING

In a conventional jig-based assembly process, subassemblies are indexed to a fixture. In such assembly fixtures, hard tooling such as end gates and mid gates along with other hard indexing features are used to locate aircraft assemblies. Aircraft parts are indexed to these datums by contact with the hard index feature. Such hard indexes are designed and built for a specific aspect of assembly geometry.

Alternatively, automated positioning and alignment systems employ any of a variety of low-powered lasers to establish virtual or soft datums to which airplane parts are located during assembly. Instead of being located to a hard index, the parts are freely manipulated until their measured positions correspond to defined nominal locations. These nominal locations are analogous to the hard points on a fixed jig.

The laser provides closed loop position feedback for the features which are being aligned. The mechanical actuators use closed-loop servo controlled feedback for the mechanical actuator itself. Since the assemblies are located via handling fittings which are frequently imprecise, and the assemblies themselves are flexible which means the locations of key features is unpredictable, the laser feedback provides absolute location feedback for the key features on the assembly.

SYSTEM DESCRIPTION

A typical automated positioning and alignment system consists of mechanical actuators (otherwise known as positioners), a control system, and a laser measurement system.

THE POSITIONERS

The positioners function to support airplane subassemblies and smoothly move them in a linear fashion in X, Y, and Z as well as rotationally in yaw, pitch and roll. Each positioner is effectively a three axis machine whose precision motion is accomplished via servo motor control with resolver feedback. Load cells in the drive mechanisms continuously measure the force imparted to the aircraft.

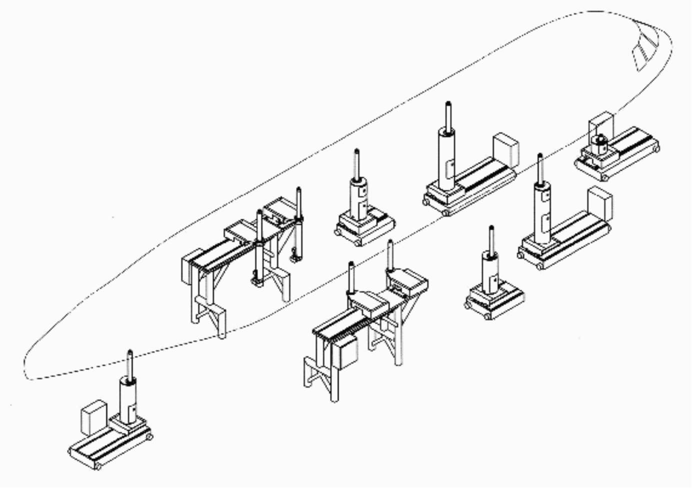


Figure 1: Conceptual Layout of Mechanical Actuators

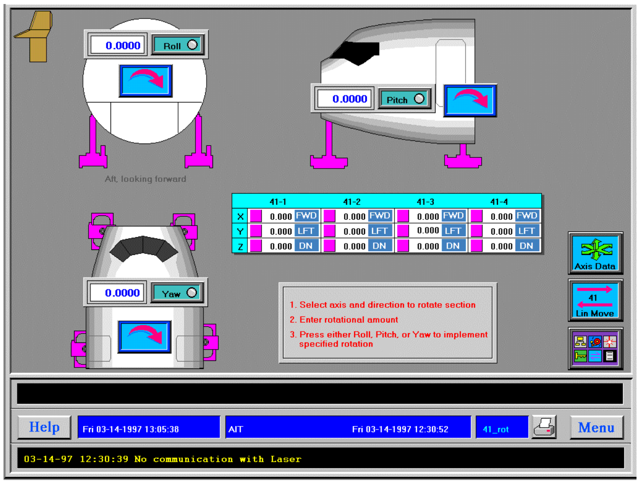
Figure 1 is a conceptual illustration of an aircraft fuselage in an automated tool. As the illustration shows, the forward section is supported by three positioners, the center section by four positioners, and the aft by three positioners.

THE CONTROL SYSTEM

The automated tool's control system consists of a high-speed multiple axis motion controller and user interface computer. Together, these components synchronize and coordinate the multiple axis moves. As part of this process, the control system stores offsets which are used to transform positioner coordinates to plane coordinates, and it stores model-specific information such as loads and nominal locations. The control system also monitors load cell readings and limit switches to prevent axis overloading and over travel.

In addition, the control system serves as the measurement system supervisor, controlling laser buck-in and operating parameters, and also as the measurement data server that makes target and sensor data available to the operator.

The control system also serves as the tools primary user interface for process control. Simplicity in the graphical user interface (GUI) ensures that the system will require minimal training and that very few errors will occur during assembly. Graphical representations of aircraft parts coupled with intuitive move controls allow shop-floor personnel to perform complicated fit-ups. These GUIs allow the user to select any linear or rotational movement for any given aircraft structure. The control system computes the required axis moves and orchestrates multiple positioner movement to effect the given move. The control system continuously gathers information from load cells and ensures that forces imparted to the aircraft stay within engineering tolerances. Figure 2 is a typical move actuation screen.



	41-1		41-2		41-3		41-4	
X	0.000	FWD	0.000	FWD	0.000	FWD	0.000	FWD
Y	0.000	LFT	0.000	LFT	0.000	LFT	0.000	LFT
Z	0.000	DN	0.000	DN	0.000	DN	0.000	DN

1. Select axis and direction to rotate section
2. Enter rotational amount
3. Press either Roll, Pitch, or Yaw to implement specified rotation

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Fri 03-14-1997 13:05:38    AIT    Fri 03-14-1997 12:30:52    41_rot
03-14-97 12:30:39 No communication with Laser
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Figure 2: Graphical User Interface

As a compliment to the GUI, a joystick provides the user with a means to closely view the fit of the subassemblies for interference and visual alignment while the aircraft assemblies are being manipulated.

The joystick is small and lightweight and can be plugged into receptacles located at various points about the tool. The LCD display on the joystick displays which aircraft assembly the user has selected for movement. The list of all aircraft subassemblies is scrolled by touching a button on the joystick.

The joystick possesses multiple personalities based on whether it is in linear or rotational mode as indicated on the joystick. An assembly can be manipulated in X, Y, or Z when linear mode is selected and yawed, pitched, and rolled if rotate mode is selected.

In addition, the joystick can be engaged to effectively limit any commanded move. Based on jog move distances configured by the user or system administrator at the joystick, the system will only move an incremental amount when the joystick is deflected. To continue moving, the joystick must be successively centered and re-deflected multiple times until positioining is achieved. This results in an accurate “bumping” positioining capability with 0.001 resolution.

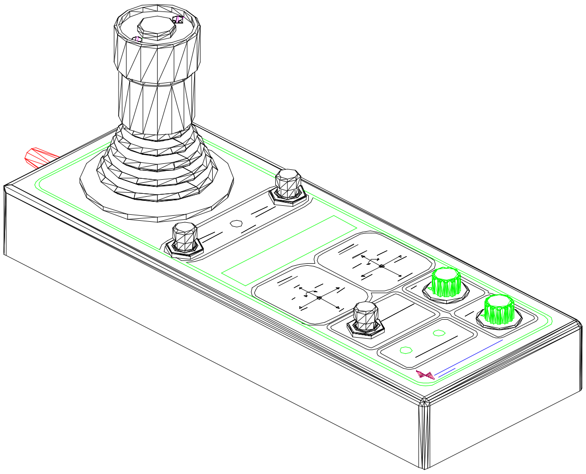

Figure 3: The Joystick

LASER SUB-SYSTEMS

Automated positioining and alignment system incorporate laser measurement technology to facilitate aircraft structure alignment and join.

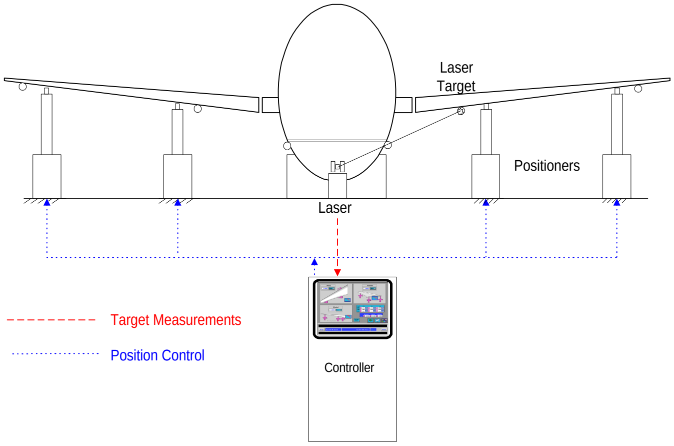

Figure 4: Laser Measurement Feedback

The laser alignment process starts by placing airplane structures on positioners equipped with servo motors. Optical targets, such as tooling balls or retroreflectors are placed on known features on the airplane structure. The laser scans the set of targets and reports this data back to the control system which displays the data as positions relative to nominal.

By executing successive moves via the GUI, the user maneuvers the structures to approach nominal join position. In order to perform final alignment of structures, the user analyzes target data along with visual inspection of the fit. This process produces the best overall assembly while maintaining an acceptable fit at the join location. After alignment, but before the fastening, measurement data and load data is captured and stored for future analysis.

TYPES OF LASERS

The aircraft manufacturing industry uses two different, general types of laser measurement systems: planar laser systems (rotating laser) and articulating laser systems (trackers). Both use the beam emitted from a laser diode to sense the location of targets mounted to an airplane structure, but they use different techniques to do so. This section will briefly describe the two techniques.

Planar Rotating Lasers - Planar measurement systems employ a laser diode which is either mounted in a rotating head or reflected off a mirror in a rotating head. The laser beam is continuously cast radially from the rotating head effectively sweeping the laser beam through a plane. Such a plane is used as a reference in one dimension (X, Y, or Z) for construction of the airframe. Targets are attached to index points on the airframe using brackets which, when the airframe is in a nominal position, centers each target in the reference plane. As such, not all index points are required to lie in the same plane, rather the projected targets are required to lie in the same plane at the nominal location.

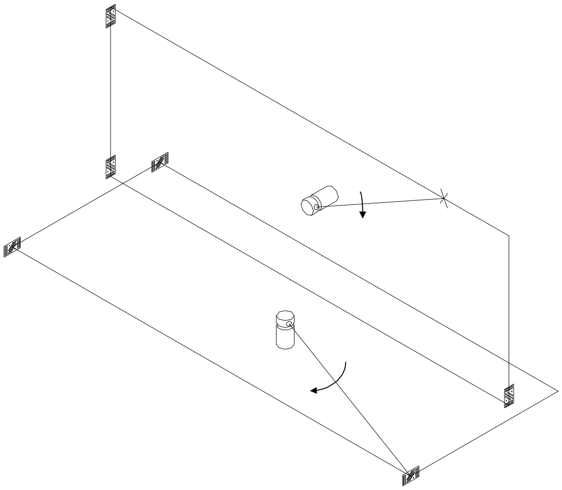

Figure 5: Laser Planes

During production, the airframe assemblies are manipulated to center the targets into the reference plane. Typically, separate lasers are used to establish reference planes in all axes that are to be measured.

Articulating Lasers (“Trackers”) - Articulating or tracking laser measurement systems employ a stationary laser diode whose beam is reflected off a tilting mirror driven about two axes. This mirror is controlled by two independent precision motors which rotate the mirror in the laser system’s azimuth and elevation. These two motors allow the beam to be directed in space. Retroreflecting devices such as corner cube prisms attached to the airplane return the beam to the laser where an absolute distance meter analyzes the properties of the returned beam relative to the emitted beam. Calculating the distance of the retroreflector from the laser. As the absolute distance is acquired, the encoder signals from the precision motors to establish azimuth and elevation of the measured point. These three pieces of data describe the location of the point in space in polar coordinates. An on-board processor then converts the data to

Cartesian coordinates with which users are familiar.

Since the laser has the freedom and capability to measure points in 3-D space, it must have some knowledge or record of the approximate location of the point in space. Consequently, an articulating laser must maintain a database of points on the tool along with each point's relevant information. As the laser completes the measurement of a given point, it proceeds to the next point in the list by moving in azimuth and elevation as required. If a signal is not received from a target at that location, the laser head, either by instruction or by default, will invoke a search routine. Such a search routine directs the laser in either a raster pattern or in a spiral until a return signal is received.

SYSTEM OPERATION AND CAPABILITIES

Automatic Alignment – The systems are designed to provide for a process of automatically aligning aircraft subassemblies. Once the lasers are measuring the airplane targets and sensors are installed and sending readings to the control system, the user can activate an auto-alignment feature on the GUI. This feature, which is activated by a single selection of an icon on the GUI, commands the system to calculate the moves necessary to reach the nominal alignment position and automatically move all axes to that position.

Section Coordinated Moves – The systems also provide the user with a process of manipulating a single aircraft assembly by entering the specific moves desired into the GUI screens. The control system, with knowledge of the selected assembly's geometry, calculates individual moves for each of the driven axes which smoothly move the assembly without constraining it. The user can yaw, pitch, roll or translate the aircraft assembly along a vector in any desired manner.

Retract and Return to Aligned – Many times the assembly process requires alignment of assemblies, subsequent separation of the assemblies to perform certain operations, and then the return of the assemblies to their precise alignment positions. The automated tools support this high degree of repeatability. Through the GUI, the user pushes a button upon alignment to store the axis position data. After the part is retracted and desired operations are performed, the system drives the motors back to their aligned position. The positional data stored by the system is transparent to the operator. A simple push of a button through the GUI notifies the system to save the alignment data, another single button stroke retracts the assembly, and a third returns the assembly to the aligned position.

Flexible Model Configuration - Automated positioning systems are flexible in that they provide the capability of assembling an unlimited number of aircraft variants as long as the body fittings of the new structure fit within the mechanical limits of the positioners and the weights within system capacities.

With the introduction of a variant, the responsible engineer creates data files off-line which describe the process data that is specific to each model configuration. These files are of a known format, and the process of creating a variant file is as simple as editing a text file. Some of the items in these data files include: assembly sequence-dependent positioner locations, axis travel speeds, load cell thresholds values, key feature locations in aircraft coordinates, and measurement system tolerance limits.

Upon the start of each build, the aircraft type is entered into the system. When this happens, the system loads the configuration-specific data file into working memory. These values are then used throughout the build process.

Dynamic Overload Protection - Protecting the aircraft assemblies during manufacturing is of paramount importance. As the automated tool manipulates assemblies of the airplane, load cells are continuously monitored (<10 milliseconds) to ensure that loads imparted to the structure are below engineering tolerances. The control system allows a user to set load limits at which loads may be halted and/or the user is alerted to the situation.

OTHER CAPABILITIES

Other features and capabilities of the automated systems include:

Automated Tool Routining - System software is designed to support tool routining during commissioning and periodically throughout the life of the tool.

Data Logging and Report Generation - The systems are designed to allow as-built data to be logged at various times throughout the assembly process (designated during the design phase) to a local hard disk in both ASCII report format and database format.

Part Path Programming - Since incremental moves associated with an assembly during alignment may change as the part geometry changes or as the process changes, the user is provided with the flexibility to alter the path of the parts during the load translation, alignment, retraction and realignment processes. This software feature, Part Path Programming, allows the user to define and redefine paths for the assembly to follow.

Real-Time Diagnostics - System software is designed to allow the operator to monitor tool functionality and to trouble shoot while the tool is in operation.

BENEFITS OF AUTOMATED POSITIONING AND ALIGNMENT

SPEED

Automated positioning allows for faster tool setup, faster positioning of assemblies, and fewer move iterations to locate the assemblies. The result is faster flow of assemblies through the factory floor, shorter cycle time and reduced work in process. Improved assembly speed is accomplished primarily through the following mechanisms:

Rapid Alignment of Assemblies

Automation of Repetitive Assembly Steps

Ability to Return to Defined Locations

Rapid Alignment or Fit Up of Assemblies - Since assembly movement is well-defined and predictable via the joystick or GUI, the only task left for the user is to inspect the fit of the subassemblies and decide how to translate or rotate the assembly to produce the best fit. Configuring a move for the assembly is as easy as selecting the arrow button on the GUI screen with a pointing device, entering a move distance in the input field and touching the Move button. The high-speed control system coordinates all actuator axes to effect a smooth, coordinated assembly movement.

Similarly, the user can move the assembly simply be deflecting a joystick. Joystick deflections directly translate into assembly movement: to pitch an assembly, the user deflects the joystick forward or aft depending on the desired pitch direction. In this mode, the user is effectively “flying” the assembly into location. When the assembly is close to its nominal or mating location, a bump mode on the joystick allows very fine, discrete assembly movements.

Automation of Repetitive Assembly Steps - At several stages during the assembly process, the mechanical actuators which hold parts or assemblies must be driven to known locations. For example, before the parts are loaded into the fixture, the actuators must be in a configured pattern which consists of known locations for all of the mechanical actuators’ end effectors. Additionally, there are times throughout the assembly process during which the end effectors must travel to a known location such as an assembly rough fit (just prior to final alignment) and tool unload position. Instead of having to recall an end effector’s spatial locations which correspond to these tasks, the system allows the execution of a canned or pre-programmed routine which sends each the actuators to defined positions. The more subassemblies comprised by the assembly, the more mechanical actuators there are, and the greater the time savings.

Ability to Return to Defined Location - For assembly processes, which require saving or logging an assembly location and then subsequently moving from and returning to that location, automated positioning produces considerable time savings. For example, many times when assemblies are aligned or joined, they are subsequently match drilled. After drilling, the assemblies are separated for deburr operations. Finally, they are mated back up for the fastening process. Without the precision and repeatability of automated positioning, the task of returning the assemblies to the same location in which they were drilled is a daunting task. In an automated positioning system, the system saves the precise location of the assemblies during the drill process, automatically separates the assemblies for deburr, and returns them to precisely the same location for fastening. This capability eliminates time-consuming manual alignment of several small fastener holes.

REDUCED DIRECT LABOR

If done manually, all of the assembly processes outlined above require multiple personnel for considerable time periods. Some personnel watch for assembly fit and clearance while others are responsible for driving the mechanical actuators. With automated positioning, only one person is required to execute positioning from the single-point GUI or joystick. Further, the joystick's mobility allows a user to freely manipulate subassemblies while simultaneously watching for clearance and fit. Direct labor savings with automated positioning is certain, though the amount realized depends on the number and size of subassemblies and the complexity of the join.

QUALITY

Automated positioning produces superior quality final assemblies through tactile subassembly handling and by providing a means to analyze as-built data.

<u>Tactile Subassembly Handling</u> - Each end-effector which attaches to the incoming subassemblies is equipped with load cells which continuously sense the load imparted by the fixture to the aircraft. The high-speed control system monitors the loads and halts motion when the loads increase beyond configured limits. The tactile feedback of this control scheme ensures that the subassemblies will not be stressed during assembly. This is in contrast to traditional assembly methods which employ manually-cranked or fixed assembly jigs. These tools do not provide continuous tactile feedback and, consequently, permit part or assembly pre-loading.

For instance, the load cells detect any interference between assemblies during manipulation, and they halt motion before the loads exceed reasonable limits. This tactile control prevents assembly damage from collision with other assemblies or fixed facilities.

Another example of the tactile control is the loading of assemblies into the automated fixture. With conventional fixtures, the subassemblies are loaded into the assembly fixture via either overhead crane or material handling dolly. Either way, the subassemblies are positioned by the crane or dolly onto the fixture's mechanical actuators. These loading devices are generally not exceptionally smooth nor graceful, and this process can induce stress into the parts if extreme caution is not exercised. With automated positioning, assemblies can be positioned in close proximity to the mechanical actuators using the crane or dolly. The control system can then drive in a controlled manner to assume the load. This way, the load transitions smoothly and evenly to all of the end-effector attach points on the assembly. This technique protects the aircraft structure from any loads.

<u>Archival of As-built Data</u> - Load cell data, actuator position data, and any measurement data which is continuously being acquired and updated during assembly can be logged in multiple formats for future analysis. This data is stored logically by assembly serial number to give a record of the assembly geometry, weight, distribution of weight, and any structural loading. Analysis of this data leads to a better understanding of the assembly and the assembly process. Further, it can produce an understanding of the quality of incoming assemblies.

The archived data not only provides a record available for the purpose of statistical process control, but it can also be used by downstream manufacturing processes. For instance, if an assembly is produced and its geometric characteristics are recorded, those characteristics can be incorporated into the setup of downstream manufacturing fixtures. As a result, manufacturing operations are no longer "stand-alone", and assembly specific data can travel with an assembly through its manufacturing process.

FLEXIBILITY

Normally, fixed 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 during which to perform the modifications.

Automated positioning and alignment systems are designed to be flexible to overcome these limitations. These systems are designed to store unique electronic data sets for different assemblies or models so that the system is capable of producing a large family of similar parts. For instance, cargo model fuselage sections may be physically different than passenger model sections. Consequently, section pick-up points, actuator locations at nominal, assembly motion paths and load thresholds are different. To accommodate such differences, the system stores parameters which characterize the unique assembly (model) and assembly process. When subassemblies are loaded into the tool for assembly, the user enters the model through the GUI, and the data sets are invoked to be used during the process. The result of this flexibility is:

Lower Investment in Fixed Tooling

Shorter Lead Time for Introduction of Variant

Production and Factory Flexibility

<u>Lower Investment in Fixed Tooling and Facility</u> - If an assembly fixture is designed to be flexible, it will build any assembly which fits into its physical and weight envelope. Because of this, a dedicated fixture is not required for each assembly within this envelope, and the associated capital expense for design, fabrication, construction and installation of each is avoided. The savings extends to plant floor space which is conserved by implementing flexible positioning. Since most assembly fixtures and surrounding work platforms consume a great deal of space, fewer fixtures save considerable space.

<u>Shorter lead time for introduction of variant</u> - Instead of relying on hard indexes for assembly location, flexible systems rely on position feedback from positioning devices. Therefore, modification of a flexible fixture for an assembly variant requires defining a parametric data set for that particular assembly rather than modifying hard tooling as in traditional fixtures.

For instance a cargo model fuselage section may be physically different than a passenger model section. Consequently, section pick-up points, actuator locations at nominal, assembly motion paths and load thresholds are different for the cargo mode. To accommodate these differences, upon introduction of the new cargo model or variant, the system is taught locations which characterize the unique section characteristics and assembly process. Similarly, load thresholds can be entered through the GUI that accurately represent the typical loads associated with that section. This data is stored and is used to automatically configure the fixture when the cargo assemblies arrive. The process of defining this new data requires far less time than designing, fabricating, installing and routining fixed features on a jig. Therefore, the lead time to introduce the variant is greatly reduced.

<u>Production and Factory Flexibility</u> - Traditional fixed tooling is sometimes capable of building multiple aircraft variants, however, it must be set up each time a different variant is scheduled in production. This set-up is usually time consuming and causes production down-time. To justify this set-up time, manufacturers schedule multiple part lots for production. With low volume, high cost assemblies, this is an undesirable scenario.

With flexible positioning systems, tool set-up for the production of an assembly variant is effortless and requires little time. For instance, through the GUI screen, the user simply enters the Model Number Configuration to be built in the fixture. The system then uploads the model-specific data such as load cell limits, aligned (nominal) positions for end effectors, any measurement nominal positions, and any intermediate process positions. The fixture is then automatically configured for the variant which is scheduled. This flexibility allows the fixture to be reconfigured between each assembly which results in complete production flexibility.

Recently, AIT has taken flexible positioning to another logical level: a positioning system which can be easily assembled on the factory floor and removed and stowed if the floor space is required for other use. Through innovative control architecture and cabling, the system can be rapidly assembled without tedious mechanical fastening and/or wire connections. This type of flexible positioning enables factory flexibility because that facility space can be used for multiple production activities.

BENEFITS OF LASER ALIGNMENT

Both fixed assembly jigs and laser alignment systems are means to control the final assembly geometry. This task is particularly challenging in aircraft assembly since the subassemblies are physically very large. The following presents the advantages of using laser alignment versus fixed assembly tooling.

REDUCED CAPITAL INVESTMENT

For each hard point on the assembly which is to be controlled, a hard tooling feature must be designed, fabricated, and accurately installed. For new aircraft programs, this cost is typically quite high. While there is a capital cost associated with a laser measurement device, it does not require very many index points on a fixture to exceed the cost of the laser.

INDEXING FLEXIBILITY

Whether to introduce an assembly variant or to modify the way in which an existing assembly is built, there may be a need to change the index plan in the assembly jig. With traditional hard tooling, a new physical feature must be designed, fabricated, and accurately installed on the jig. Changes using this process can require months to implement. Laser alignment facilities store feature locations electronically and by assembly model number. Introduction of a new assembly variant or the modification of an indexing plan on an existing assembly is as simple as modifying an electronic file containing these feature locations. The benefits are identical to those achieved using flexible automated positioning. The cost and lead time associated with engineering changes are minimized.

QUALITY BY ELIMINATION OF PRELOAD

When subassemblies are indexed to hard fixture points, they are constrained and cannot be freely manipulated. These forces which are required to index the subassemblies also commonly cause part preloading. The datum becomes a constraint to the assembly process.

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

COST SAVINGS THROUGH DECREASED TOOL ROUTINING

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 consumes 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 the indexing is accomplished by lasers and, the validation can be done in the form of laser calibration and certification. This off-tool verification does not interrupt production activities.

CONCLUSION

More and more, aircraft manufacturers are relying on automated positioning and alignment systems to take the guesswork out of the process of mating and joining large airframe assemblies. These systems allow an operator to move an aircraft assembly in linear or rotational paths without knowing precisely how the supporting mechanical actuators must move. The result is time and cost savings, improved quality and consistency, and flexibility.