SAE INTERNATIONAL

High Accuracy Assembly of Large Aircraft Components Using Coordinated Arm Robots

2016-01-2133

Published 09/27/2016

Carl Landau

Electroimpact Inc.

CITATION: Landau, C., "High Accuracy Assembly of Large Aircraft Components Using Coordinated Arm Robots," SAE Technical Paper 2016-01-2133, 2016, doi:10.4271/2016-01-2133.

Abstract

Aircraft manufacturers are seeking automated systems capable of positioning large structural components with a positional accuracy of ±0.25mm. Previous attempts at using coordinated arm robots for such applications have suffered from the use of low accuracy robots and minimal systems integration. Electroimpact has designed a system that leverages our patented Accurate Robot technology to create an extensively automated and comprehensively integrated process driven by the native airplane component geometry. The predominantly auto-generated programs are executed on a single Siemens CNC that controls two Electroimpact-enhanced Kuka 6 axis robots. This paper documents the system design including the specification, applicable technologies, descriptions of system components, and the comprehensive system integration. The first use of this system will be the accurate assembly of production empennage panels for the Boeing 777X, 787 and 777 airplanes.

Introduction

In 2015 Boeing sought a turnkey automated solution for accurately placing long carbon fiber stringers (stiffeners) onto carbon fiber skin panels to form the empennage (tail assembly) vertical and horizontal stabilizing surfaces. Stringer placement had previously been done manually using tooling specific to each panel, and the impending 777X would have required six new dedicated tools. Automation could potentially reduce costs, improve quality, decrease production times, and improve safety. With 14 skins and 120 stringer variations, Electroimpact proposed a comprehensively integrated dynamic automated positioning system. This paper describes the Electroimpact automated stringer placement system.

Alignment Systems

The automated stringer placement system is one of a new generation of dynamic automated position systems. These types of systems can be seen as the third generation of aircraft component positioning systems, made possible by advances in machine tool accuracy and flexibility.

Fixed Tooling

The most established way of assembling two aircraft components with high positional accuracy is using an assembly fixture. In fixed tooling, the frame indexes geometry (generally edges, faces or tooling holes) to hold components in their design positions during assembly.

Smaller "loose tooling" can also be used to allow temporary indexing of one component relative to another part or an assembly fixture.

This approach is most effective for small to medium sized parts, and is less well suited to large parts with low relative stiffness. Aircraft manufacturers are attempting to reduce fixed tooling due to its high cost, long design/build time and low flexibility (it is generally rendered useless by a significant design change).

Determinant Assembly

Determinant assembly (DA) replaces assembly fixtures with a number of matching high positional accuracy holes to position components relative to each other. While this approach has been used extensively in both aircraft[1] and assembly fixture[2] construction, it must be incorporated into the part design phase and is not suitable for all components. In particular, it is not well suited to large parts with low relative stiffness and high positional tolerances due to the difficulty of ensuring alignment of multiple holes between two components.

Dynamic Automated Positioning

A number of specialist companies offer dynamic automated positioning systems for aligning large aircraft sub-assemblies such as adjacent fuselage sections, or the wings to the fuselage. These systems have the potential to be superior to both conventional fixed tools and DA systems because they allow the relative positioning of the components to be adjusted according to measurements of the actual sub-assemblies. This can allow the creation of assemblies that are more accurate than their components. Dynamic positioning also

1. https://www.electroimpact.com/WhitePapers/2004-01-2832.pdf
2. https://www.electroimpact.com/WhitePapers/2004-01-2832.pdf

has the advantage of not requiring the machining of high positional tolerance holes, further reducing manufacturing cost and increasing flexibility.

Advances in the flexibility and accuracy of machinery are allowing this type of dynamic positioning to be used on smaller assemblies. However many of these systems require laser tracker metrology devices to measure part and machine positions, which significantly increases move times due to their required settling and measurement periods.

Design Criteria

Stringer Dimensions

The general shape of the stringers is that of long I-beams, with upper cap widths that vary along the length of each stringer. The system design must accommodate not just the varying cap sizes within each stringer, but also the variation in lengths between stringers.

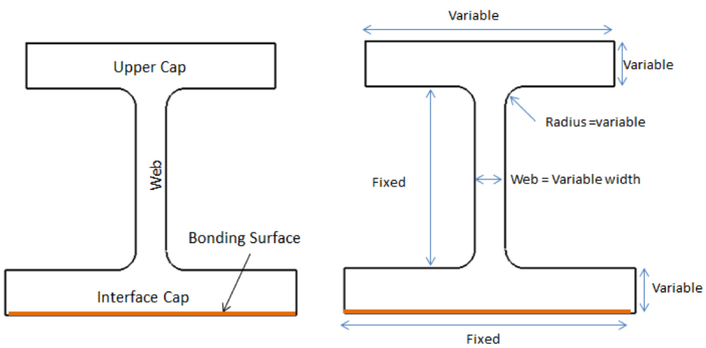

Figure 1. Stringer Cross Section

The stringers vary in length between 1.6m and 13.2m and weigh less than 13.6kg each.

Placement Requirements

The placement accuracy required by the system is ±0.6mm in the plane of the skin panel, relative to skin tooling reference points. The system must accommodate a range of stringers on a range of panels, and different application pressures may be required. The system must therefore be able to apply pressures between 35kPa and 620kPa. The feed rates must be variable between 0.05m/s and 0.5m/s. The overall assembly time must be less than 3 hours per panel (1 skin with up to 9 stringers) for all panel and stringer combinations.

System Description

Overview

The solution developed by Electroimpact incorporates the two enhanced 6 axis arm robots into an integrated 24 drive CNC controlled solution. Each robot is mounted on two horizontal axes, and holds an end effector custom designed for stringer placement.

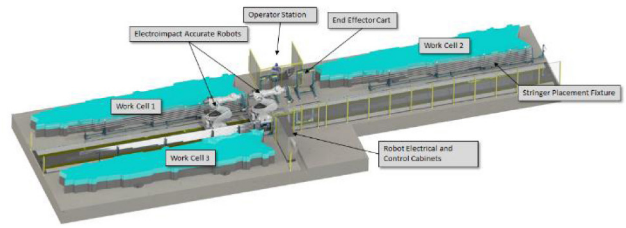

Figure 2. Stringer Placement Cell Overview

Travel within and between the work cells is accomplished though a 36m bed (X-axis) with platforms (sleds) mounted on rails. Each sled has a perpendicular horizontal axis (Z-axis) with 1.6m of travel.

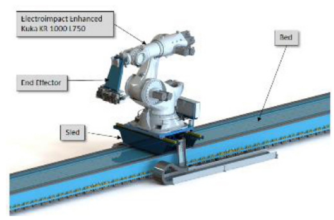

Figure 3. Primary Axis Components

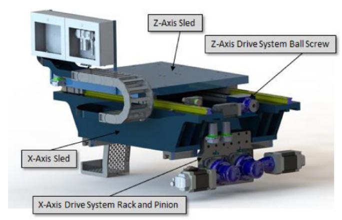

Figure 4. Sled Components

Arm Robots

Articulated arm robots are a type of robot that uses rotary joints for movement. These rotary joints are generally arranged in a chain, with each joint supporting the ones further down the chain. Although widely used in other industries, their accuracy has limited their use within the aerospace industry.

Robot Accuracy

The repeatability of high quality articulated arm robots tend to be ±0.1mm, with some manufacturers selling high precision versions of lower payload units with a repeatability of ±0.05mm. Unfortunately, this headline repeatability figure generally does not result in a similar on-part accuracy in production for a number of reasons including:

- Working volume: The repeatability is generally from the base to the flange of the robot, and does not include additional axes, end effector offsets or the impact of end effector loading.
- Uni-directionality and pose changes: If a program commands the end effector to a target location, then the repeatability may rely on approaching the target from the same direction and in the same pose as when the robot was calibrated.
- Part position compensation: The accurate measurement of the true part location, and subsequent calculation and application of appropriate offsets are critical in achieving on-part accuracy but often not included in baseline robot packages.
- Clamp motion: External forces (such as clamping or drill thrust reaction) are integral to operation, but result in additional

inaccuracies that make the repeatability figures even less achievable.

For these reasons, few robot manufacturers publish actual on-part positional accuracies. The majority of aerospace industry applications require part accuracies of ≤±0.25mm. This accuracy cannot be achieved with a 99.7% (3-sigma) confidence level using an unaided articulated arm robot. The most common method for achieving this positional accuracy using articulated arm robots is by utilizing an external metrology device (generally a laser tracker) to provide positioning feedback that can be used to refine the positioning of the robot axes. Although this has been effective in R&D and low rate production environments, the required limiting of robot speeds makes such systems unsuited to higher rate production activities.

Accurate Robot Technology

Electroimpact has taken a uniquely flexible and integrated approach to achieving high positional accuracies using articulated arm robots. The Accurate Robot Technology[3] starts with a high quality Kuka arm robot, adds on-device external position feedback for each axis, and then upgrades the hardware and software of the motor drives and motion controller.

This combination of high-resolution external feedback and a high-order kinematic calibration model result in an increase in dynamic and static global accuracy, effective elimination of drive train backlash, and accurate response to external forces applied at the end effector. These robotic systems are able to achieve volumetric accuracies of <±0.25mm with a 99.7% (3-sigma) confidence level over the complete working volume, independent of relative motion and robot pose.

End Effectors

The end effector is the process head of a robot, and is the interface through which the robots interact with the part. An ATI tool changer is installed at the end of axis 6 on each accurate robot to allow the end effectors to be easily removed for maintenance, or swapped between robots.

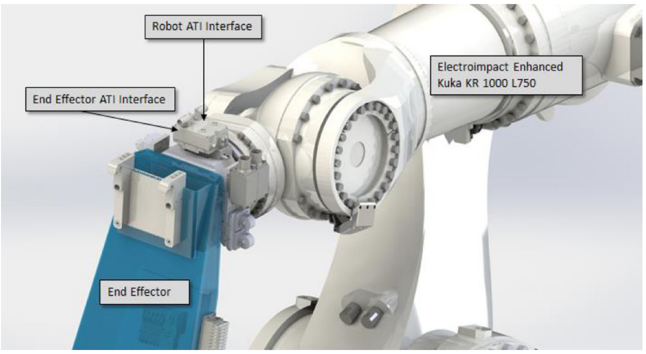

Figure 5. ATI Interface

The end effectors are the most novel mechanical design in this system, with two designs; a primary (fully featured) end effector, and a secondary (reduced functionality) end effector. The primary end effector is responsible for placing the stringer and applying the pressure required to fix it in place. The secondary end effector is used to assist in holding and moving the stringer, and ensures that no part of the stringer contacts the skin prematurely.

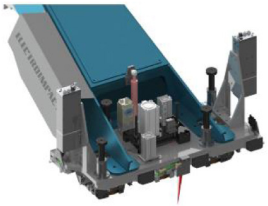

Figure 6. Primary End Effector

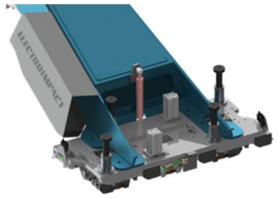

Figure 7. Secondary End Effector

End effector functionalities include

- Workpiece Measurement: A workpiece distance laser on the end effector can be used to locate workpiece and tooling geometry such as surfaces and edges. This is used in conjunction with two high accuracy automated feature recognition cameras to accurately measure and locate the workpiece components in the cell. The cameras can also be used to read 1D and QR codes to verify component identification details.
- Vertical Indexing: The nominal distance from the skin can be set and adjusted using an independent axis.
- Horizontal (perpendicular to stringer length) Indexing: Guide rollers are used to set the horizontal position of a stringer.
- Travel along Stringer Length: Brakes can be applied to the top of a stringer to prevent it from sliding through the guide rollers. This can be used to allow the other end effector to move along the stringer length along its own guide rollers.
- Lifting: Cap lifter rollers on each end of the end effectors can be engaged to the underside of the stringer cap, lifting as required.
- Compaction: Once the stringer has been moved into position, an independent roller axis is used to apply the force required to fuse the stringer to the skin panel. This axis includes
  - CNC controllable pressure regulator to set the compression force
  - Compression load cell to measure the actual force, allowing the system to compensate for frictional losses
  - Laser distance sensor to monitor the pressure roller extension

Stringer Cart

Each stringer will have a double sided adhesive tape applied to the interface at the time it will be picked up by the robots.

Requirement for the mobile stringer placement fixture include:

- The fixture must be usable in every automated placement cell

3. https://www.electroimpact.com/WhitePapers/2010-01-1846.pdf

- The stringers must be positioned for easy manual removal of the backing paper
- The stringers must be held securely during long term storage and transport of the fixture
- The fixture will need to be capable of holding a full set (up to nine) stringers
- The fixture must accommodate the full range of stringer sizes
- The fixture must index the stringers sufficiently for the system to accurately pick up each stringer

The fixture is made up of 5 stringer support posts, each capable of holding up to 9 stringers. Their positions are staggered to accommodate a wide range of stringer lengths, allowing for a minimum of two contact points per stringer for the shortest stringers. One additional post holds up a vertical plate which will index the root end of all stringers. Each post can be rotated 180 degrees to accommodate mirrored cells without rotating the entire cart.

In addition to configurable posts, the stringer fixture also allows for a "transport" configuration by extending the arms with the caster wheels for added stability.

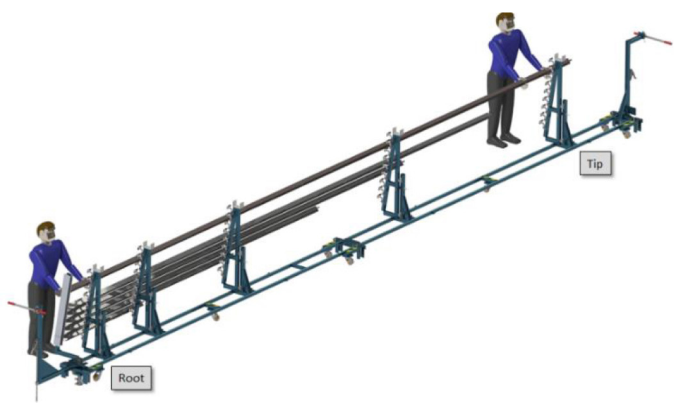

Figure 8. Stringer Cart

The position of the fixture within the cell is determined by floor indexing pins on each end of the fixture.

The fixture weighs less than 450kg fully loaded, and can be moved in and out of the cell by two people using the handles at each end.

The Manufacturing Process

The manufacturing process begins with the creation of the NC programs using the offline programming application.

Offline Programming

Offline programming allows the creation of machine NC programs without using the physical device, generally on a computer. This can be enhanced by adding a virtual device to simulate the program movements to detect collisions and robot singularities. For devices that can achieve a given tool center point (TCP) in more than one axis configuration, or cases where device collisions are more likely, it is best if this simulation can be performed while creating the NC program. This is called in-process simulation.

The majority of Electroimpact machinery is programmed using offline programming software with integrated in-process simulation.

Although the offline programming of Electroimpact machinery generally supports a high degree of manual input, the stringer placement application is far more geometrically constrained and thus mostly automated. A separate program is generated for each stringer, and a master panel program calls these individual stringer programs in the desired order.

The majority of the program is generated from the user selection of geometry, with the procedure as follows

1. The NC programmer selects a stringer on the stringer cart
2. The NC programmer selects the same stringer on the skin panel
3. The OLP software interrogates the stringer geometry (eg. the stringer root and tip end planes, and an index face on the stringer web), and automatically calculates a path for the two robots to pick the stringer off the cart, and lay it down on the panel.
4. The NC programmer has a limited ability to edit the program such as altering the sled positions for a more desirable pose, or adding additional commands (such as changes to the roller pressure).

All of the initial program creation is done in the one of the three manufacturing cells. The OLP software can then automatically generate a preliminary version of the program for either of the other two zones using coordinate transformation. The NC programmer can then make minor changes to sled positions to improve the robot poses in the new zones.

Stringer Cart Loading

The stringers are manually loaded in to the stringer cart in a separate cell, and a double sided tape is applied to the base cap.

Cell Loading

The two robots retreat to the end of the assembly cell, and the skin frame is loaded into the cell by an automated guided vehicle (AGV). The loaded stringer cart is then loaded into the cell and indexed into position. Once the cell is clear of operators, the safety system for the cell is engaged and the part program is initiated.

Skin Registration

The first task in the part program is locating and identifying the skin. This is challenging because the skin frames are not indexed within the cell and their positioning can vary by up to 75mm. The workpiece distance laser and automated feature recognition cameras provide a fully automated "registration" routine for this task. Once located and identified, a six degree of freedom coordinate transformation is performed to align the nominal program coordinates to the actual skin position. With the skin accurately located, the stringers can now be individually located, identified, picked up and placed on the skin.

Stringer Location

The workpiece distance laser is used to verify that there are no stringers in the cart impeding access to the target stringer. Once access is confirmed, the target stringer is accurately located and identified. The location measurement data is used to offset the end effector pickup locations along the stringer, compensating for both positioning and deformation irregularities.

Stringer Pickup

To ensure that the stringers are not damaged by relative movements between the end effectors during stringer movement, the automated stringer placement robots utilizes the Siemens 840D sl CNC SYMO compile mode. This provides a low level native support for synchronized motion between two devices on parallel yet synchronized channels under a common TCP (tool center point) driven by a single NC program.

With the skin and stringer located and identified, the end effectors are moved to their pre-pickup locations above the stringer. The synchronized motion mode is then engaged, and both end effectors lower onto the stringer, and engage the upper cap and web. The secondary end effector brake is applied (to prevent the stringer from moving longitudinally) and both end effectors perform synchronized moves to remove the stringer from the cart. Without disengaging its guide rollers, the primary end effector moves along the stringer and uses the workpiece distance laser to precisely locate the root end.

Stringer Placement

With the stringer pickup complete, the robots perform a coordinated move to accurately position the stringer over the skin. The synchronized motion mode is then disengaged and the placement move begins. The primary end effector is used to control the stringer-skin contact location and the compaction pressure, which is adjustable along the length of the stringer. The secondary end effector is used to keep the stringer tip aligned with the primary end effector and clear of the panel.

Figure 9. Primary End Effector Angle

The primary end effector path and orientation are driven by the design model geometry, offset by measurements of the actual skin and stringer geometry. During the placement move, a slight roll towards the root end of the stringer is maintained by the primary end effector to ensure that the stringer does not contact the skin before the roller. The secondary end effector maintains a constant bend radius in the stringer to lift the stringer tip away from the panel. As the primary end effector moves along the stringer, the secondary end effector initially maintains this bend radius by lowering towards the panel. Once the primary end effector reaches a specified distance from the secondary end effector, the secondary end effector disengages its brake, and maintains the bend radius by moving towards the stringer tip.

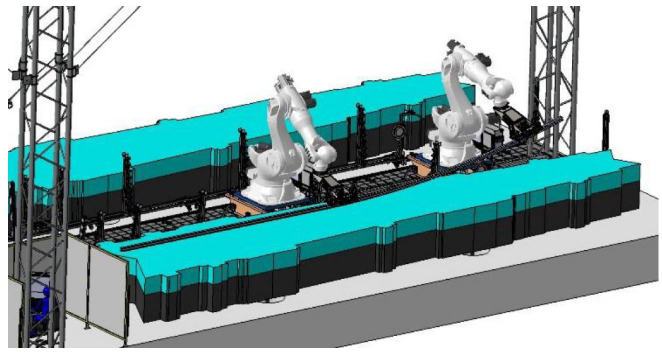

Figure 10. Stringer Placement

When the primary end effector approaches the secondary end effector at the stringer tip, the secondary end effector disengages from the stringer, and the robot moves to a clear location. The primary end effector then completes the placement of the stringer, and the robots move on to the next stringer.

Conclusion

Boeing sought a turnkey solution for accurately placing long carbon fiber stringers of varying lengths onto carbon fiber skin panels. In response, Electroimpact raised the bar on dynamic automated positioning systems with a comprehensively integrated solution based on two of the industry's highest accuracy robots. The result is a production cell capable of providing aerospace placement accuracies for a wide range of stringer lengths and geometries.

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

http://papers.sae.org/2016-01-2133