2007-01-3821

Robotic Drilling System for 737 Aileron

Joe Atkinson, John Hartmann
Electroimpact, Inc.

Simon Jones, Peter Gleeson
Boeing-Hawker de Havilland, Australia

ABSTRACT

Boeing's wholly owned subsidiary in Australia, Hawker de Havilland produces all ailerons for the Boeing 737 family of aircraft. Increasing production rates required to meet market demand drove the requirements for a new updated approach to assembly of these parts. Using lean principals, a pulsed flow line approach was developed. A component of this new line is the integration of a flexible robotic drilling/trimming system. The new robotic system is required to meet aggressive tack time targets with high levels of reliability.

The selected system was built on a Kuka KR360-2 conventional articulated arm robot. A significant challenge of this project was the requirement for the process head to work efficiently on an aileron in an existing jig. As a result a new side-mounted drill and trim end effector was developed. Automated tool changers for both cutters and pressure foot assemblies eliminated the requirement for in- process manual intervention. The robot was also configured to allow safe operation in two opposing work zones. This permitted the robot to continue working while parts are loaded and unloaded from an adjacent cell, improving the overall cell efficiency.

INTRODUCTION

The 737 aileron robot cell was developed to drill and countersink over 750 holes as well as trim the trailing edge and tooling lugs from the Carbon Fiber Reinforced Plastic (CFRP) skins. Material stacks include CFRP, Aluminum, Titanium, and Stainless Steel. The requirement for minimal operator intervention led to incorporating an automatic tool and nosepiece changer to handle up to sixteen cutters/tools and up to six nosepieces.

This lean system was created to replace an aging, gantry style machine while utilizing the pre-existing part-holding jigs. The new robot had to immediately take over a sustaining program in a high rate environment.

MAIN SECTION

Hawker de Havilland identified the requirement for a turnkey lean replacement system to build the 737 ailerons. As a sustaining program, only a small budget was available. As a cost-saving measure, it was decided to keep the pre-existing part- holding jigs and invest in a new automated drilling and trimming system. The existing machine was approaching the end of its service life and upon installation completion of the new system, the older system would be completely phased out. The new system would therefore need to ramp up very quickly to meet the high volume demand.

Calculations based on current drilling cycles coupled with estimated operator interaction times allowed for the completion of a single aileron within a 5.5 hour timeframe. Positional tolerance for hole placement was set at ± 0.020 inches in X and Y. The final part profile of the tooling lugs and trailing edge were to be trimmed to ±0.020 inches.

Figure 1: Overall system

Figure 2. 737 Aileron Robot working with an existing jig.

The System

The system is based on a stationary robotic drilling system. Parts are moved into the cell in their assembly jigs and indexed using index points in the floor. The parts flow through the cell and are addressed on both sides by the robot.

Designing a drilling machine around an existing jig presents many challenges. The 737 aileron, although a relatively small part, requires a very large range of motion due to the requirement to address holes around the leading edge. The normal vector of these holes is at approximately 75 degrees rotation from the primary main skin panel normal vector.

A large amount of rotation from the main panel to the leading edge drove the design of the side mounted end effector. This design reduces the majority of the motion to three axes (See Figure 2, axis A2, A3, and A6) of the robot coupled with the X-axis track for positioning. The actuator fitting and jig locating flags partially obscured some hole locations, which drove the development of specialized nosepieces. These design constraints as well as the requirement for the system to operate with eight different pre-existing and slightly different part-holding jigs drove the selection and design of the following components.

Robot

The robot selection for this system was based on the familiarity and successes of previous robot drilling systems manufactured. The decision to purchase a Kuka KR360-2 allowed Hawker de Havilland to maintain consistency among their Australian sites. The Kuka KR360-2 6-axis articulated arm industrial robots are currently being used in Hawker de Havilland Australia's, Melbourne facility for similar applications.

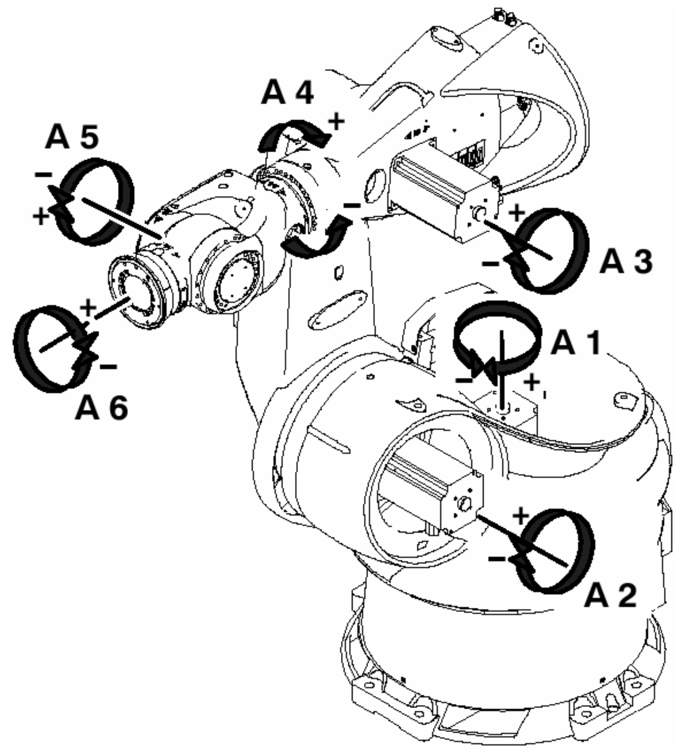

Figure 3. KUKA Robotics KR 360/2 Robot.

The off-the-shelf robot system complete with control cabinet, operating software, and control pendant has a reach of 111.3in (2826mm) to the mounting flange. This robot has an 800lb (360 kg) capacity, which provides the necessary stiffness during clamp and drilling cycles. Once installed, the accuracy (utilizing the Kuka Absolute Accuracy Package) was found to be in the 0.050 in. to 0.060 in. range and the published repeatability of the system, not including the external axis, is ±0.006" (±0.15mm). By further positional mapping and subsequent real time compensation as well as specification of approach paths and limiting the axis feed rates, the system was able to reliably demonstrate the ability to operated within the specified ± 0.020 in. positional tolerance over the part envelope range.

All main structural members of the robot with the exception of the mounting base and mounting flange are manufactured from cast aluminum, which provides optimal stiffness and low weight. The joints and gear boxes are selected to minimize backlash and are life time lubricated (20,000 hrs.). All axes are servo driven with resolver feedback using Kuka fast measurement technology.

End effector

The side mounted end effector consists of a light weight aluminum base structure, which attaches the working part of the end effector to the Kuka mounting flange. The orientation of the end effector aligns 3 axes of the robot, which maximized stiffness and minimized the robots motion.

The end effector consists of three sub assemblies, the pressure foot axis, pressure foot and spindle assembly. Each part plays an important role in the performance of the system.

Pressure Foot Axis

The function of the pressure foot axis is to provide precise pressure to a part in order to stabilize the system during drilling. This stabilization insures that the relative position of the pressure foot to the part does not change during drilling. This feature guarantees high depth accuracy, which is critical to cutting countersinks. The clamp axis is redundant to the robot motion. However, it can be more precisely controlled via load cell feedback. The system is designed to have a variable clamp capacity of 50 to 300 lbs. with a mechanical system disconnect at a force of 500 lbs.

The design of the pressure axis coupled with the flexibility of the robot also allows the software to calculate the drilling thrust load. Since the drill thrust load is redundant to the pressure foot axis, application of the drill thrust effectively unloads the pressure foot axis. By monitoring the pressure foot axis load cell, we can directly infer the drill thrust load with a high degree of precision. Monitoring the drill thrust then allows the operator to maximize cutter life and hole quality by setting a maximum thrust threshold for each cutter size.

The Frame and Pressure Foot

The end effector frame and pressure foot react the loads created by pushing up against the part surface. The complete end effector frame moves relative to the robot during engagement with the part. This servo-axis provides the required control for precision motion required for very thin parts. The frame and pressure foot motion is controlled using and integrated strain gage load cell. The load cell is calibrated to provide clamp load feedback to ± 5% of the commanded load in 1 lb. increments independent of the end effectors orientation.

The pressure foot contains an automated nosepiece changer mechanism designed to grab and index the nosepieces during tool changing process. This allows not only the cutter but also the pressure foot themselves to be automatically changed.

The Nosepieces

To provide full access to the parts while held in their existing jigs, new unique nosepiece assemblies needed to be designed. Four different configurations were developed to allow 100% access to the require areas. The majority of the holes could be drilled with one nosepiece. The leading edge area required a special long nosepiece to give the end effector enough clearance from the upper beam of the part-holding jig. A separate nosepiece was used to reach into low edge margin areas to drill holes for the installation of nut plate retaining bolts around the hinge brackets. The fourth nosepiece use by this system is a chip shroud, which is used for the trimming of CFRP. This nosepiece does not contact the part but helps direct the swarf created into the vacuum collection system.

Each nosepiece contains a spherical swivel clamp pad to reduce the possibility of marking a part due to off-axis clamping. Vacuum collection is directed toward the working end of the nosepiece with a integral air jet system, which directs the dust and chips into a collection system. Boelube mist is incorporated into the three drilling nose pieces to aid in cutting titanium, aluminum and stainless steel material stacks. The Boelube application can be tailored for each drilling cycle depending on material type and thickness.

The External Axis

The external or X-axis of the system is intended to maximize the envelope of the system without compromising the stiffness of the robot. By keeping the end effector as close to the robot base as possible the deflections of the links is minimized. The decision to manufacture a custom X-axis bed segment was taken solely to enhance the accuracy. The purpose-designed bed provides for precision alignment and allowed us to select high precision mechanical drive components. Motion is provided by a rack and pinion driven sled mounted on linear guide ways. The X-axis motor was purchased from the robot OEM to insure compatibility. The X-axis bed was installed directly on top of an existing floor using standard concrete anchors, which resulted in minimal foundation costs.

The Operating System

The Kuka robot comes with its own proprietary operating system, which runs Microsoft Windows© embedded software. The programming software included provides robot and external axis motion and positioning only. A separate Fanuc CNC is supplied to control the end effector motion and process functionality. Both the robot and end effector are then controlled by PC based cell control. The cell control runs the Boeing developed flexible software package called Robotic Assembly Cell Controller (RACC).

RACC acts as the interface between the robot motion platform, the end effector and the operator. It provides intuitive graphical information to the operator on both the process and NC operation. After the NC tapes are optimized to minimize tool changes and path distances, they are loaded into the RACC software. Through numerous databases RACC is able to position the end effector and start the desired cycle.

The Tool Changer and Coupon Stand

In order to minimize operator interaction with the cell an automatic tool and nosepiece changer was incorporated into the coupon test stand. Since there is no shuttle table on this end effector, the nosepiece must be released in order to change tools. Each tool is assigned a pocket for storage. Each nosepiece has a unique identifier, which allows the controller to make proper identification. When a tool change is commanded, the end effector releases the nosepiece into its appropriate pocket and returns the cutter to its pocket. The end effector then picks up the next tool specified in its commanded pocket. To verify the tool is correct a 2D barcode reader reads a barcode engraved on the tool holder. When the barcode matches the NC program, the system acquires the nosepiece necessary for that portion of the program.

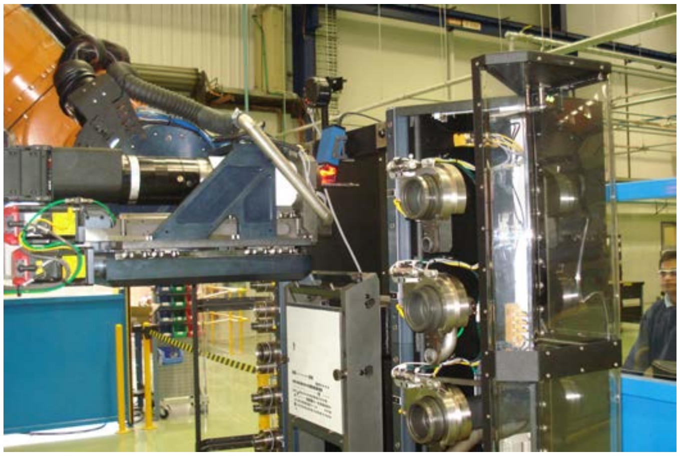

Figure 4. End effector in tool change process.

In the event that a new cutter has been installed, the robot system will drill a test hole in a coupon located between the tools and nosepieces. After drilling the test hole the operator is notified to verify the countersink and adjust if necessary.

The tool changer has room for sixteen tools and six nosepieces. There are two 12inch square coupon locations for drilling test holes as well as one 3x12 inch coupon for verifying the Y-flange countersinks in their approximate orientation.

Cell Safety

The three-zone cell layout provides operator safety in all aspects of the robot operation. The perimeter of the cell is fenced with solid fencing and utilizes light curtains for the entrances. Depending on the configuration chosen by the operator, light curtains are activated to protect the personnel from the robot motion. In the event a light curtain is broken the system goes into a "feed hold" state, which stops any motion of the robot. Different zones can be selected by the operator to either allow access to the adjacent work zone or to block access to entire cell. Since the tool changer is accessed by both working zones the cell must be entirely isolated prior to a tool change to ensure no personnel are vulnerable, when the robot swings over to the tool stand.

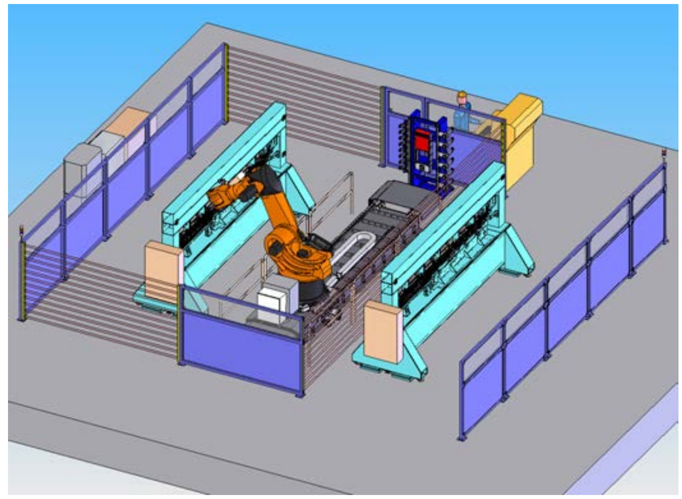

Figure 5. Robot cell layout showing zone 2 active.

Due to the large jigs and other visual limitations a safety reset was placed inside the cell so the operator must check the work zones prior to resetting the zone light curtains. This added safety step ensures that no personnel become locked within the cell while the robot activated.

THE PROCESS

NC Program

The NC program data is loaded into the RACC software. It is up to the operator to determine, which NC data set is required for the particular job. There are eight jigs with slightly different geometric coordinate transformations. By selecting from the program list, the operator matches the program with the specific jig in the drilling cell.

Scanning

The robot system starts the process by picking up a Renishaw RMP60 wireless touch probe. Each jig has six tooling spheres (three per side) located in unique patterns. Once the operator has selected the program, which matches the jig in the cell, the robot synchronizes itself to the jig. If the pattern does not match the coordinates in the program an error message is shown. The operator then can determine whether the chosen part or the program is incorrect. This feature insures that the proper jig/program selection is made.

Test Coupon

Various test coupons are available for process testing. The coupon stand will accommodate all materials and stack thicknesses. After initial setup typically only a CFRP coupon is used to set countersink depths after a cutter change or regrind. The multiple test coupon stand provides a place to improve process parameters on simulated part surfaces.

Drilling and Ink Marking

Using a Precise SD60124 spindle designed for high speed drilling, as well as low-speed, high-torque, the system is easily capable of drilling a 0.250 inch hole in titanium at 300rpm or drilling CFRP at up to 20,000rpm.

Through a series of databases and the NC program, the system can automatically vary the speed and feeds for different stacks, thicknesses, cutter diameters as well control breakout speeds for burrless drilling.

After servicing or NC data changes, the operator has the option of ink marking to verify hole positions prior to drilling on a production part. By slowly spinning a spring-loaded felt pen, fully clamping onto a part and ink-marking the location, precise locations and edge margins can be determined before any holes are placed.

Trimming

The 737 aileron has six tooling lugs, which must be removed. In addition, the trailing edge is trimmed after assembly to generate the final profile. This is accomplished by using a Menlo carbide burr cutter, which spins at 20,000rpm in the spindle. The robot executes a single pass cut for each trim operation. Cutting dust is collected by the vacuum and the excess material falls to the floor.

SYSTEM ACCURACY

The system accuracy takes into consideration many factors. These factors include an imperfect kinematic model of the robot, inaccurate calculation of the tool center point (TCP), track alignment, payload deflection, robot misalignment, inaccurate gear ratios, backlash along with others. The robot selected for this project included an accuracy package (KUKA absolute accuracy package), which further enhanced the robot's off-the-shelf accuracy. In addition, the robot control also compensates for payload provided it is given the center of gravity and mass accurately.

Unclamped Positional Accuracy

Considering all the factors, which contribute to the inaccuracies of the system, several compensation routines must be used to correct the commanded tool point. The RACC software provide significant accuracy enhancement over the OEM purchased compensation package. A best-fit routine of the spindle tool point centerline (TCP) is used map the robot over its working zone. A laser tracking system is used to gather the compensation data. The inaccuracies of the robot track are compensated using a six-degree of freedom transform that is a function of track position. The entire compensation is performed using a well-documented calibration procedure.

Field testing of this system has shown the compensated unclamped 3-D accuracy of the robot and track system (inside the part envelope) to be within ±0.020 inches (99.7% confidence level).

Anti-skate Routine

Each axis position on the robot is measured at the back of the servomotor using a resolver. Consequently, any deflections forward of the resolver (shaft torsion, belt stretch, gear lash, etc.) are not accounted for. As static pressure is applied to the work piece, moments are created about each of the six robot axes. This causes local deflection, and ultimately movement at the tool point relative to the panel surface or "skating". The magnitude and direction of this skating is dependant upon the position of the robot and the applied force vector. At full clamp load, 300 lb., this skating can be as much as 0.050 inches, instantly throwing the position of the machine out of tolerance.

To prevent this problem, an anti-skating algorithm is used to predict the deflection of the tool point and compensate the robot axes in an equal and opposite directions. Compensation motion is triggered as panel contact is established. The result has been the reduction of skating of approximately 95-99% in all positions regardless of nose tip friction, robot orientation, and clamp load. Calculations are made on the fly and are completely transparent to the operator and NC programmer. The anti-skating routine is fundamental to the accuracy enhancement features. [2]

CONCLUSION

Increased capabilities of commercially available industrial robots are making low cost, lean systems a reality for aerospace companies. With advancements in structural stiffness and compensation, the six-axis articulated robot is a prime candidate for small envelope aerospace machine tool motion platforms. Absolute accuracy remains on the edge of acceptability for many aerospace assemblies. However, new techniques have been deployed and are currently being further enhanced, which will bring the accuracies of these systems closer to aerospace expectations. The combination of an industrial robot and a purpose built end effector for the 737 aileron provides a successful example of a lean high rate aerospace production system.

ACKNOWLEDGMENTS

Electroimpact would like to acknowledge Boeing-Hawker de Havilland. Hawker de Havilland designs and manufactures aircraft components for many aerospace companies.

REFERENCES

1. KR360/2 Specification 07.05.02 (www.kuka.com)
2. DeVlieg, Russ, ONCE (One Sided Cell End Effector) Robotic Drilling System, SAE 2002 01-2626

CONTACT

Joe Atkinson
Project Engineer
Electroimpact, Inc.
(425) 348-8090
www.electroimpact.com

John Hartmann
Vice President
Electroimpact, Inc.
(425) 348-8090
www.electroimpact.com

Simon Jones
Project Engineer
Hawker de Havilland
Bankstown, Australia
+61 2 9772 8441

Peter Gleeson
Project Engineer
Hawker de Havilland
Bankstown, Australia
+61 2 9772 8104

ADDITIONAL SOURCES

www.kuka.com

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CFRP: Carbon fiber reinforced plastic
CNC: Computer numeric control
NC: Numeric control
RACC: Robotic assembly cell controller
TCP: Tool center point
Y-Flange: Leading edge fittings on the 737 aileron.