High-Accuracy Robotic Drilling/Milling of 737 Inboard Flaps

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ABSTRACT

The processes of drilling and milling Boeing 737 inboard flaps at Triumph Aerostructures have been enhanced by an accurate articulated robotic system. Tool point positioning is handled by an off-the-shelf 6-axis KUKA KR360 robot riding on a linear axis. Each of the 7 axes is enhanced with secondary position encoders. A single process head performs all required functions, including one-sided pressure application, touch probing, barcode scanning, drilling/countersinking, measurement of hole diameter and countersink depth, and face milling. The system is controlled by a Siemens 840Dsl CNC which handles all process functions, robot motion, and executes software technologies developed for superior positional accuracy including enhanced kinematics, automated normality correction, and anti-skid correction. The layout of the assembly cell allows the robot to span four fixture zones. Part programs are generated offline in the Catia environment using an offline programming and simulation package.

INTRODUCTION

Triumph Aerostructures - Vought Aircraft Division, located in Stuart, Florida USA, performs assembly of commercial aerospace components, including the inboard (IB) and outboard (OB) flaps for the Boeing 777, the center wing box for the Boeing 767, and the inboard flaps for the Boeing 737. Specific to the 737 IB flaps, additional capacity was required to meet rate increases. A ship set of IB flaps contains approximately 2150 holes and the throughput must meet or exceed a rate of 15 ship sets per month. Drilled stacks consist of combinations of aluminum, titanium, and carbon fiber-reinforced plastic (CFRP). Holes range in size from 4.8mm (3/16″) to 9.5mm (3/8″), typically with countersink, with a hole diameter tolerance of −0.00/+0.08mm and a countersink depth tolerance of +/− 0.05mm. Each hole must be drilled normal to the surface within +/−0.5 degrees. Hole positioning is held to +/−0.25mm and is relative to the fixture reference frame. Face milling is achieved using a 76mm diameter fly cutter and held to a 63rms finish tolerance. At Triumph, the drilling and milling operations were already handled by an automated gantry-based system but could not support the additional workload. In lieu of a second gantry, Triumph selected a high-accuracy robotic solution. Either system could meet the drilling and milling requirements, however, the robotic system offered Triumph four distinct advantages:

1. Flexibility. The large range of motion inherent to an articulated arm enables the system to be applied to various products. Should the rate requirement decrease in the future or change significantly from its initial application, it can continue to be adapted and utilized on other assemblies, including those with complex geometries.

2. Lower cost. Because industrial robots are produced in high volume their cost is low and reliability is high compared to customized positioners.

3. Minimal installation disruption. As with most automation, the robotic system had to be installed into an active factory and disruption to production was to be minimized. The robotic system is modular and can be easily broken down into smaller, manageable components, such as the 6-axis positioner, linear track sections, control cabinet, etc. Each component can be maneuvered via forklift and rough installed in only a few days.

4. Large working volume (dual zone). The first axis of the robot provides a huge advantage as far as working volume. When mounted to a linear axis, the robotic system can be configured to perform assembly operations on either side of the bed ways, effectively doubling the system's working volume.

Within the last 10 years, significant mechanical and control improvements have made robots a viable option for mid-range assembly tolerances (+/−0.75mm). However, manufacturers commonly give one third of the overall assembly tolerance to automation systems, and in most cases this overall tolerance is less than +/−0.75mm, requiring the positional accuracy of the automation to be +/−0.25mm or better. Existing technologies are available for global accuracy improvement to this level, such as directly teaching positions or real time guidance via metrology (laser tracker, indoor GPS, camera systems). As design changes and variants are common in aircraft structures, and the location of assemblies within the automation cells are typically not tightly controlled, unique and time-consuming teaching methods become obsolete. Manufacturers require the ability to program systems offline. Guiding robots real-time using metrology has demonstrated improvement in positional accuracy, but at the cost of sensitive, expensive equipment. External systems also tend to slow the system down, restrict the working range, and offer line of sight challenges. In some cases when positional tolerances are extremely tight these technologies cannot be avoided, however it is desirable to have an inherently accurate automation system whenever possible.

BODY

Triumph's intent was to obtain a system with the performance and control of a tailored machine tool while maintaining the flexibility and low-cost of an articulated robot. Electroimpact's recently-developed Accurate Robot technology is built upon the use of an off-the- shelf conventional articulated robot motion platform supplied by KUKA Robotics. To this system secondary feedback is added to each rotary joint. The end effector and ancillary components are integrated and the entire system is CNC controlled by a single Siemens 840Dsl. The CNC handles all controls requirements, including robot positioning and multi-function end effector processes. Crucial is its ability to directly utilize secondary feedback on any axis and provide a means to utilize customized high-order kinematics. The CNC is also a familiar interface to programmers and operators, using traditional M and G codes. The result is a robotic motion platform that can provide positioning accuracy on par with conventional machine tools. The elimination of the conventional robot controls and the integration of both motion and process control into a single CNC package has greatly simplified operation and maintenance, while at the same time providing simplicity in controls topology.

Figure 1. Accurate Robot system

The automation system is the integration of two main subsystems; the positioning system and the multi-function end effector:

POSITIONING SYSTEM

The positioning system presents the process head to the work piece. For Triumph, the primary positioner is a 6-axis articulated KUKA KR360 robot. Because robots are used primarily in the automotive and packaging industries, these systems are mass produced and have been refined for high reliability. When feasible, adapting articulated arm robots for assembly of aerospace structures tends to produce a lower cost automation solution. However, as delivered, the robot cannot position well enough to meet the tolerances required for the flap.

The accuracy in which features are placed via automation is a function of two main criteria; 1) The positional accuracy of the motion platform in free space, and 2) The ability of the motion platform to remain in position when loads are applied. For a drilling application, this would require the machine to position itself at the programmed location and remain stationary when pressure foot and drill thrust forces are present. Although an off-the-shelf robot can perform the required manipulation of the process tooling, it may not meet the positional accuracy and rigidity required for the majority of aerospace assembly tasks. A typical 3 meter reach robot using a nominal kinematic model exhibits an accuracy of about +/− 2 to 4mm within its working volume. Due to manufacturing and assembly variation, the physical robot does not match the nominal kinematic model. A unique kinematic parameter set can be developed to better describe individual arms. This unique model can include higher-order parameters that describe actual physical dimensions, non-linear axis behavior, and effects on tool center point (TCP) position altered by the masses of the robot links and attached payloads. In practice, this has proven to achieve positional accuracies of nearly +/−0.5mm using a standard off-the-shelf robot system.

The position and orientation of the TCP is obtained by driving the robot axes to angular positions based on the kinematics of the arm. Errors in joint angle are fed through the kinematics and yield error in the resulting TCP. Off-the-shelf robots obtain the position for each axis at the servo motor. Downstream of the motor feedback can be backlash, transmission wind up, harmonic errors, and so on. Although the unidirectional repeatability of robots is generally good, omnidirectional typically is not. Testing of omnidirectional repeatability using a 3 meter arm has shown magnitudes of up to 0.4mm. Poor repeatability is caused by uncertainty in joint position. Because the system's accuracy can only be as good as its repeatability, the best a standard system can ever achieve in ideal conditions is 0.4mm. Therefore, fundamental to system accuracy is precise knowledge of the position of each axis. Controlling based on input position also limits the stiffness of the mechanical unit as axis compliance and backlash go unaccounted for. The result is poor joint stiffness and significant TCP error when loads are applied. Joint deflection results both from the masses of the links and from process forces. When drilling and fastening, clamp force is typically applied causing the TCP to skid out of position. Test results from various articulated arms have shown that the deflection at the joints make up 50-80% of the total TCP deviation.

To maintain adequate control of an axis, machine tool designers commonly use secondary position encoders. The secondary encoder is mounted at the output of the axis rather than the input. Transferring this technology to an articulated robot (Figure 2) yields much tighter control on axis position and, in turn, a system that can be calibrated to higher accuracy. Secondary encoders reduce omnidirectional repeatability to nearly zero and have been validated using a laser tracker while exploiting the combined effects from moving all axes. Results have shown a maximum deviation under 0.04mm at 3 meters. This is an improvement of 10x over a non-enhanced system. With the repeatability in check, a more representative kinematic model can be obtained. Further, with secondary encoders at each axis, local joint error is effectively eliminated. With real-time compensation of the remaining deflections in the links and bearings, the system can maintain ON-PART accuracy of +/−0.25mm or better (Figure 3).

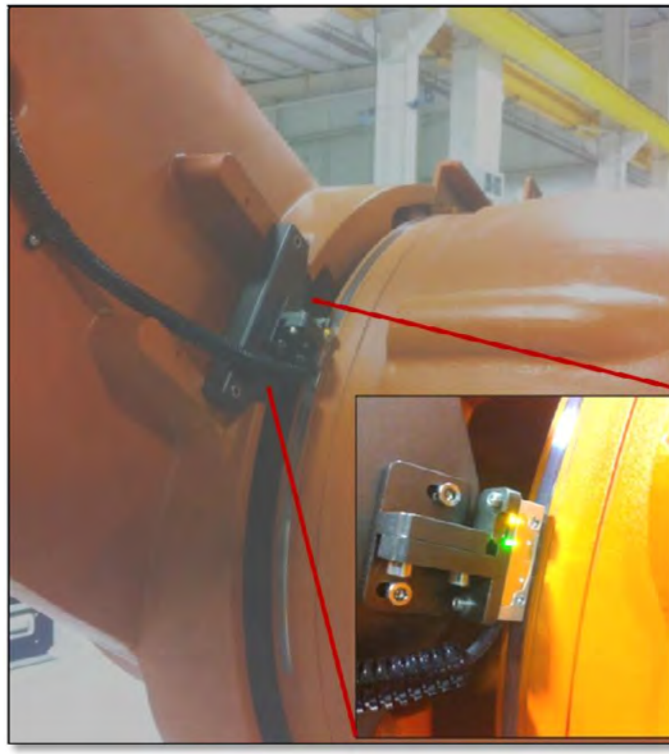

Figure 2. Secondary encoder mounted to output of robot axis

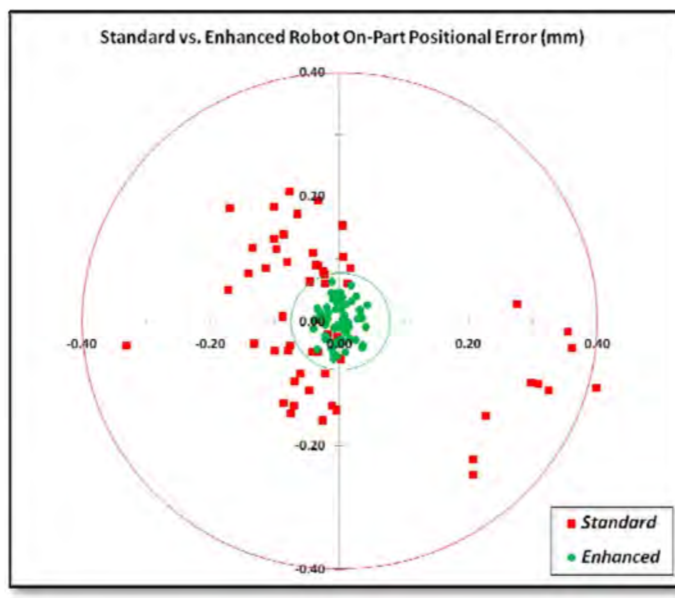

Figure 3. Accuracy comparison: Standard vs. Enhanced

MULTI-FUNCTION END EFFECTOR

All process functions are carried out by a single multi-function end effector (Figure 4). The assembly of the 737 IB flap requires systems for providing one-sided pressure to the work piece, auto-normalization, Boelube delivery, vacuum swarf extraction, automated vision, automated touch probing, precision drilling and countersinking, hole inspection, and milling capability. The MFEE is controlled with the Siemens 840Dsl CNC that is also used to control the robot. All process tools (spindle, probe, and camera) are mounted to a single plate (shuttle table) which is servo indexed to present the current process tool to the TCP. The tools, shuttle table, pressure foot, and supporting frame are mounted to a servo-controlled "clamp" axis. Each component provides specific functionality:

Figure 4. Multi-function end effector. Left to right: nose piece, camera, hole probe, spindle

Nosepieces - The nose piece is what makes physical contact with the product. The nosepiece is fitted with a spherically compliant tip, Boelube delivery, vacuum recovery, chip blast, 5-bit identification, and a damage preventing breakaway system. Sensors are built-in to measure the normality between the end effector and the part surface. Attachment of the nose piece to the pressure foot is made using a rotary quick-connect.

Shuttle Table - The shuttle table serves to accurately present each process tool to the nosepiece. The shuttle table is linearly actuated under servo control with closed-loop position around a high-resolution secondary encoder. Each process tool is precisely located on the shuttle table by the use of hardened pins/bushings. These pins eliminate the necessity for process tool alignment. The MFEE for the IB flap application uses a 4-position shuttle table for the three process tools plus a spare slot for additional future process capability.

Clamp Axis - The clamp axis provides one-sided mechanical pressure to the work piece during drilling and inspection operations. Clamp pressure is required for system stability and panel surface location. The axis is servo driven with load cell feedback and actuates parallel to spindle feed. For the IB flap, the system has been designed to provide continuous programmable load from 50 to 400 lbs. Both the shuttle table and the end effector frame mount to the clamp table, and are thus involved in clamp axis motion.

Frame/Pressure Foot - The end effector frame and pressure foot provide overall stiffness for the clamp axis. The frame is directly attached to the clamp table. At the front of the end effector, between the top of the frame and the clamp table, is the pressure foot. The pressure foot houses the nosepiece assembly. A force sensing load cell is housed in the pressure foot directly behind the nose piece which provides feedback to the CNC used to control the applied pressure from the clamp axis.

PRODUCTION PROCESS

For the 737 IB flap, the robotic system is mounted on a servo-controlled linear axis and spans four fixture zones (Figure 5). The holding fixtures for the flaps are rolled into the cell and set down on floor indexes. As the robot works in one cell, the other can be safely accessed by personnel. With this layout, the robot is able to continuously operate - maximizing the investment and throughput. Processes are required on both sides of the assembly. Once one side is complete, the fixture is manually rotated and presented again to the automation. Programmable safety laser scanners are used to stop the machine if a safe distance is not maintained by personnel. Two fixed scanners are mounted to the bed way and monitor each fixture zone, with a third scanner mounted to the robot sled that provides protection against intrusion of the coupon stand area.

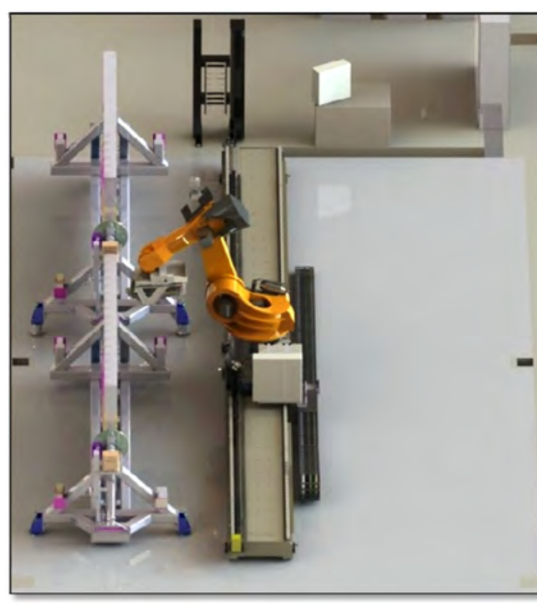

Figure 5. Top view of automation cell

Offline programming and simulation of the robotic drilling is accomplished within the Catia V5 environment. Product engineering data, such as fastener vectors and associated attributes, are pulled from the model and combined with user inputs such as robot head orientation and linear track position. This is then processed to create an NC program that the robotic drilling system can execute. Each position can be simulated in the CAD environment and checked for collisions, robot singularities, and optimum configuration. Escape paths are designed to ensure safe approach to and retraction from the product at any point in the program.

The product, when presented to the automation, is a tacked, closed structure comprised of skins, ribs, and spars. Stacks are any combination of CFRP, aluminum, and titanium. Holes are placed on both upper and lower surfaces. The fixture reference frame is determined automatically by probing features on the frame using a wireless touch probe mounted in the robot spindle (Figure 6). The machine drives to nominal features on the fixture frame, captures their actual position by touching off on various points, and determines the offset between the actual feature location and the nominal location. This is performed over a set of features allowing for a best-fit transformation to be established.

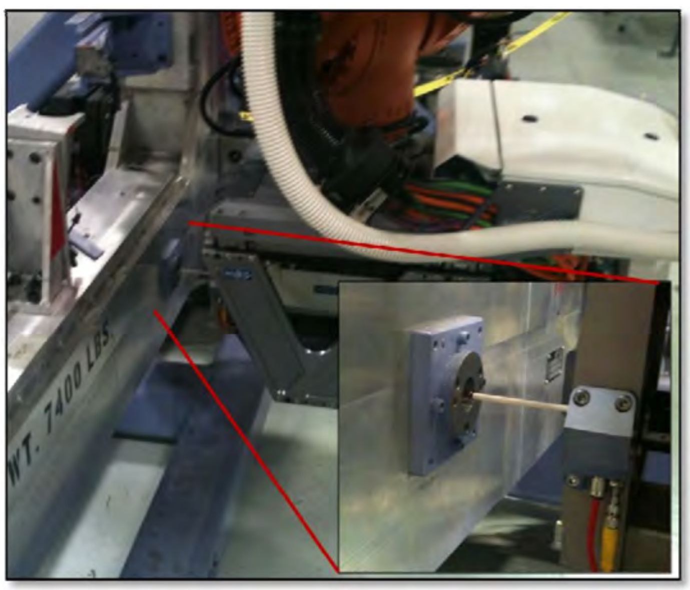

Figure 6. Wireless touch probing of fixture targets

Drills are automatically exchanged at the coupon/tool change stand located at one end of the bed way (Figure 7). As a precaution, the length of the installed tool is auto-measured internally within the MFEE to double-check the proper tool is loaded. If the tool has not been previously used or has been altered, reground, etc., the system will perform a drilling cycle in a coupon. At the coupon, the system will drill, countersink, and measure a single hole and display the measured results to the operator for verification or adjustment. Once an acceptable hole has been placed in the coupon, the system is allowed to work on the product.

Figure 7. Coupon stand and tool change station

Following the probing and coupon drilling processes, the system executes drilling and inspection cycles. At each location, the robot is positioned to present the tool center point (TCP) of the end effector at a nominal flying height above the part. The end effector then extends the clamp axis under closed-loop force control. Once contact is established, sensors built into the nose provide feedback of the angle at the TCP between the surface tangent and the spindle centerline. If deviation beyond a specified threshold from normal exists, the robot automatically normalizes the end effector. Synchronously, translations along the panel surface due to the deflection of the robot arm from the applied clamp load (referred to as “skidding” or “skating”) are counteracted. The clamping process is complete once the pre-defined clamp load is established. From panel contact to completed clamping process, including normality and skid corrections, typically takes 2-4 seconds depending upon the rigidity of the product structure.

At the start of drilling, Boelube mist is applied to the pierce point at a programmable rate. The mist is applied continuously throughout the drilling cycle to lubricate the cutting surfaces, cool the bit and panel, and aid in the collection of composite dust. All swarf is collected using an integrated vacuum system. The spindle assembly utilizes a Fischer-Precise 20k rpm, liquid-cooled, pneumatic automatic drawbar cartridge mounted to a custom servo-controlled feed system with integral glass scale linear encoder. Adaptive tuning parameters are used to optimize spindle performance at low speed, high-torque (titanium) and high-speed operation (CFRP and aluminum). Because the required feeds and speeds vary between stack materials, the spindle is programmed to use specified parameters based on its position within the stack, including peck drilling if needed. Parameters can also be adjusted within layers to minimize exit burrs or fiber breakout. Once the hole is drilled through, the spindle is rapidly fed to the start of the countersink and a new set of parameters are used to finish out the hole. Drill thrust is monitored during the entire cycle and is used for tool wear tracking and broken drill bit detection.

Inspection of the hole is optional, generally frequency-based, and performed in-process while still under clamp load following the drill cycle. Immediate inspection of the hole provides real-time feedback that the system is carrying out a quality process. It significantly reduces overall inspection time and provides statistical process control data tagged to each location. The probe is mounted adjacent to the spindle on the shuttle table. The probing system utilizes a standard 2-point split ball gauge. The balls on the probe are extended outward under light spring pressure to ride along the inner surface as the probe is plunged through the hole. These mechanically actuate a linear shaft which is precisely measured using a high-resolution encoder. The accuracy of the diameter measurement is +/− 0.005mm. Diametrical data is collected every 0.01mm along the length of the hole and can be measured at 0 and 90 degrees. The result is a complete profile of the hole and the collected data is analyzed for consistent and in-tolerance values at any requested location within the stack (Figure 8). The countersink depth is measured using the same probe, but utilizes a reference surface and spherical lander located just upstream of the 2-point gage. The gage is extended out through the back of the hole allowing the reference surface to bottom in the counter sink and the spherical lander to make contact with the panel. The relative offset between reference and lander is used to accurately measure the countersink depth with repeatability at 0.013mm. Auto-calibration of the probe is performed prior to each measurement cycle and is carried out simultaneously with the drill cycle to eliminate any time penalty. Collected data for diameter and countersink depth is automatically verified to be within process limits before proceeding further. Should the data indicate limits have been exceeded, the system is halted and the operator alerted.

Face milling operations are performed unclamped. A 76mm fly cutter is manually installed into the spindle and the nose piece is replaced by a quick connect shroud (Figure 9). Material is removed from four aluminum carriage pad surfaces to a tolerance of +/− 0.13mm to each other and within +/−0.38mm to the nominal engineering reference plane. The final surface finish is 63rms. Full cutting depth is accomplished using multiple passes. Stability under cutting load is aided both by the secondary axis encoders and by specifically tuning the robot for dynamic path-accurate operation.

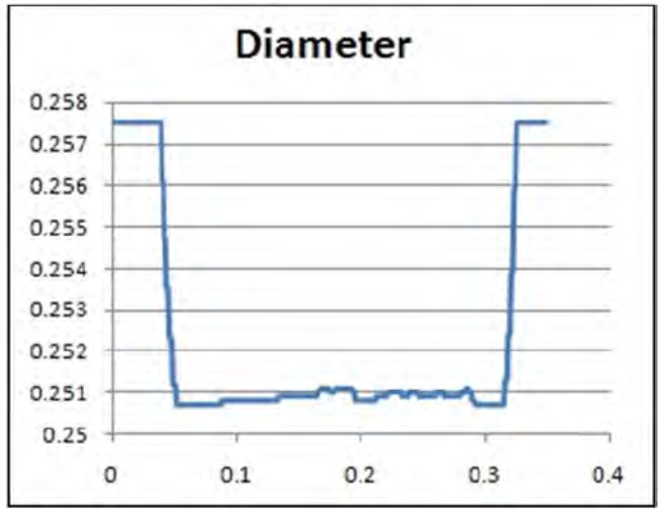

Figure 8. Hole profile data collected by probe

Figure 9. 76mm end mill and shroud for face milling operations

SUMMARY/CONCLUSIONS

Triumph Aerostructures - Vought Aircraft Division sought an automated solution to drill and mill Boeing 737 IB flaps containing 2150 holes at a rate of 15 ship sets per month. A robotic solution was selected which offered distinct advantages of flexibility, lower cost, minimal installation disruption, and a large working volume. The robotic drilling system was designed to locate, drill, countersink, and measure skin to substructure fastener holes as well as face mill aluminum carriage pad surfaces. The performance and control of a tailored machine tool and the flexibility and low-cost of an articulated robot were combined into a single "Accurate Robot" solution with all system functions controlled by a single CNC. On-part positional accuracy was enhanced by the addition of secondary position encoders on each robot axis and by the utilization of a high-order kinematic model. Process functions were achieved using a production-hardened multi-function end effector.

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DEFINITIONS/ABBREVIATIONS

Boelube
Cutting lubricant. Boelube is a registered trademark of The Boeing Company

CAD
Computer-Aided Design

CFRP
Carbon Fiber Reinforced Plastic

CNC
Computer Numerical Control

GPS
Global Positioning System

IB
Inboard

MFEE
Multi-Function End Effector

NC
Numerical Control

OB
Outboard

Omnidirectional
From any/all directions

TCP
Tool Center Point

Unidirectional
From one direction

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. This process requires a minimum of three (3) reviews by industry experts.

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