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Applied Accurate Robotic Drilling for Aircraft Fuselage

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ABSTRACT

Once limited by insufficient accuracy, the off-the-shelf industrial robot has been enhanced via the integration of secondary encoders at the output of each of its axes. This in turn with a solid mechanical platform and enhanced kinematic model enable on-part accuracies of less than +/-0.25mm. Continued development of this enabling technology has been demonstrated on representative surfaces of an aircraft fuselage. Positional accuracy and process capability was validated in multiple orientations both in upper surface (spindle down) and lower surface (spindle up) configurations. A second opposing accurate robotic drilling system and full-scale fuselage mockup were integrated to simulate doubled throughput and to demonstrate the feasibility of maintaining high on-part accuracy with a dual spindle cell.

INTRODUCTION

The aerospace industry has been interested in the use of articulated arm robots in aero structure production for many years, with its roots being in their successful implementation in automotive plants. Industrial robots offer airframe manufacturers significant benefits in cost and flexibility. Robotic drilling cells can reduce assembly line footprint and increase drilling accessibility. Typical drilling applications in aerospace have consisted of large gantry or post style drilling systems requiring significant facility footprints and clear access to the product. Numerous spindles can be applied via robot within a similar volume resulting in a reduced quantity of cells to reach full rate. When confronted with the high demands required for aerospace assembly however, robot systems have often not been able to meet customer requirements.

Drilling complex contour skins to substructure for the fuselage section of the aircraft was the benchmark application for the accurate robotic drilling system. Robots mounted on linear axes were placed on either side of the product and configured to drill upper and lower skins. The product was highly contoured and comprised of panels that were both fixed and removable. The system was operated in two modes, guided and unguided. The goal for unguided accuracy was global +/-0.25mm and made up the majority of the work content. When operating in guidance mode, the machine was expected to place holes with an accuracy only limited by the guiding device (laser tracker), or less than +/-0.125mm. Material stacks included CFRP, aluminum, titanium, and various steels. Automated processes include drilling of substructure only, drilling and countersinking skin and substructure together, and in-process inspection of the hole diameter and countersink depth.

A complete production representative cell was constructed to validate the entire automated robotic drilling system. The demonstration cell included two enhanced accurate robotic arms traveling on linear ways with a single multi-function drilling and countersinking head. The head included systems for automatic spindle normalization, hole inspection, and automatic tool changing. Testing was performed on full-scale representative work pieces. Programs were generated offline and simulated in the product's native CAD environment. On-part positional accuracy and process performance were validated. Additional product-specific requirements were also demonstrated, which included offline programming with simulation and automated collision avoidance. The primary leap in technology, and focus of discussion, was the development of a system to enhance off-the-shelf articulated arms to enable global positioning better than +/-0.25mm over the envelope of the product. Robot positions requiring tighter tolerances were guided via laser tracker to achieve extreme accuracy with the drawback of additional cycle time.

ACCURATE ROBOT DEVELOPMENT

The accuracy in which a robotic system can drill a hole in a work piece is primarily a function of the positional accuracy of the robot and its ability to remain in position when external loads are applied. Loads in a drilling application arise from pressure foot and drill thrust forces. Although an off-the-shelf robot can perform the required manipulation of the process tooling, it fails to meet the positional accuracy and rigidity required for a radial tolerance of 0.25mm. On a typical industrial robot the position feedback for each axis is located at the servo motor. Between the feedback and joint, error is introduced from backlash and wind up. Although the repeatability of robots from one direction is generally good, repeating from multiple directions is not. Testing has demonstrated magnitudes of up to 0.5mm using various 3 meter arms in typical working envelopes. System accuracy can only be as good as it's repeatability, and therefore the best a standard system could achieve in ideal conditions is 0.5mm. Additional motion loss in the joints results from moments induced by link masses and applied forces. Relatively low pressure foot loads (<200 kgf) applied at the TCP can alter the position up to 2mm (referred to as "panel skid") with the majority of this deflection coming directly from the joints. Therefore, fundamental to system accuracy is precise knowledge of joint position.

To maintain adequate control of each axis, a patent pending system of high-resolution encoders were mounted at the joint outputs (figure 1). These secondary sensors are standard product in machine tool applications and exhibit high resolution with negligible hysteresis. Applying this technology to an articulated robot yielded much tighter control on axis position and, in turn, higher tool center point (TCP) accuracy. Repeatability from multiple directions was improved by an order of magnitude to less than 0.05mm. Removing slop in the joints enabled a more representative kinematic model to be obtained. Factors for joint compliance and backlash were replaced by more descriptive parameters that were previously difficult to ascertain.


Figure 1

When drilling and countersinking, clamp force is typically applied to stabilize the process and minimize interlaminar debris. Because articulated arms lack stiffness, significant deflection occurs when external forces are applied. The majority of this deflection comes from the joints given a normally-equipped robot. Results from testing various articulated arms has shown that the deflection at the joints make up 50-80% of the total TCP deviation. With secondary encoders, local joint error is negligible. Deflection still occurs in links, bearings, and base mounting plate, so an arm with high mechanical rigidity is desired. Any remaining deflection is compensated real-time by including a deflection model of the system in the kinematics combined with an integrated load cell in the end effector.

AUTOMATION SYSTEM DESCRIPTION

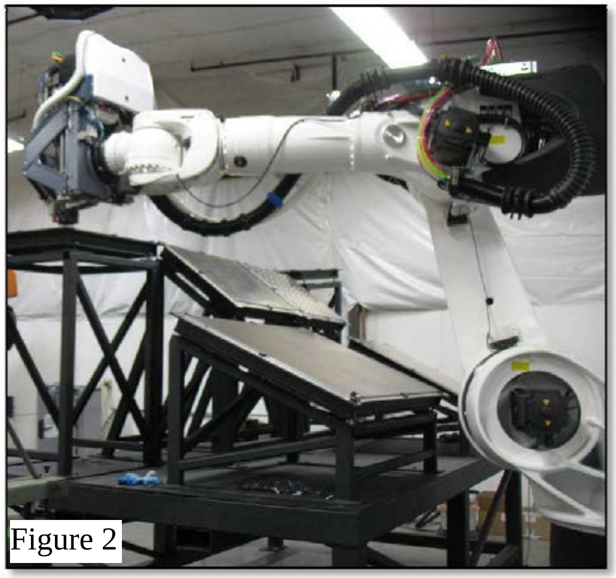


Figure 2

After thorough evaluation of industry leading robots, the KUKA KR500/L340 was selected as the robotic motion platform of choice. The KUKA robot offered sufficient reach with high stiffness. Encoders were mounted to each axis by Electroimpact. The working envelope was expanded by mounting the robots on linear slides to enable full coverage of the product. A multi-function end effector was integrated on one robot which was validated to meet all drilling, countersinking, and hole inspection requirements. The drilling spindle was designed to provide enough torque (10Nm continuous) for -12 holes in Ti, and high speeds (20k rpm) for composite and aluminum materials. The automated hole measuring probe used a split ball gauge mated to a precision encoder to provide a profile of the hole, report stack thickness, and measure countersink depth. The process tools were mounted to a servo-controlled pressure foot axis. The pressure foot and nose piece included integral normality sensors, load cell, flood coolant delivery, and vacuum recovery. Surrounding the nose piece were metrology targets used for guided hole patterns. All systems were controlled via an industry standard Siemens 840Dsl CNC which handled control of both the robot and end effector, and it offered a familiar interface to programmers and operators. Enhanced kinematics were developed by Electroimpact and executed using Siemens' Volumetric Compensation Interface (VCI).

ACCURACY VALIDATION

Analyzing position deviations off-part provides a good measure of the quality of the machine, its repeatability, and the accuracy of the enhanced kinematic model. To determine, a laser tracker target was placed in the TCP and the system was run through various positions within the working envelope of the product. Data was collected at each position using a laser tracker, compared to the commanded position, and the 3-dimensional radial error was calculated. Accuracy was reported in terms of "3-sigma" which is defined as the average plus 3 times the standard deviation of the sample. This provided an accuracy value with 99.7% confidence given the assumption that the data was normally distributed. Measuring features placed on the work piece (on-part) provides a better measure of what is actually occurring in production. This demonstrates both the accuracy of the system and its static rigidity. For the drilling systems, the radial deviation on the panel was examined. Because the position in the surface normal direction was not controlled by the machine, 3-sigma accuracy was reported in two dimensions parallel to the surface. The second robot in the demonstration cell was added after completion of system accuracy validation, therefore the following reported data is for the initial fully-functional robotic drilling system only.

Off Part Accuracy

To ensure the system could globally position to +/-0.25mm within the working envelope, 3-dimensional off part accuracy was validated. The working volume on the upper surface per robot was approximately 3090 x 820 x 1410 mm. TCP location data was collected via laser tracker at 42 production representative locations throughout the volume. The robot and linear axis were integrated with secondary encoders and calibrated. Programmed positions exercised all axes of motion including the linear axis. The resulting 3-sigma accuracy was +/-0.12mm (figure 3). Lower surface work consumed a slightly smaller volume at 2500 x 850 x 1900 mm, but contained increased contour change. Data was again collected via laser tracker. The system was driven to 24 representative locations and demonstrated an accuracy of +/-0.16mm (figure 4).

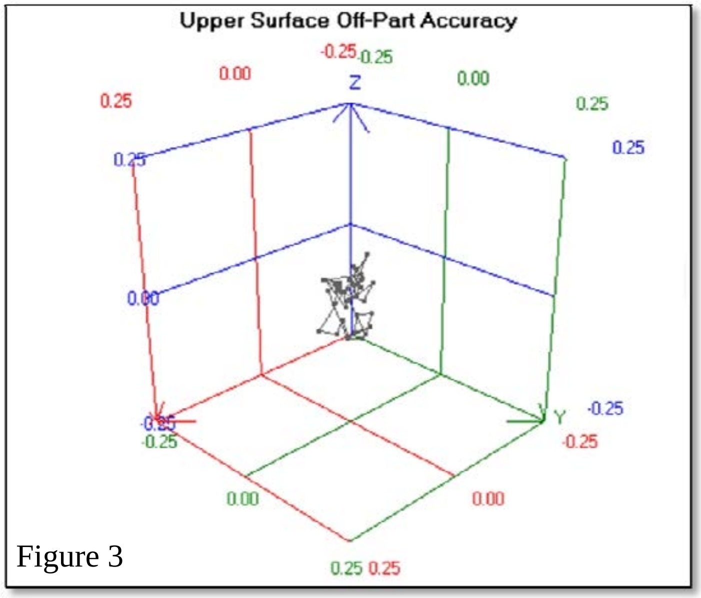


Figure 3

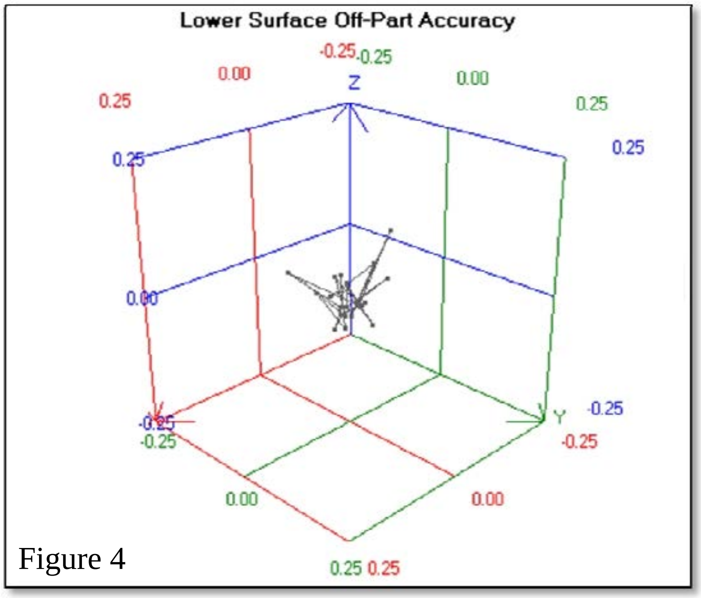
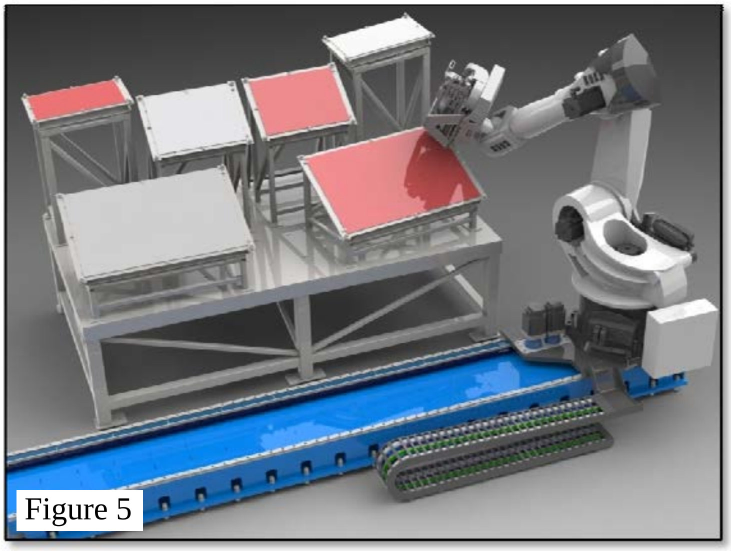


Figure 4

On Part Accuracy

"Validation" tooling was constructed to place coupon panels of relative hole pattern size in locations and orientations that approximated both upper and lower surfaces of the fuselage section. The robot was programmed offline to drill each panel with a grid of countersunk holes. The position of each hole was measured in place using a laser tracker by nesting an SMR (spherically-mounted retro reflector) in the countersink. When all holes were measured together in the global coordinate frame, a value for the on-part drilled hole accuracy was obtained. Coupons were also evaluated separately with the laser tracker to determine pattern accuracy and validated independently using a coordinate measuring machine (CMM).



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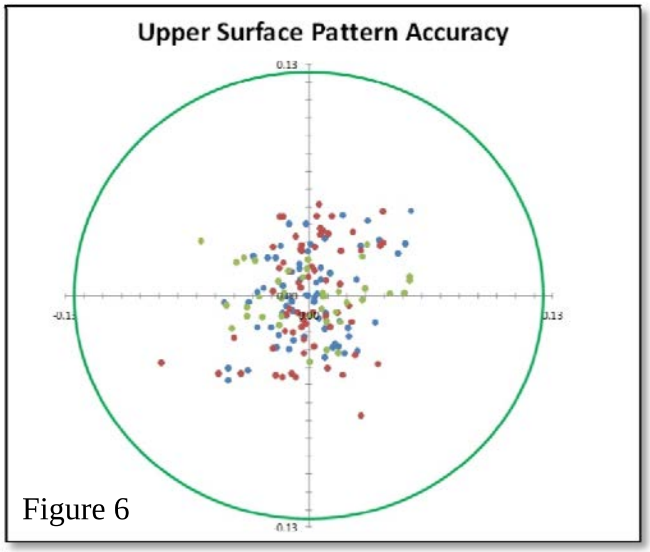

Figure 6

When drilling the extremely tight tolerance patterns, the system utilized metrology guidance. The robot globally positioned and clamped on the work piece and its position was measured with the laser tracker. If a correction was required, the robot was moved and re-measured. Given that the accuracy of a laser tracker is about 0.05mm, the TCP was guided into position within a band of 0.05mm in an attempt to keep the sum of errors below the goal of +/-0.125mm. This added an average of over 15 seconds per cycle. Each robot could reach 50% of upper and lower surfaces of the fuselage section. The upper surface contained 3 major areas of tight tolerance patterns and were approximated within the validation tool using (1) 1400 x 840 mm pattern, (1) 770 x 560 mm pattern, and (1) 770 x 320 mm pattern as shown in figure 5 Results showed that all 168 holes were within a 3-sigma accuracy of +/-0.08mm, noted figure 6. The lower surface contained (2) major areas consisting of tight tolerance patterns and were approximated by (2) 1400 x 840 mm coupons figure 7. The robot was again guided to each location with the laser tracker and the drilled holes were measured both via tracker and CMM. All 128 holes were within a 3-sigma accuracy of +/-0.075mm shown in figure 8.

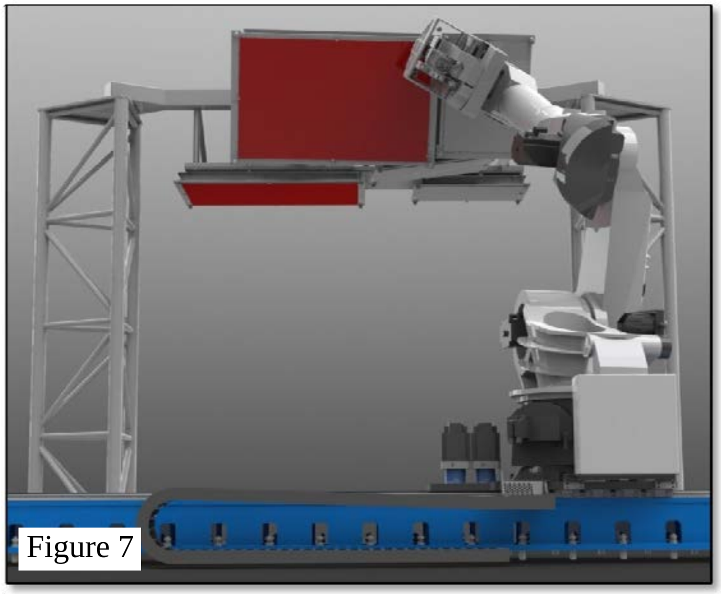

Figure 7

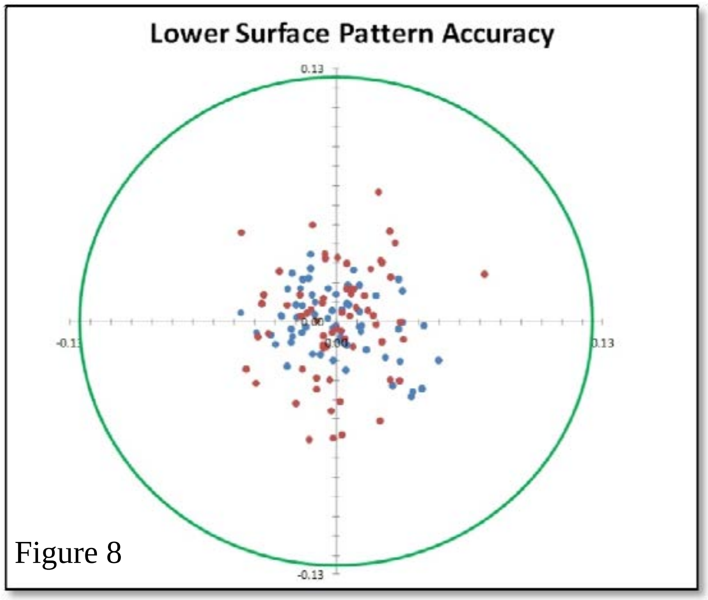

Figure 8

Unguided Drilling

The majority of the work content for the automation was unguided drilling and countersinking. For this process, reliance on system accuracy was exercised. In practice, the aircraft tooling is not accurately located within the assembly cell. Automation systems typically utilize touch probing or vision systems to perform a direct measurement of features on the fixture or product to spatially-align (resync) the drilling system to the work piece. This entails probing 3 or more locations to create a 6DOF transformation. For this specific case, no probing or vision systems were installed, so the resync function was accomplished via the in-cell laser tracker. The laser was used to indirectly provide the transformation by first measuring (4) fixed targets on the validation tool, then (3) unique positions of the robot within the working envelope. This process was fully automated. Once the relationship between part and automation was established, the part program was executed and holes were drilled unguided in the global coordinate frame.

Three main regions on the upper surface were identified and approximated on the validation tool using (1) 1400 x 840 mm, (1) 770 x 560 mm, and (1) 770 x 320 mm (figure 9) coupons and were spread over a volume of 3950 x 1000 x 1950 mm. A total of 168 holes were drilled with a resulting 3-sigma accuracy of +/-0.24mm (figure 10). A noticeable mean shift can be identified at each region. Upon further investigation, an error was discovered in the use of the (4) fixed target locations established by the laser tracker. The error was identified and rectified after the tooling had been broken down and reconfigured for lower panel drilling, therefore no additional data was collected in the upper surface configuration. Results were estimated to improve by 20% or better and were validated during lower surface testing.

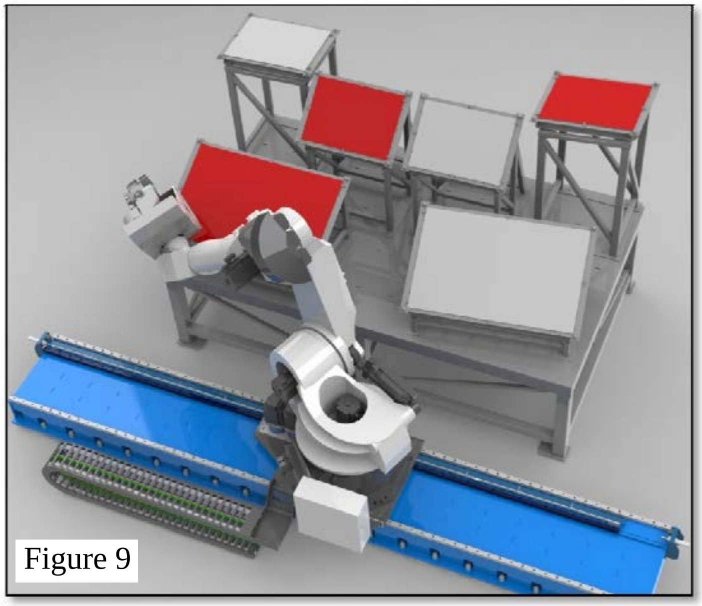

Figure 9

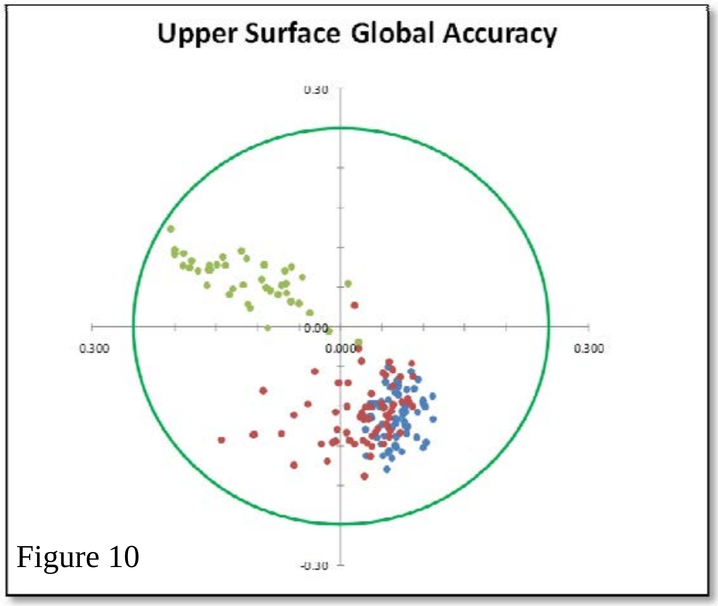

Figure 10

Lower surface fixed skin drilling was largely located at the forward end of the fuselage section. The surfaces were approximated by (2) 770 x 560 mm and (1) 770 x 315 mm coupon plates (figure 11). The total hole set of 189 were spread over a global volume of 1200 x 850 x 1700 mm. The relationship between the work piece and automation was again established using the laser tracker, but with the software error discovered after the upper surface testing now fixed. A 3-sigma value of +/-0.15mm was demonstrated (figure 12).

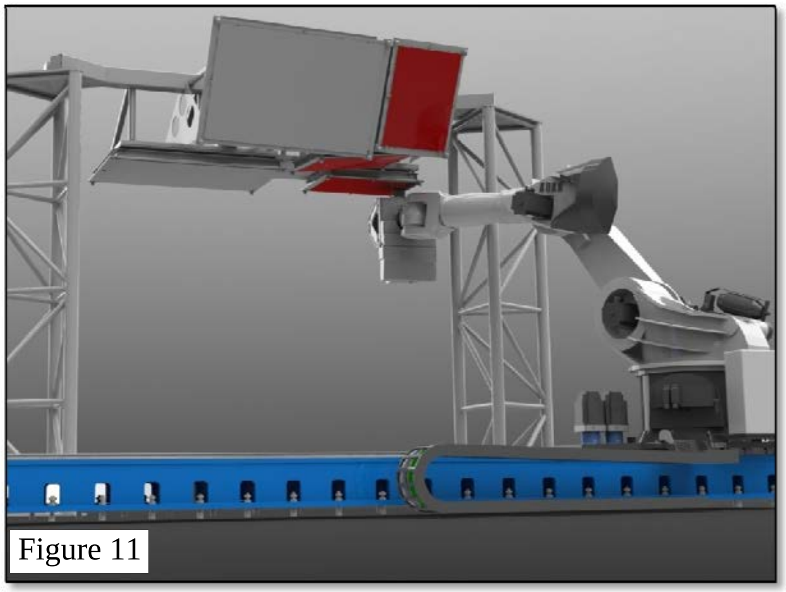

Figure 11

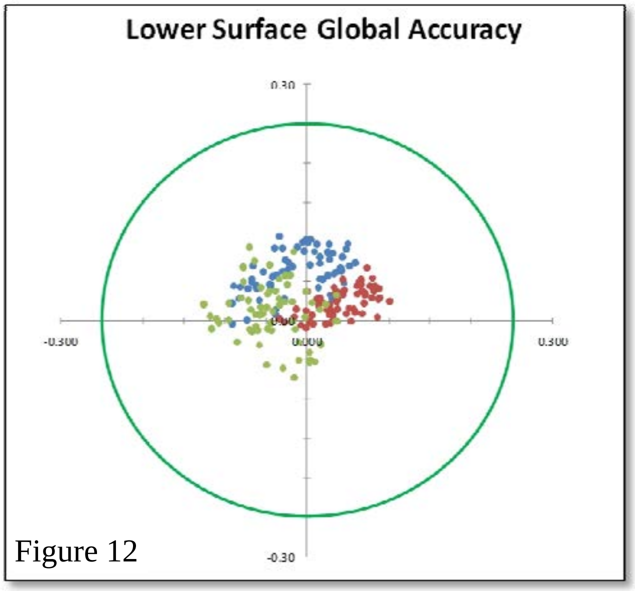

Figure 12

DUAL ROBOTIC DRILLING CELL DEMONSTRATION

With the accuracy of the system validated, a more production representative cell was constructed to demonstrate additional required capabilities. The cell included a second robot and track system, an automated tool changing and setup station, full-scale mockup of the center fuselage section, and additional software systems for offline programming and collision avoidance.

In production, each automation cell would utilize two robotic drilling systems. The two systems are positioned opposite one another allowing each to work independently - effectively doubling throughput. To demonstrate, a second accurate robotic positioner was integrated. Interaction between systems had to be minimal to maintain high efficiency, and because part programs would be run independently, a software monitoring system was used that continuously compared the relative positions of the two systems to prevent collisions when both are working near the crossover point at part centerline. Process tools were not installed on the second system since process capability had been previously validated. However, a clamp nose assembly was included to enable the machine to apply clamp pressure to the work piece. The clamping system was used because the systems work in close proximity and any movement or vibrations from one could not significantly transfer to the other.

The validation tool was set aside and replaced by a full-scale mockup demonstration tool of the fuselage section. The skeleton of the demonstration tool was built up from a combination of steel, wood, and fiberglass with the final layer being a machinable polyester resin. The mold line of the fuselage was accurately machined and holes were placed to affix production-representative composite panels. The tool represented about 70% of the entire surface with the half facing the fully-functional drilling system being complete and the other side being clipped since testing of the second system was entirely inboard.

Offline programming and simulation of the robotic drilling was accomplished using a suite of software from CENIT North America. The programming environment was entirely inside Catia V5. Product engineering data such as fastener vectors and associated attributes were pulled from the model and combined with user inputs such as robot head orientation and linear track position. This was then post-processed to form an NC program that the robotic drilling system could execute. Each position could be simulated in the CAD environment and checked for collisions, robot singularities, and optimum configuration. Escape paths were built in to ensure safe approach to and retraction from the product.

Once the programs were generated and simulated, they were transferred to the machines and executed. The composite panels were drilled, countersunk, and measured with the fully functional drilling system while the opposite system was simulating drill cycles by performing the clamping function. Testing of collision detection and error recovery systems were combined with drilling tests. The systems demonstrated that no part damage occurs mid-process if the system is e-stopped, put in feedhold, or experiences a power failure. Safe, automated recovery from these events was also demonstrated. Both systems executed guided and unguided processes and in-process positional data was collected via tracker for each hole location to validate system accuracy. Panels were then inspected independently to verify proper hole placement.

SUMMARY/CONCLUSIONS

Testing has concluded that the accurate robotic drilling system is a viable option for the automation of drilling and countersinking on the aircraft fuselage. Integrating secondary encoders to each robot joint provides actual axis positions as opposed to inferred positions from motor encoders. This precision feedback is run through an optimized kinematic model to produce a motion platform of high accuracy. Global on-part positioning below +/-0.25mm has been demonstrated using long reach, heavy payload articulated arms. Required hardware for enhancement is minimal, retaining cost competitiveness with standard robotic systems. The completeness of the test cell has minimized implementation risk, while insuring a successful technical and business case solution that is controlled, accurate, safe, and efficient. Primary challenges of the robotic solution for high accuracy have been solved with flexible production processes in mind resulting in a wide range of application opportunities. It is expected that the success and accomplishments of this development activity will continue to open doors for more economic and flexible automation opportunities.

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DEFINITIONS/ABBREVIATIONS

3-Sigma: Measure of accuracy, +/- (average + 3 * Stdev)
DOF: Degrees of freedom
TCP: Tool center point