

## Applied Accurate Robotic Drilling for Aircraft Fuselage

2010-01-1836

Published  
09/28/2010Russell Devlieg  
Electroimpact Inc.Todd Szallay  
Northrop Grumman Corp.

Copyright © 2010 SAE International

### 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  $\pm 0.25\text{mm}$ . 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  $\pm 0.25\text{mm}$  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  $\pm 0.125\text{mm}$ . 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  $\pm 0.25\text{mm}$  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  $0.25\text{mm}$ . 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  $0.5\text{mm}$  using various 3 meter arms in typical working envelopes. System accuracy can only be as good as its repeatability, and therefore the best a standard system could achieve in ideal conditions is  $0.5\text{mm}$ . Additional motion loss in the joints results from moments induced by link masses and applied forces. Relatively low pressure foot loads ( $<200\text{ kgf}$ ) applied at the TCP can alter the position up to  $2\text{mm}$  (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  $0.05\text{mm}$ . 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.

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.

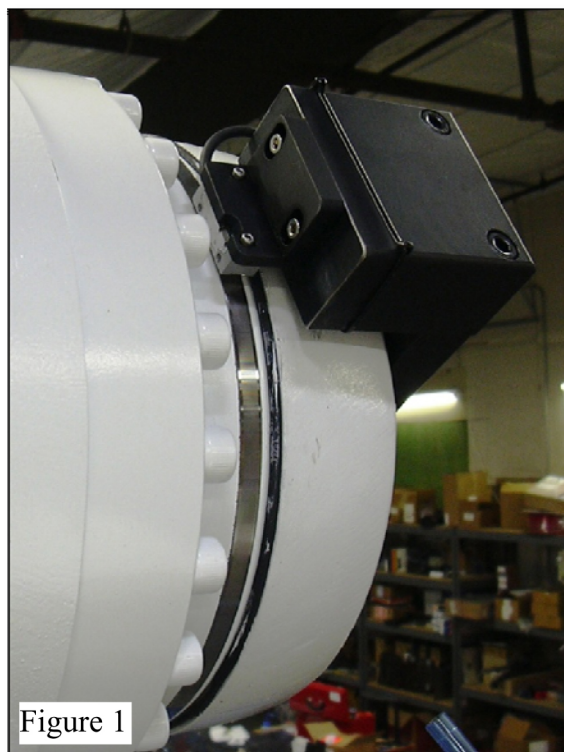


*Figure 1.*

## AUTOMATION SYSTEM DESCRIPTION

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 ( $10\text{Nm}$  continuous) for  $-12$  holes in Ti, and high speeds ( $20\text{k rpm}$ ) 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).

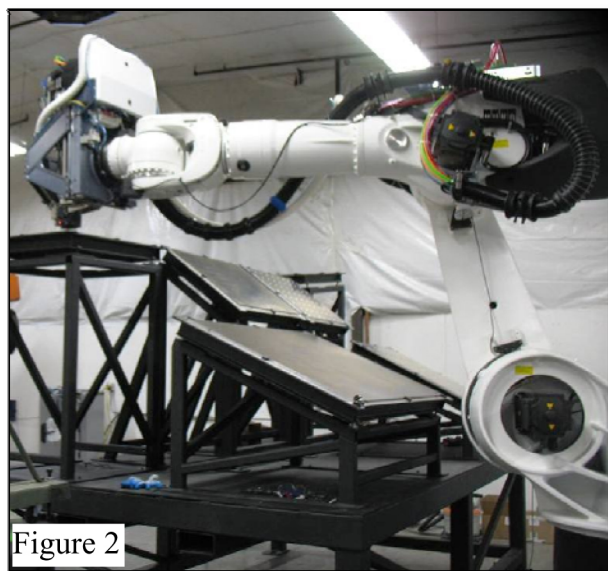


Figure 2.

## 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  $\pm 0.25$  mm within the working envelope, 3-dimensional off part accuracy was validated. The working volume on the upper surface per robot was approximately  $3090 \times 820 \times 1410$  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  $\pm 0.12$  mm (figure 3). Lower surface work consumed a slightly smaller volume at  $2500 \times 850 \times 1900$  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  $\pm 0.16$  mm (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).

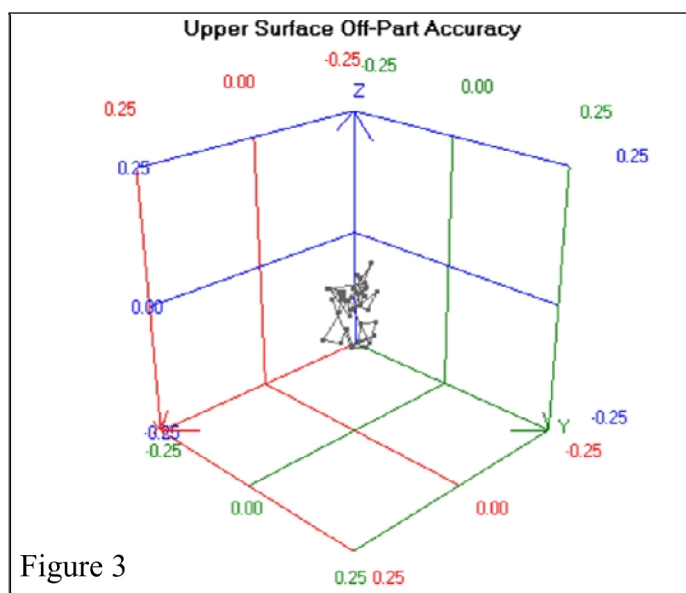


Figure 3.