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Expanding the Use of Robotics in Airframe Assembly Via Accurate Robot Technology

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ABSTRACT

Serial link articulated robots applied in aerospace assembly have largely been limited in scope by deficiencies in positional accuracy. The majority of aerospace applications require tolerances of +/-0.25mm or less which have historically been far beyond reach of the conventional off-the-shelf robot. The recent development of the accurate robot technology represents a paradigm shift for the use of articulated robotics in airframe assembly. With the addition of secondary feedback, high-order kinematic model, and a fully integrated conventional CNC control, robotic technology can now compete on a performance level with customized high precision motion platforms. As a result, the articulated arm can be applied to a much broader range of assembly applications that were once limited to custom machines, including one-up assembly, two-sided drilling and fastening, material removal, and automated fiber placement.

INTRODUCTION

Assembly tolerances in aircraft structures have driven automation manufacturers to design custom, dedicated equipment that will meet accuracy requirements. Though successful, custom machines are relatively expensive, and for shorter term contracts, are difficult to justify as their scope is typically focused on a single application. Production implementations of articulated arm robots in aerospace have been active for many years with varying degrees of success. Interest in them derives from their successful implementation in automotive manufacturing. Robots offer airframe manufacturers benefits in both cost and application flexibility. Because their mass is relatively low, foundation requirements are minimal and often systems can be installed on top of existing slabs. The articulated arm spans a large working envelope capable of navigating along highly curved surfaces and into tight spaces. Because robots are produced in high volume their cost is low and reliability is high compared to customized positioners. Within the last 10 years, significant mechanical and control improvements have made robots a viable option for mid-range assembly tolerances (+/-0.75mm).

Manufacturers commonly give 1/3rd of the overall assembly tolerance to automation systems, and in most cases this overall tolerance is less than +/-0.75mm, requiring the automation accuracy to be +/-0.25mm or better. Existing technologies are available for global accuracy improvement to this level. These include real-time guidance via metrology (laser tracker, indoor gps, camera systems), directly teaching positions, etc. Design changes and variants are common in aircraft structures and the location of assemblies within the automation cells are typically not tightly controlled. Manufacturers therefore require the ability to program systems offline, whereby teaching methods become obsolete as they are inherently time-consuming and unique. Guiding robots real-time via metrology has proven to greatly improve positional accuracy, however, the automation system must include expensive, sensitive equipment. External systems also tend to restrict the working range and suffer from line of sight issues. In some cases these technologies cannot be avoided (e.g. when required global accuracy is at or below 0.15mm), however it is desirable to have an inherently accurate standalone automation system wherever possible.

MAIN

As performance and control of tailored CNC systems are desired with the flexibility and low-cost that articulated robots offer, a combination of these technologies has been developed. The "Accurate Robot" system is controlled via industry standard Siemens 840Dsl CNC which handles all controls requirements and offers a familiar interface to programmers and operators. Drawing from common axis configuration in machine tool design, the robot arm was integrated by Electroimpact with secondary position sensors at the output of each axis (figure 1). Repeatability is significantly improved enabling the system to be calibrated to accuracies below +/-0.25mm over a large global volume. This patent pending system has broadened the range of applications for unguided industrial robots in the aerospace industry to include high-precision single and dual-sided drilling and fastening, accurate material removal (trimming, milling), and accurate robotic fiber placement.

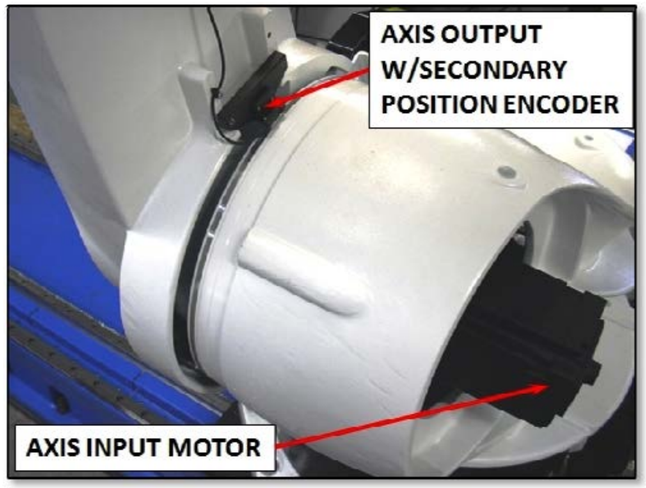

Figure 1. Robot axis with secondary encoder

Identification and Elimination of Inaccuracies

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 or on-path when loads are applied. For a drilling application, this would require the machine to position itself at the programmed hole location and remain stationary when pressure foot and drill thrust forces are applied. For path-related applications such as trimming or fiber placement, the system must be dynamically stable, remain on its programmed trajectory and resist forces induced from cutting, compaction, etc. (figures 2 and 3).

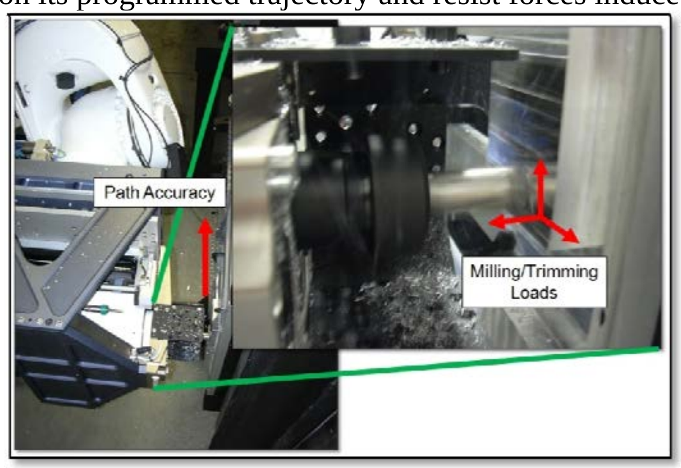

Figure 2. Robotic Milling/Trimming

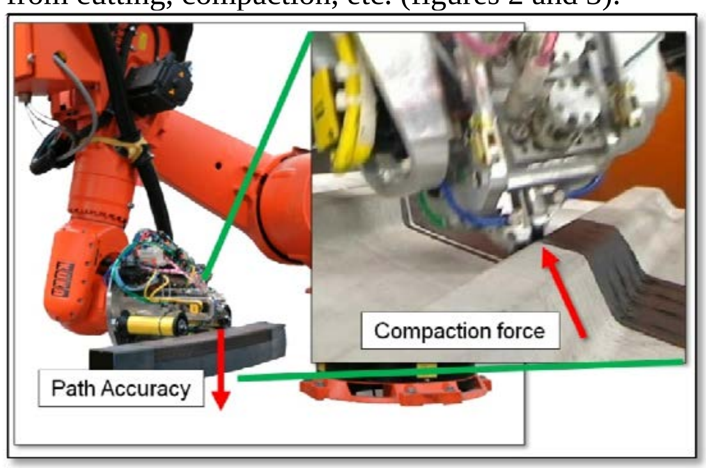

Figure 3. Robotic fiber placement

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 the majority of aerospace assembly tasks. With dual-sided processes such as bolt and collar installation, the problem is compounded as both systems must align well enough to reliably feed and install a collar on a pin. The error in alignment between heads can be as large as the sum of the accuracies of the two systems (figure 4).

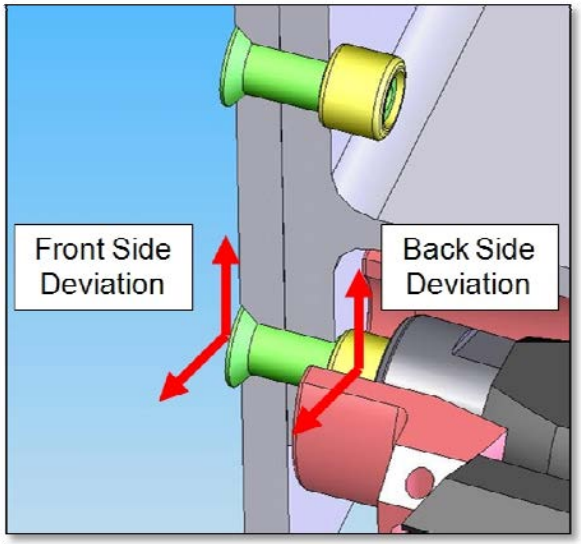

Figure 4. Dual-sided alignment

The tool center point TCP position is obtained by driving the robot axes to angular positions based on the kinematics of the arm. On a typical 3 meter robot, the standard model, which is based on nominal geometric dimensions, exhibits an accuracy of about +/- 2 to 4mm within its working volume. Because the physical robot never exactly matches a nominal model due to manufacturing and assembly variation, a unique kinematic parameter set can be developed to better describe individual arms. This unique model can include higher-order parameters that describe the effects on TCP position altered by the masses of the robot links and attached payloads as well as non-linear axis behavior. In practice, this has proven to achieve positional accuracies of nearly +/-0.5mm in a restricted range using a standard off-the-shelf robot system.

With any kinematic model, the output pose of the system is a function of its inputs. For a typical articulated arm, the inputs are the six robot joint angles. Therefore, any errors in joint angle are fed through the kinematics and yield error in the resulting TCP position. On a typical robot the position feedback for each axis is located at the servo motor. Ahead of the feedback are numerous sources of error such as backlash, wind up, and scaling. Although the uni-directional repeatability of robots is generally acceptable, omni-directional is more substantial. Testing of omni-directional repeatability using a 3m arm in typical working volumes has demonstrated magnitudes of up to 0.5mm. Poor repeatability is caused by uncertainty in joint position. Because the system's accuracy can only be as good as it's repeatability, the best a standard system could ever achieve in ideal conditions is 0.5mm. Therefore, fundamental to system accuracy is knowing the position of each axis.

The location of the axis feedback on a standard robot also limits the stiffness of the mechanical unit. Because the axis position is held at its input, compliance and backlash go unaccounted for. The result is poor joint stiffness which yields significant TCP deflection when loads are applied. Joint deflection results both from the masses of the links and from externally applied process forces. If not compensated, droop from the link masses and payload can exceed 3mm or more at the TCP. Additionally, relatively low forces (<200 kgf) applied at the TCP (as is common in drilling or cutting applications) can alter the position up to 2mm with the majority of this deflection coming directly from the joints.

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. Sensors are typically high resolution and exhibit high repeatability with little to no measureable hysteresis. Transferring this technology to an articulated robot yields much tighter control on axis position and, in turn, a system that can be calibrated to higher accuracy. Secondary encoders reduce omni-directional repeatability to nearly zero and has been validated via laser tracker while exploiting the combined effects from moving all axes, as would occur in normal operation. Results have shown a maximum deviation under 0.05mm at 3 meters. This is an improvement of 10x over a non-enhanced system. Removing slop in the joints has additional benefit when tailoring the enhanced kinematic chain as factors for joint compliance and backlash are eliminated and can be replaced by more descriptive parameters that were previously difficult to accurately solve for.

With the repeatability in check, a more representative kinematic model can be obtained. To do so requires an accurate metrology system (e.g. laser tracker). The end effector is fitted with at least three metrology targets, one in the tool point and the other two or more located on a rigid portion of the end effector. The robot is programmed to run through a set of unique random poses within the working range of the system. At each location, position data for each of the targets along with the robot axis positions are captured and used to solve for the kinematic parameters using common regression techniques. Data not used in calibration is collected at additional poses within the working volume to validate the system accuracy.

The next step in achieving accuracy on the work piece is to evaluate where the robot goes when an external load is applied. External loads are introduced in a variety of ways during assembly operations. When drilling and fastening single or dual-sided, clamp force is typically applied to stabilize the process, trimming and milling impart cutting loads, and fiber placement typically requires compaction force to properly adhere the material to a mold. Because the articulated arm lacks stiffness, deflection occurs when an external force is applied. As described earlier, given a normally-equipped robot the majority of this deflection occurs at the joint. Results from testing various articulated arms showed that the deflection at the joints make up 50-80% of the total TCP deviation. With secondary encoders at each axis, local joint error is negligible, however deflection still occurs in the links, bearings, base mounting plate, etc. Preferred is a platform that exhibits high stiffness so the level of compensation can remain low. Real-time compensation of external load deflection is accomplished by including a deflection model of the system in the kinematics combined with integrated load cells in the end effector.

<u>Case Study: On-Part Drilling Accuracy Comparison</u>

Accuracy has been analyzed between two similar robotic drilling systems. "System 1" (figure 5) comprises a drill head mated to a high-quality industrial robot, KUKA KR360-2, on a linear slide and is currently in production drilling and countersinking aircraft flaps to a required tolerance of +/-0.75mm. "System 2" comprises a drill head mated to an accurate robot, KUKA KR500/L340 with secondary feedback, also mounted on a linear slide. System 2 is designed to drill and countersink fuselage panels to a tolerance of +/-0.25mm. Both systems are mechanically very similar with a notable dissimilarity being that System 2 utilizes a 0.5 meter arm extension which should put it at a disadvantage when comparing end of arm accuracy. Each system was evaluated for both on and off part accuracy within their respective working volumes.

Figure 5. System 1 - Standard Robot

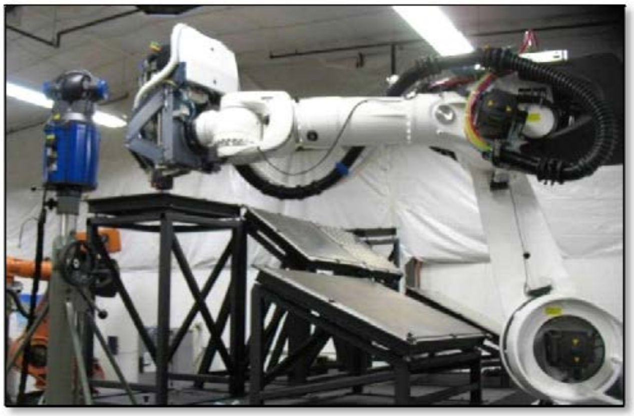

Figure 6. System 2 - Accurate Robot

Off part accuracy evaluation provides a good measure of the quality of the machine, repeatability, and kinematic model. Both systems were calibrated using high-order models and positional data was collected at each TCP using a FARO laser tracker. System 1 had a working volume of 4420 x 770 x 150 mm and was positioned within this volume at 23 locations that represented production poses. The resulting accuracy was +/-0.27mm reported in terms of "3-sigma" which is the average of the deviations between actual (measure with tracker) and nominal (programmed) plus 3 times the standard deviation of the sample. This provides a value with 99.7% confidence given the assumption that the data is of normal distribution. The working volume for System 2 was larger at 3090 x 820 x 1410 mm. Data was again collected at 42 production representative locations with a resulting accuracy of +/-0.12mm. This shows that even with a longer arm and larger volume, System 2 was over 2x more accurate.

On part accuracy was compared by analyzing patterns of holes drilled on representative work pieces. Measuring features placed on the work piece provides a good measure of what actually occurs during production. This demonstrates both the accuracy of the system and its static rigidity. For drilling systems, the radial deviation of the hole parallel to the surface is examined. As described earlier, robotic platforms deflect when externally loaded. For drilling systems this is commonly referred to as panel skid. Both systems in this study utilized anti-skid technology which actively counters movement based on real-time load cell feedback.

System 1 drilled a pattern of holes over an area of 3240 x 220 mm (0.71 square meters). The pattern contained 56 production representative locations and each feature was measured with a FARO laser tracker. Because the position in the surface normal direction is not controlled by the machine, accuracy is reported in two dimensions parallel to the surface. System 1 demonstrated a 3-sigma hole pattern accuracy of +/-0.45mm. System 2 drilled a pattern of 64 production representative locations in an area of 1400 x 840 mm (1.18 square meters). The resulting pattern accuracy was +/-0.08mm, conclusively demonstrating the improvement when using the accurate robot technology (figure 7).

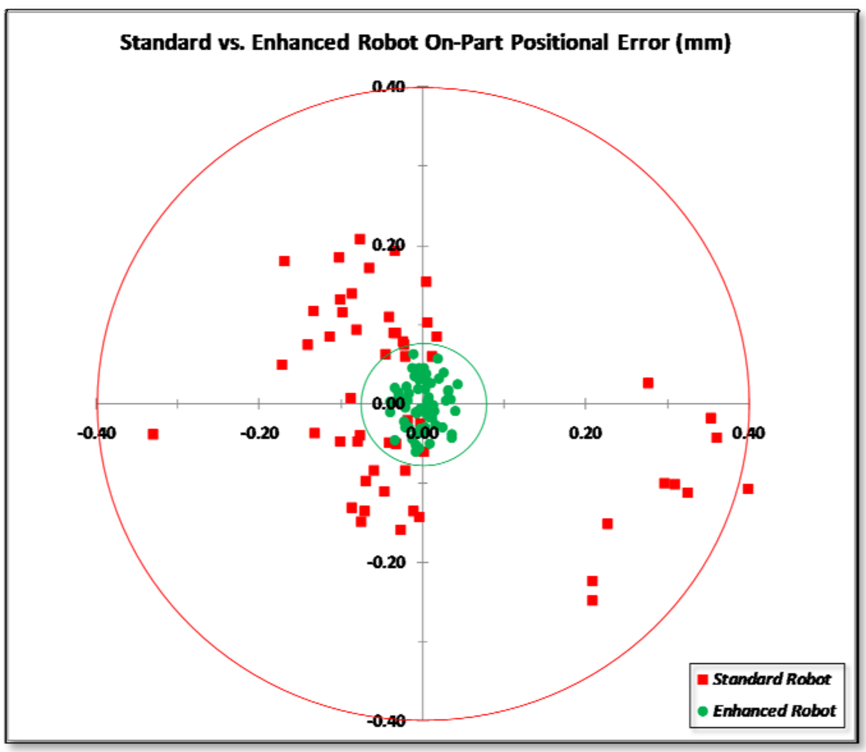

Figure 7. On-Part Accuracy Comparison

SUMMARY/CONCLUSIONS

Development of the accurate robot technology has greatly expanded the practical applications for articulated robots in airframe assembly both for point-to-point and path applications. 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 and high virtual stiffness. Global and on-part positioning below +/-0.25mm has been demonstrated using long reach, heavy payload articulated arms. Required additional hardware for enhancement is minimal, retaining cost competitiveness with standard robotic systems. Range and flexibility of the arm is not affected and because accuracy is achieved without guidance, no line of sight consideration is required. As a result, the articulated arm can be applied to a much broader range of assembly, including one-up assembly, two-sided drilling and fastening, material removal, and automated fiber placement.

REFERENCE

1. {Insert 1 reference per ordered list item.}

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ACKNOWLEDGMENTS

KUKA Robotics, www.kukarobotics.com

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DEFINITIONS/ABBREVIATIONS

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

APPENDIX