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One-Up Assembly with Robots

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ABSTRACT

Demand in Aerospace for assembly systems utilizing industrial robots is rapidly increasing. Robotic systems can often be implemented for smaller, labor intensive products where work is performed from a single side (e.g. close out of skins to spars/ribs). To justify the costs of automation and to maximize build efficiency, the industry is striving toward "one-up" assembly, whereby the product is assembled one time - drilled, inspected, and ultimately fastened - without removal of components for deburring, cleaning, sealing, etc. To qualify this for production on The Boeing Company's 787 moveable trailing edge (MTE) assemblies, the robotic systems required certain key capabilities to not only produce a quality process, but also verify quality via highly developed measurement systems.

INTRODUCTION

Globalization of aircraft production has spread the manufacture of aerospace component assemblies amongst many smaller aerospace suppliers. As these suppliers generally have much lower capital, justification for investment in factory automation is met with high performance expectations and low cost demands. As production rates increase, efficiency in layout and reduction of floor space is critical since these smaller tier suppliers generally have limited capacity. Manufacturing assemblies "one-up" eliminates not only a complete stage of the component's build, but also eliminates the needed floor space for it. Merging this with low-cost robotic automation makes for a particularly attractive solution with unique design challenges.

Hawker de Havilland, a Division of Boeing located in Melbourne Australia, is responsible for design, fabrication and assembly of the ailerons, flaps, spoilers and fairings which comprise the MTE control surfaces for the Boeing 787 Dreamliner. These assemblies are predominantly composite material and present challenges to conventional aerospace assembly methods in achieving the program goals for rate, quality and cost. During initial project planning and design, HdH

Figure 1

explored several approaches to assembly automation and decided to pursue a commercial robot assembly system with separate robots each equipped with a multiple function end effector. This approach was considered low risk compared to alternative machine configurations in part because HdH had extensive experience with a similar system, ONCE, in production drilling assembly holes on the F/A-18E/F trailing edge flaps (Ref. 1). The new 787 robot systems would be located in flexible cells which could handle several different assemblies. The overall system rate capability could be easily expanded by adding additional robots.

The project assembly plan developed by HdH would encompass several phases starting with a conventional drill, disassemble, clean and then reassembly with fastener installation. From this initial phase the process would progress to a final assembly plan where both outer skins would be installed permanently on the substructure before moving to the robot cells. The robot cell would then drill, countersink and install all the fasteners on both upper and lower skins for each assembly without any subsequent skin removal for cleaning or deburr thus achieving a one-up process after the initial fit-up. There are roughly 20,000 fasteners per shipset for these assemblies with projected production rates of up to 14 shipsets per month. Each of these ~280,000 holes each month must meet very strict standards for hole diameter, countersink diameter, location, fastener flushness, etc. To achieve this final goal of one-up assembly, individual manufacturing processes in the robot cell would need to provide predictive, high quality and repeatable results while minimizing direct intervention by the equipment operator.

HdH chose Electroimpact as the assembly system partner and, through a series of joint planning sessions, developed detailed requirements for the initial system tooling and assembly robots to drill the fastener holes (see Fig. 1). The primary robotic system requirements included automated vision scanning of tack fasteners and locating features, high speed spindles to drill and countersink in one step, a tool presetter to minimize errors in tool setup, automated tool change, and automated hole quality units to measure diameter, countersink and provide real time statistical process control. The system was also required to apply pressure from one side with automated normality correction and load control. Measurement of drilling thrust would provide additional process control options for monitoring tool wear. Finally, the system included space provisions and flexibility for adding future fastener installation modules to achieve the final one-up assembly goal.

MAIN SECTION

REQUIREMENTS FOR AUTOMATION

The turn-key automated assembly system consists of numerous sub-systems each vital to the end products' quality and build efficiency. There exist (5) main sub-systems; the positioning system, the process head, inspection systems, the machine programming system, and part fixturing and tooling systems. Discussion will be limited to the first (3) sub-systems.

Positioning System

The positioning system presents the process head to the work piece. It must do this accurately, efficiently, and reliably with little need for operator intervention and maintenance. Each automated assembly application presents unique design challenges and the positioning system is tailored to meet these. Particularly attractive for smaller assemblies is the articulated-arm industrial robot. As it is used primarily in the automotive sector, these systems are "mass" produced and have been consistently improved for high reliability and ease of use. Adapting articulated arm robots for assembly of aerospace structures can produce a lower cost automated system assuming the customer understands the limitations of the positioning system. As the industrial robot is tailored towards lower accuracy, repetitive work, there exist challenges and limitations when faced with high aerospace tolerances. The MTE assemblies for the 787 vary in size from roughly 10 to 35 feet long and up to 5-1/2 feet in height. To remain normal to the surface at all fastener locations and to avoid obstructions both via assembly components and tooling, a high degree of flexibility was required. An articulated arm mounted to a linear axis running the length of the part proved to be a very efficient approach. This solution was selected by Hawker De Havilland for the 787 MTE work package.

As delivered, the robot itself cannot position well enough to meet the tolerances required for the MTE assemblies. Add to this the errors introduced by the linear axis, the location of the assembly within its fixture, and the location of the parts within the assembly and very quickly system becomes ineffective. For these systems, however, the accuracy problem was addressed by combining (3) key technologies; accuracy compensation, automated vision, and automated normalization.

Some of the many sources of positional error include imperfect kinematic model of the robot, tool definition error, mounting skew, linear axis misalignment, thermal effects, payload deflections, working load deflections, as well as many others. Performing a system calibration using a metrology system reduces these errors to manageable levels. The positional data collected during the calibration is used to define a true kinematic model of the robot. The 6 DOF ideal transformations for the tool point and mounting skew are determined, and the misalignments in the linear axis are mathematically reduced. Deflections due to payload and working loads are predicted and compensated for by characterizing the stiffness of the arm. These enabling compensation methods yield machine accuracies that can work for many aerospace applications.

As compensation aids in achieving acceptable global accuracy, automated vision helps to align the machine to the work piece and establish a locally accurate system relative to the assembly. Because there is variation in the position of individual components held in the fixture, the alignment of assembly to robotic system changes from shipset to shipset. Using the automated vision camera system, the machine drives to nominal target locations on the fixture or work piece, captures a high-resolution digital image of the target, and determines the offset between the actual feature location and the nominal location. This is performed over a series of targets allowing for a best-fit corrected transformation to be established.

Once the machine is positioned at its target location, the hole and fastener typically must be placed normal to the surface. Differences between the CAD assembly model and the physical assembly as well as angular error within the robot system can lead to non-conforming fastener vectors. Because the curvature on most aerospace surfaces continuously changes as you move along it, it is necessary to locally sense the angle between the process head and the part surface. The signals from sensors integrated into the nose piece of the head are fed into the robot's controller. The controller then uses these values to automatically rotate the process head about the tool point to achieve a perpendicular orientation.

Process Head

The process head contains all the systems necessary to complete the preparation and, optionally, the installation of a fastener (e.g. drill spindle, hole measurement probe, vision system camera, etc.). For one-up assembly, the process must be accurate, clean, repeatable, and verified automatically. To eliminate the need to take the assembly apart to deburr and clean, there must be minimal exit burrs, fiber breakout, and interlaminar contamination. To then install a permanent fastener, the hole must be checked for correct size, the countersink must be verified, and the stack thickness must be determined. Additionally, the fastener must be pre-checked for proper grip length and post-checked for proper installation and head flushness.

To begin the process, pressure is applied to the part via the nose tip which is centered about the tool point of the end effector. Applying pressure serves to stabilize the system, provide an accurate reference for the location of the skin surface, enable automatic normalization, and serves to close gaps between skin and substructure components. The load applied is accurately obtained via closed-loop servo and load cell control. The desired load is determined by the NC programmer and is set to always be greater than the maximum expected drill thrust. Higher loads can be used in stiffer areas to ensure gap closure. Fundamental to the Electroimpact end effector is that the process tools are integral to the pressure axis. This results in the highest possible stability as process forces are resolved internally yielding no change in load to the part nor the robot arm during the entire process.

Once pressure is applied and automatic normalization is complete, the drilling and countersinking process is commenced. The drill spindle is designed to operate over a wide range of applications, from low rpm/high torque conditions to high speed (20,000 rpm) operation. The spindle is liquid-cooled for thermal stability which aids in maintaining tight depth control. Control of depth is further enhanced by the inclusion of high-resolution linear position feedback on the quill axis. To produce high quality and repeatable holes, each layer within a given stack is treated differently. As CFRP is efficiently drilled at high speeds and feeds, Ti requires significantly reduced parameters with the option of peck drilling for deeper stacks. Further, parameters are adjusted within layers to limit exit burrs and fiber breakout. Cutter geometry is tailored to reduce burrs and breakout, and the cutting material was developed for long life in CFRP. To ensure a consistent hole is being produced throughout the life of a tool, the drill thrust is monitored real-time. Data is collected, stored, and analyzed to track the condition of the cutter (see Fig. 2). Tools exceeding particular thresholds are removed from service to avoid risking poor hole quality.

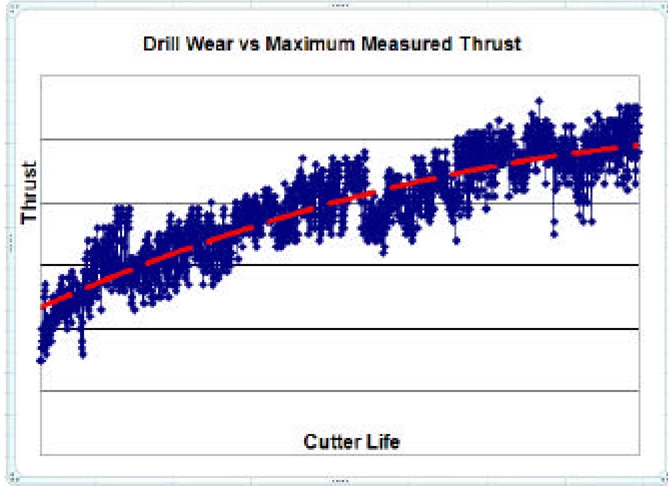

Figure 2

In-process inspection of the hole provides instant feedback that the system is carrying out a quality process. It significantly reduces overall inspection time, provided SPC data tagged to each location, and is essential for one-up fastener installation. The probe is mounted to the process tool table on the end effector and utilizes a 2-point split ball gage. The balls on the probe are extended outwards via light spring pressure and as the probe is plunged thru the hole, the balls collapse inward to ride along the inner surface. The balls are mechanically coupled to a linear shaft and movement of the shaft is precisely measured via a high-resolution linear encoder. Diametrical data is collected every 0.002" along the length of the hole and can be measured at 0 and 90 degrees. The result is a complete profile of the hole, less countersink, and the collected data is analyzed for consistent and in-tolerance values at any location within the hole (see Fig. 3). Using developed algorithms, the data is also used to report stack thickness and gap magnitude (if any). The stack thickness data determines the grip length of the fastener and because the thickness of CFRP is more variable than metallic materials, real-time measurement enables one-up fastener installation. 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 thru 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. Collected data for diameter, countersink depth, and stack thickness is stored and verified to be within process limits before proceeding further.

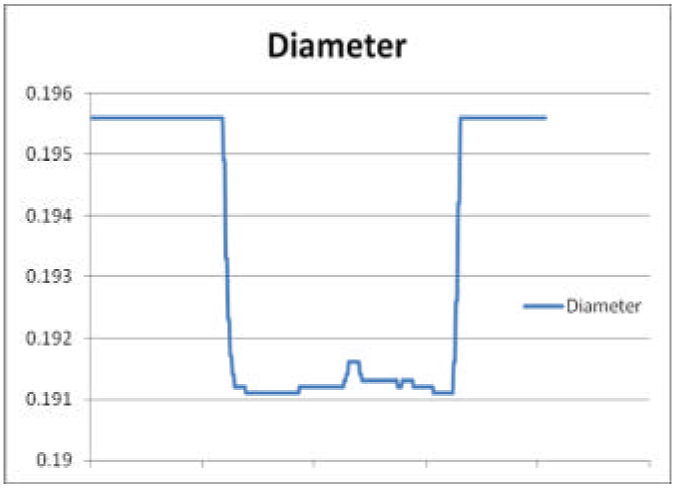

Figure 3

CONCLUSION

Results and Progress

Production results with the three initial robot systems provided automated recording of process results for hole diameter, countersink and thrust values for all the holes drilled. Evaluations of this data indicated good correlation to previous test data generated during preliminary and final acceptance testing of each system. Hole diameters were repeatable and produced Cpk values consistently above 1.5 indicating good process control. As a result it was decided to reduce the inspection frequency through random sampling with the control system constantly monitoring results and automatically providing random measurement per requirements of an approved procedure.

With processes repeatable and in control per initial goals of the assembly cell, the initial phase of one-up assembly has been implemented on the non-closeout skin on three of the four primary assemblies at HdH. This implementation required qualifying a special procedure to provide an exception to the process specifications which typically require disassembly and cleaning after drilling. The third phase with one-up assembly on both skins of an assembly is in planning for initial implementation later this year.

Development of fastener installation processes for the final phase of complete drill and fastener installation is in work. A testing robot system has been fitted with a blind fastener insertion module to provide drill, hole measurement, and fastener install functions. This unit is being used to finalize the total process and provide general risk reduction testing of preliminary hardware. The primary goal is to provide fastener installation processes with the same reliability demonstrated on production drilling.

REFERENCES

1. ONCE (ONe-sided Cell End effector) Robotic Drilling System. Russell DeVlieg, Kevin Sitton, Edward Feikert, John Inman. 2002 SAE Aerofast, Paper No. 2002-01-2626.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CFRP: Carbon fiber reinforced plastic (composite)

DOF: Degrees of freedom

HdH: Hawker De Havilland

MTE: Moveable trailing edge

ONCE: One-sided Cell End Effector

SPC: Statistical Process Control