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Robotic Trailing Edge Flap Drilling System

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ABSTRACT

The second generation of Electroimpact's ONCE robotic drilling system has been successfully deployed in production. The automated system for drilling and inspection of skins to substructure in trailing edge flaps comprises an off-the-shelf KUKA KR360 robot integrated with an Electroimpact process head, 7th axis linear rail, and roll-over assembly fixture. The process includes drilling up to 3/8" in diameter holes, countersinking, and inspection of CFRP/Al/Ti stacks using a 20k rpm, ATC spindle. Automated vision feature recognition and auto-normalization capabilities ensure proper hole vector and location with verification of diameter, countersink depth, stack thickness, and drill thrust being measured in-process. Tailored nose pieces enable access to nearly 100% of the structure with flood coolant, compliant tip, and vacuum swarf extraction capability.

INTRODUCTION

The Trailing Edge [flap] Drilling System (TEDS) is the second generation of the ONCE robotic drilling system [1] and is tailored to locate, drill, countersink, and measure skin to substructure fastener holes. Immediate production demands meant expedited delivery of the system was required and due in service roughly 5 months from date of purchase. To meet this need, the baseline system was based upon Electroimpact's latest robotic drilling technology designed for a commercial Boeing aircraft with nearly identical process requirements. As standard, the system comprises a rigid 7th axis rail, 6-axis articulated KUKA KR360 robot, and a multifunction end effector (MFEE). Unique to TEDS included custom nose pieces, high-torque tailored spindle tuning, vision and lighting customization, part sensing capabilities, and a complete roll-over product holding fixture. The MFEE provides a fixed platform with modular tools that can be configured for a variety of process functions. The end effector has evolved from years of aircraft production and development experience. The NC programming development, as well as cutter design and process validation, was led by Boeing Research and Technology, Boeing St. Louis. System capabilities include automated vision to locate specific product features, closed-loop one-sided clamping, auto-normalization, drilling and countersinking holes up to 0.375" in material stack combinations of aluminum, titanium, and/or composite, and inspection of hole diameter and countersink depth. A complete shipset contains over 2500 holes and the system is designed to produce each hole to a diameter tolerance of +/-0.04mm, a countersink depth tolerance of +/-0.05mm, and a normality tolerance of +/-0.5 degrees. The system entered production in April, 2009.

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MAIN SECTION

SYSTEM DESCRIPTION

The overall TEDS cell is the integration of (4) main subsystems; 1) the product holding fixture, 2) the positioning system, 3) the multi-function end effector, and 4) the cell control/operator interface. Specified for this system, the latter was developed by The Boeing Company and is proprietary.

Product Holding Fixture - The product comes into the TEDS cell fully assembled held together with accurately located tack fasteners. Because the robot must access both sides of the part, the holding fixture is designed to rotate along a horizontal axis to present either side (Figure 1).

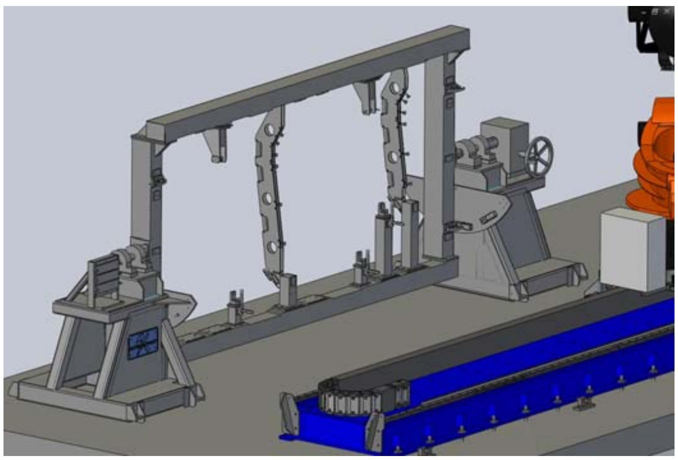

Figure 1. Rotating holding fixture

The basic layout of the fixture consists of the rotating picture frame held by two fixed piers. Actuation of the frame rotation is made via hand wheel and gearbox. Three indexed rotary positions are used to allow access to the upper and lower surfaces, plus the high-curvature leading edge. The frame is roughly located near the index, then manual shot pins are engaged to position it in a repeatable fashion. The product is located and held in the frame using two hinge indexes to set the position and two trailing edge clamps to clock it. Because the frame must accept a R/H and L/H part, the hinge indexes and trailing edge clamps are manually mirrored within the frame. Opposite the working side, a set of upper or lower rigid contour boards are attached to the frame which contact and match the shape of the product to provide backup support to react the majority of the clamp load during the drilling process.

Positioning System - The positioning system presents the process head to the work piece. For TEDS, the primary positioner is a 6-axis articulated KUKA KR360 robot. To expand the working volume of the robot, it is mounted to a rigid servo-controlled linear axis (Figure 2). Because robots are used primarily in the automotive and packaging industries, 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 tends to produce a lower cost automated system assuming the customer understands its limitations. As delivered, the robot cannot position well enough to meet the tolerances required for the trailing edge flap (TEF) assembly. Some of the many sources of positional error include an

Figure 2. Positioning system - robot and track

imperfect kinematic model of the robot, tool center point (TCP) definition error, mounting skew, linear axis misalignment, etc. A system calibration via metrology system is required to best describe the true kinematic model of the robot and ideal 6 DOF transformations for the tool point and mounting skew. Determination of the track-induced error is also accomplished via metrology. Resulting accuracy is on the order of +/-0.5mm.

Multi-Function End Effector - All process functions are carried out by a single multi-function end effector (Figure 3). The TEDS process required systems for providing one-sided pressure to the work piece, auto-normalization, flood coolant delivery and vacuum extraction, automated vision, precision drilling and countersinking, and hole inspection. The MFEE is controlled via Fanuc CNC which handles all the logic, I/O, and servo controls. All process tools (spindle, probe, 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 then mounted to a closed-loop (around load) servo-controlled "clamp" axis. Each system provides specific functionality:

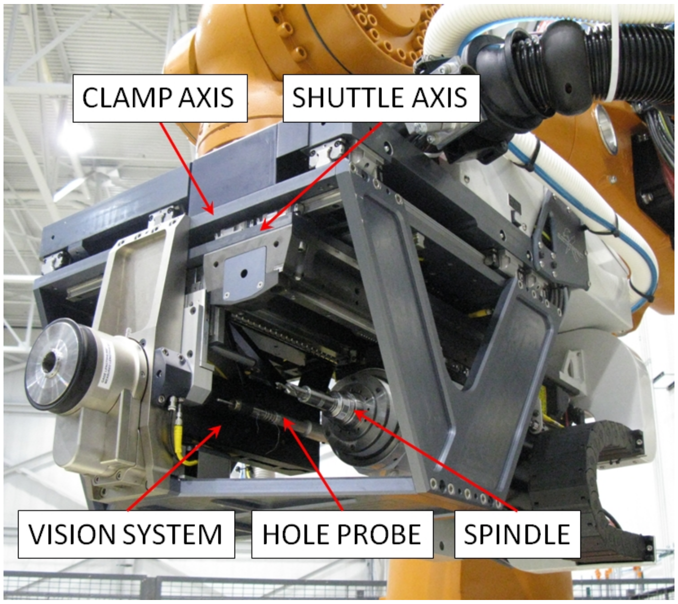

Figure 3. Multi-function end effector

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

Shuttle Table - The shuttle table serves to accurately present each process tool to the nosepiece. The shuttle table is linearly actuated via servomotor 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 TEDS application uses a 4-position shuttle table for the (3) process tools plus a spare slot for additional future process capability.

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, which is what makes the physical contact between the end effector and the work piece. The force sensing load cell is also housed in the pressure foot directly behind the nose piece. The cell provides force feedback to the CNC, which is used to control the applied pressure from the clamp axis.

Nosepieces - Large hinge and actuator fittings required the design of three (3) unique nose pieces. For the majority of the holes, a fully functional "standard" nose piece is used which is the shortest of the lot and can provide all the functions desired, including auto-normalization. To get around the fittings on the product, very narrow and extended length nose pieces were required (Figure 4) which necessitated the elimination of the normality function. All other capabilities remained. Each nosepiece is fitted with a spherically compliant tip, coolant delivery, vacuum recovery, chip blast, 5-bit identification, and a damage preventing breakaway system. Attachment of the nose piece to the pressure foot is made via rotary quick-connect.

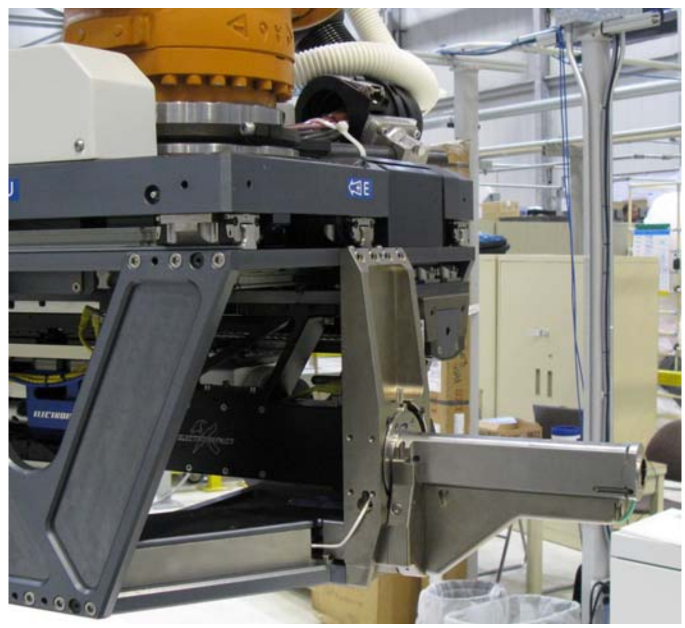

Figure 4. Special long nose with compliant tip, flood coolant delivery, and vacuum extraction

PRODUCTION PROCESS

The product, when presented to the automation, is a tacked, closed structure comprised of skins, ribs, and spars. Stacks are any combination of carbon fiber-reinforced plastic (CFRP), aluminum, and/or titanium. Holes are placed on both upper and lower surfaces, including the high-curvature leading edge (Figure 5) and adjacent to actuator and hinge fittings.

Figure 5. [1] High-curvature leading edge showing tack fasteners and drilled hole patterns

A typical process begins with automatic location of tack fasteners, or "scanning". The actual position of the features are used to shift the programmed points accordingly to wash out any assembly variation and maintain proper edge distance. Using the automated vision camera system, the machine drives to nominal tack locations on the product, captures a high-resolution digital image of the tack head, and determines the offset between the actual feature location and the nominal location.

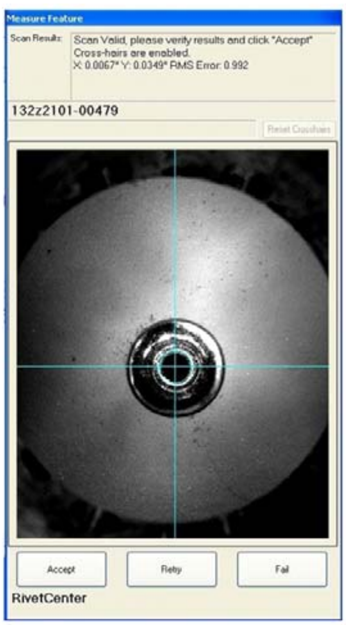

Figure 6. Image captured and recognized by automated vision system.

This is performed over a series of tacks allowing for a best-fit transformation to be established. A custom light ring was designed to illuminate the field of view from a fairly large distance from the product due to the significant protrusion of the hinge fittings. To ensure no affect on exposure or shadowing from ambient light, 21 high-intensity LEDs were used and sent thru a mild diffuser. The camera itself is mounted on the process tool table and is presented to the TCP for image acquisition. This minimizes errors typically observed with offset camera systems since the TCP is located along the fastener vector while acquiring the image. Once acquired, the target feature is recognized using Cognex Vision Pro software and an offset is returned from spindle center. The image along with graphics to indicate feature recognition are displayed on the operator console for reference. Should the feature fail recognition (damaged head most typical cause), the image along with a set of crosshairs is displayed for the operator to perform a manual alignment (Figure 6).

Following the scanning process, the system begins its execution of the drilling and inspection processes. At each hole 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 along the fastener vector 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 is controlled closed-loop around the sensors to normalize the end effector. Synchronously, translations along the panel surface due to the deflection of the robot arm from the applied clamp load (a.k.a. "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 1-3 seconds depending upon the rigidity of the product structure.

Once clamping is complete, the drill process begins. Occasionally in certain areas (high-curvature, flexible, etc.) it is desired to measure the exact pierce point of the surface relative to the nose tip to retain high countersink accuracy. In this case, the spindle is used to "touch off" on the panel with the drill tip prior to drilling the hole. As drill thrust is continuously monitored, the feed position at which contact between the tip and panel is made can be accurately sensed. This process is optional and is usually left out in favor of going straight into the drilling cycle. At the start of drilling, a stream of flood coolant is applied to the pierce point at a rate of roughly 0.5 l/min. The coolant 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 (Figure 7).

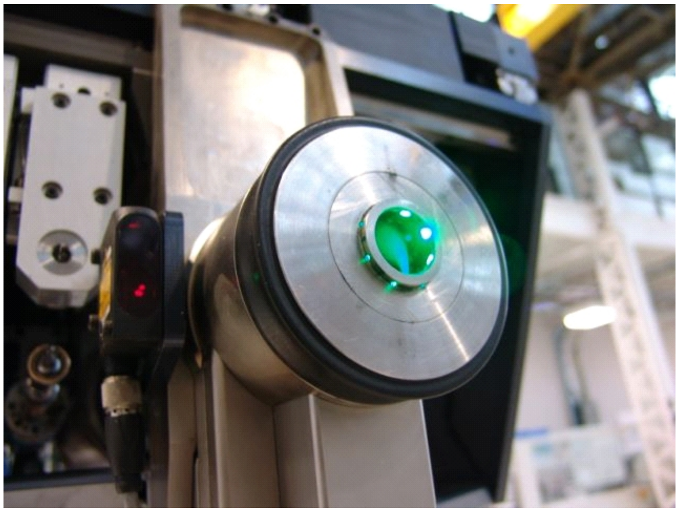
Figure 7. Auto-normalizing nose piece with integral flood coolant delivery with vacuum extraction

All swarf is collected via integrated vacuum system, and the coolant is filtered and recirculated. The TEDS spindle 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. Dual tuning parameter sets are used based upon operating rpm to optimize the spindle performance to low speed, high-torque (Ti) or for high-speed operation (CFRP and Al). Because the required feeds and speeds vary dramatically between stack materials, the spindle is programmed to use specified parameters based upon its position within the stack. Titanium requires the option of peck drilling for deeper stacks. Further, parameters are adjusted within layers to limit exit burrs and fiber breakout. Hole diameters are held within +/-0.04mm. Once the hole has been drilled thru, the spindle is rapidly fed to the start of the countersink and a new set of parameters are used to finish out the hole. Countersink depth is held to +/-0.05mm. Drill thrust is monitored during the entire cycle and is used for tool wear tracking and broken bit detection.

Inspection of the hole is optional, generally frequency-based, and performed in-process while still under clamp load immediately following the drill cycle. In-process inspection of the hole provides instant 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 process tool (shuttle) table. Fundamentally, the probing system utilizes a standard 2-point split ball gauge. 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. These are mechanically coupled to a linear shaft and movement of the shaft is precisely measured via high-resolution linear encoder. The repeatability of the diameter measurement is +/-0.005mm. 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 requested location within the stack (Figure 8).

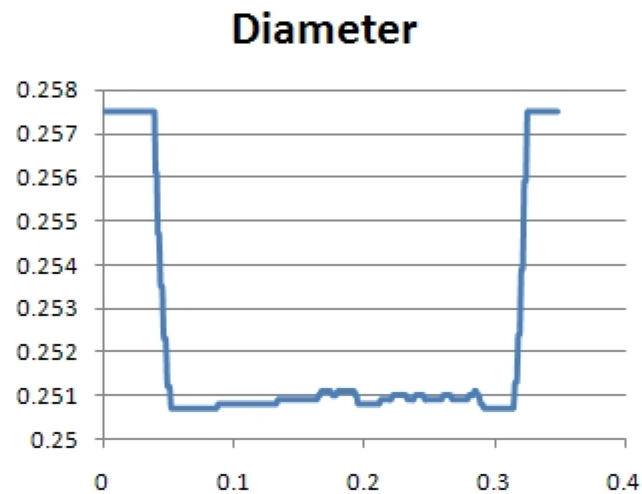

Figure 8. [2] Hole profile results using automated probe

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, with repeatability at 0.013mm. Auto-calibration of the probe is performed prior to each probe cycle and is carried out simultaneously with the drill cycle to eliminate any time penalty. Collected data for diameter and countersink depth is immediately and automatically verified to be within process limits and stored to a database before proceeding further. Should the data indicate limits have been exceeded, the system is halted and the operator alerted.

The various cutting tools used by TEDS are uniquely identified with a 2D barcode. Setup and measurement of each tool is handled offline with ID-tagged data collected in a database. Prior to installation into the spindle, the tool is scanned which makes all the measured data available to the machine. 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 automatically perform a drilling cycle at the coupon test stand, which is located on one of the fixture piers. At the coupon, the system will drill, countersink, and measure a single hole and display the measured results to the operator for verification and/or adjustment. Once an acceptable hole has been placed in the coupon, the system is then allowed to work on the product.

CONCLUSION

Automated assembly of aerospace structures using robotic positioning systems can be an ideal, cost effective solution given the appropriate application. For the TEF, all requirements were met and has resulted in much improved throughput, reduced manufacturing personnel, and much higher quality versus manual techniques. The inherent flexibility of the articulated positioner along with the capabilities of the multi-function end effector make it also possible to expand the applications within the cell to allow manufacture of additional products.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CFRP: Carbon fiber-reinforced plastic

MFEE: Multi-function end effector

NC: Numerical control

TCP: Tool center point

TEDS: Trailing Edge (flap) Drilling System

TEF: Trailing edge flap