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ONCE (ONe-sided Cell End effector) Robotic Drilling System

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ABSTRACT

The ONCE robotic drilling system utilizes a mass produced, high capacity industrial robot as the motion platform for an automated drilling, countersinking, and hole inspection machine for the skin to substructure join on the F/A-18E/F Super Hornet wing trailing edge flaps (TEF). Historically, robots have lacked the accuracy, payload capacity, and stiffness required for aerospace drilling applications. Recent improvements in positional accuracy and payload capacity, along with position and stiffness compensation, have enabled the robot to become an effective motion platform. Coupled with a servo-controlled multifunction end effector (MFEE), hole locations have successfully been placed within the specification's +/-0.060" tolerance. The hole diameters and countersinks have proven to be very accurate, with countersink depth variation at 0.0025" worst case.

INTRODUCTION

The ONCE System was developed to drill, countersink, and measure fastener holes in the wing trailing edge flaps on the Boeing F/A-18E/F Super Hornet at Boeing/HdH (formerly ASTA Components) in Melbourne, Australia. The projected production rate is 8 flaps per month. Many systems were assessed for cost, functionality, risk and multiple system acquisition costs. The Electroimpact ONCE system was selected as the preferred system. The concept was to incorporate a multifunction end effector and an off the shelf industrial robot. 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 robot/MFEE system will drill, countersink and inspect the outer mold line holes of the targeted assemblies. The unique NC programming development, as well as cutter design and process validation, was led by Phantom Works, Boeing St. Louis.

System capabilities include scanning to locate part/structure with a resynchronization camera, one-sided clamping (pressure locally applied to work piece), drilling and countersinking holes from ϕ0.147" to ϕ0.375 in material stack combinations of aluminum, titanium, and composite, and multiple-depth hole measurement. Space is also available for adding a hi-lok or Jo-bolt insertion module.

The two main sub-systems, the robot and the MFEE, are controlled separately. A central cell controller PC is used to decode NC programs, control process sequencing, and track data such as cutter life and hole diameters. There exists multi-leveled compensation provided by all three system partners, Electroimpact, Boeing, and KUKA Robotics, to achieve the high hole location accuracy and quality standards demanded by the aerospace industry. Special drill and countersink cutters were developed for improved efficiency and life necessitated by the high amounts of composite and titanium in the work piece.

The combination of the robot, MFEE, fixture, controls, tooling, and compensation are all required in making the system successful. Each is detailed in the Main Section.

MAIN SECTION

THE SYSTEM

There were a multitude of design challenges faced with drilling and countersinking the F/A-18E/F Super Hornet TEF that shaped the design and selection of the system components, as well as the degree of accuracy improvement required. For example, the upper surface has roughly a 90-degree curve as you go from the leading to trailing edge. The hinge fittings protrude approximately 9.0 inches from the skin surface. Stacks in some regions of the flap are up to 1.0" thick titanium requiring a countersunk ϕ3/8" hole. With the design criteria and specification requirements in place, the following components were selected/designed to accomplish the task:

Robot

The robot selected for this application was the KUKA Robotics KR350/2 (figure 1) paired with the KL1500/2 linear unit. The KR350 is a 6-axis articulated arm industrial robot. The rated payload is 350 kg (770 lbs.) and is capable of moving at full speed (2 m/s) with max payload. Although the payload capacity is oversized for this application by a factor of 3, the higher payload capacity implies a stiffer robot. The maximum reach (to the mounting flange) is 2535mm (100 inches).

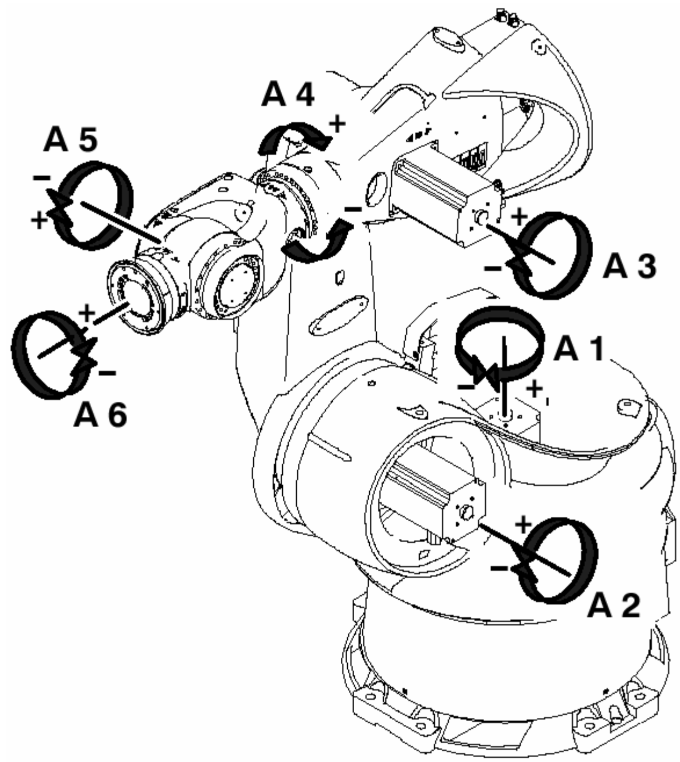


Figure 1. KUKA Robotics KR 350/2 Robot

All main structural members of the moving unit are made of cast aluminum alloy. Each member has been optimized for low weight and high rigidity. The result is a stiff robot with a high natural frequency that is resistant to vibration. The gears and joints are designed to minimize backlash and are lifetime lubricated (i.e. 20,000+ hours of operation). All axes are servomotor driven with resolver feedback.

The robot is equipped with a controller, whose power and control electronics are integrated into a common cabinet. Robot motion is programmed, calculated, and executed via PC inside the cabinet. The language used for motion and logic programming is KRL (KUKA robot language).

The repeatability of the robot is 0.006"-0.008". This was verified through several tests using a laser tracking system. Inherently, however, the articulated arm design is not accurate in the context of machine tools. To improve the out-of-the-box accuracy of the standard robot, the Absolute Accuracy Package was purchased. This package involves further mapping of the robot at the KUKA factory to develop a much more accurate kinematic model of the specific serial numbered robot as compared to the nominal model. Accuracy improvement is on the order of up to 5 times.

The KL1500/2 linear slide is an off-the-shelf unit from KUKA Robotics designed for use with the KR350 robot. The slide is mounted to the floor using concrete anchors with minimal concrete requirements (>B25 DIN 1045). The carriage rides on heavy-duty rollers along ground rails connected to the track. Power transmission is made through a reduction gearbox to a rack/pinion. The maximum rate of travel at full payload is 1.45 m/s.

Multifunction End Effector

The ONCE end effector is a lightweight, multifunction drilling and inspection tool head (see figures 2/3) designed for use with the KUKA KR350 6-axis robot. The basic platform of the end effector consists of the base that attaches to the robot, the clamp axis, the shuttle axis, the frame and pressure foot, the nosepiece(s), and the process tools. End effector motion is controlled by a Fanuc 18i series CNC. Each sub-assembly performs a unique task essential to the performance of the system:

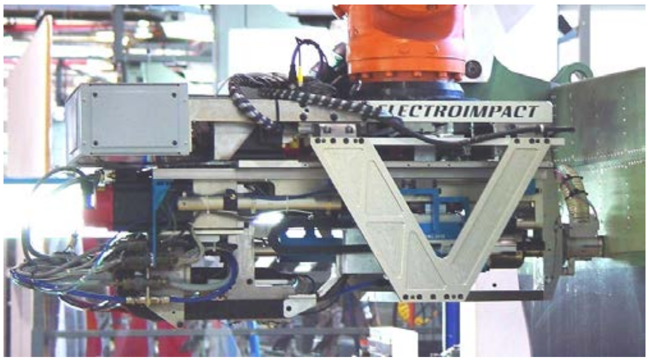


Figure 2. ONCE end effector

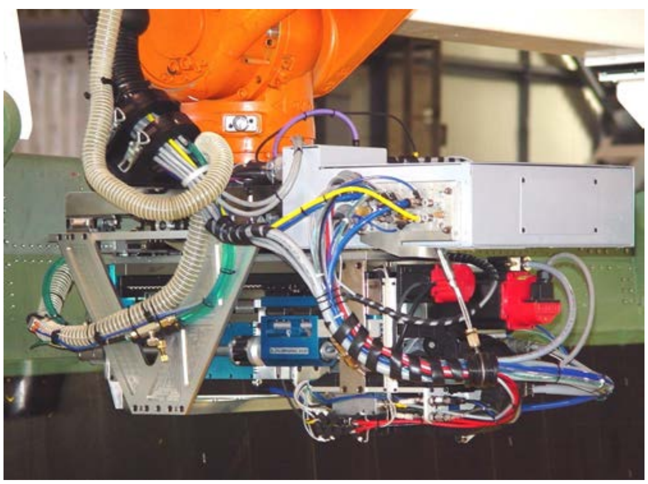


Figure 3. ONCE end effector

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. The clamp axis consists of two major components, the clamp drive and the clamp table. The clamp drive provides the linear motion for the clamp axis. It is servomotor driven through a timing belt assembly to a precision ball screw. The system has been designed to provide continuous pressure of 50 to 550 lbs. with +/-10 lb. accuracy. 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. All the process tools mount to the shuttle table. Similar to the clamp table, the shuttle table also consists of two major components, the shuttle drive system and the shuttle table. The shuttle drive system linearly actuates the shuttle table via servomotor, timing belt, and precision ball screw. 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 position of the shuttle table is closely measured using a linear glass scale encoder. The MFEE for this application used a 4-position shuttle table for the camera, spindle, hole probe, and a spare slot for a future pin insertion tool.

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 located between the pressure foot and the top of the frame. The cell provides force feedback to the CNC, which is used to control the applied pressure from the clamp axis.

Nosepieces

The large hinge fittings and actuator fitting on the TEF required the design of three (3) separate length nosepieces. Each nosepiece was fitted with a spherical compliant tip with the contact patch being of a high-friction material to limit skating. The attachment of the nosepieces is made by a quick-connect assembly to speed up the changing process. The military spec for drilling titanium and composite required that the part be flooded with coolant while drilling. The coolant keeps the titanium from heating and captures the composite dust. Each nosepiece is capable of spraying flood coolant and/or boelube mist at the panel. The coolant and swarf are carried via vacuum and air blast through a vacuum tube back to a collection tank. With the drill body enclosed by the nosepiece coupled with the vacuum and air blast, no mess is created - everything ends up in the collection tank. Figure 4 shows the longest of the three nosepiece assemblies.

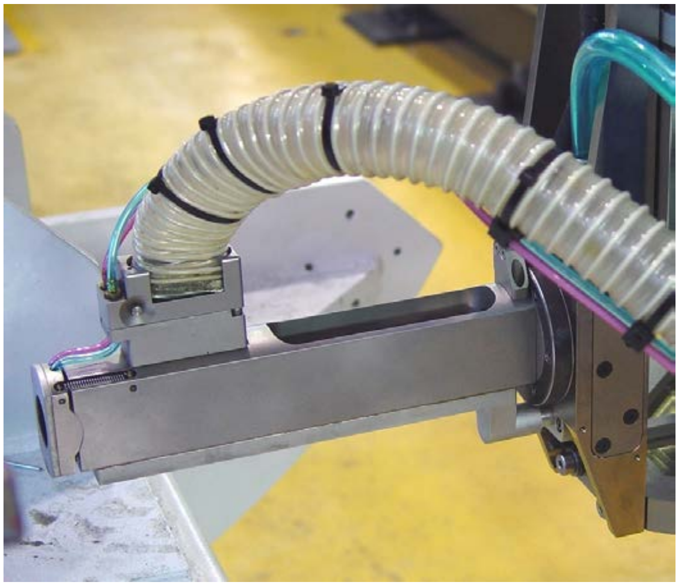


Figure 4. Long nosepiece

Process Tools

Resync Camera (figure 5): Due to the variability in the location of the substructure components in the TEF, the resync camera is used to visually scan the work piece to determine, and correct for, deviations between the nominal machine position and the desired position. It utilizes a 3-position air cylinder (for the three nosepiece lengths) to position a "lip-stick" camera to the work piece. An LED array is used to illuminate the local scanning area. The camera is equipped with a crosshair generator that is aligned to the spindle centerline.

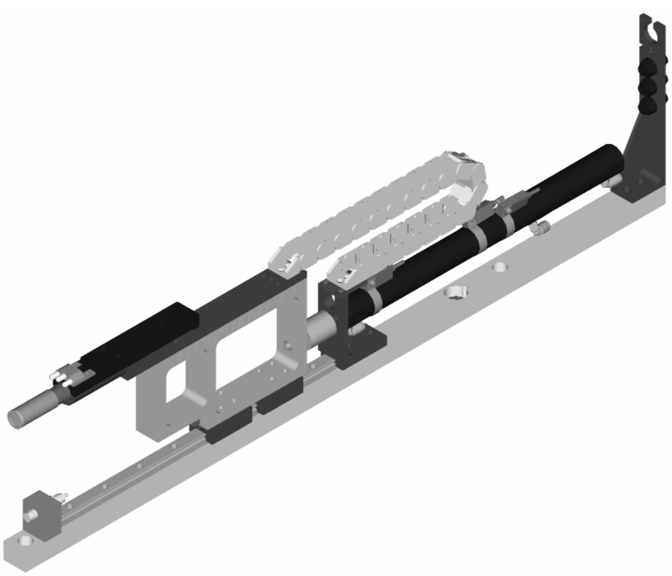


Figure 5. Resynchronization Camera

Drill Spindle (figure 6): The Electroimpact model 14 spindle is designed for high thrust and high torque for drilling and countersinking up to ϕ3/8" holes in titanium. The spindle motor is servo-driven and controlled via digital drive. The maximum continuous torque of the spindle is 150 in-lbs from 300 to 5000 rpm, with a maximum designed rotational speed of 6000 rpm for the aluminum and composite layers. The spindle can deliver a continuous feed thrust of up to 450 lbs.

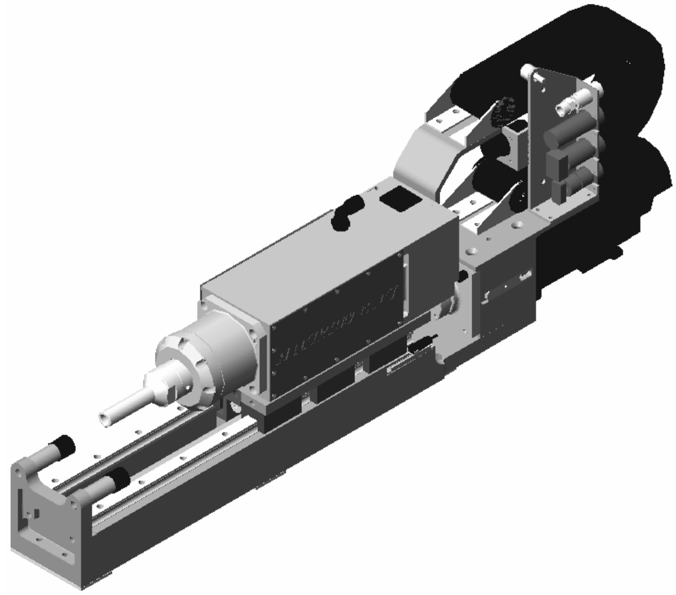


Figure 6. Model 14 Drill Spindle

Hole Probe (figure 7): The hole probe utilizes a 2-point ball contact gage coupled with an accurate LVDT (linear variable-differential transformer). The voltage signal from the LVDT is calibrated and converted to yield diametric measurements with an accuracy of +/-0.0002". The probe self-zeroes itself every cycle for improved accuracy. The measuring tip is fed via servomotor and can be positioned in multiple depths within the hole. A 90-degree rotary actuator is used to measure at 0 and 90 for each given hole depth.

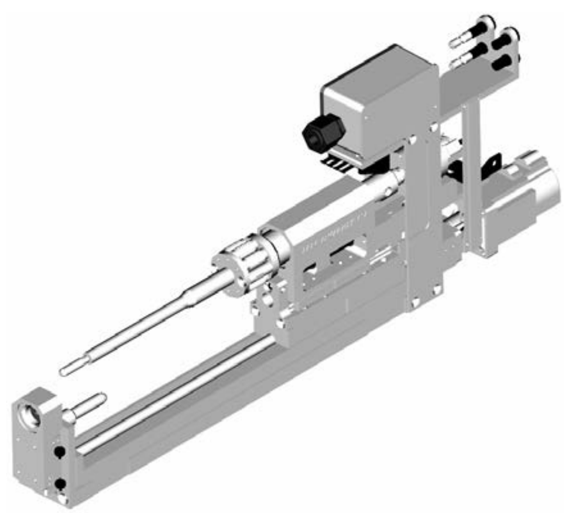
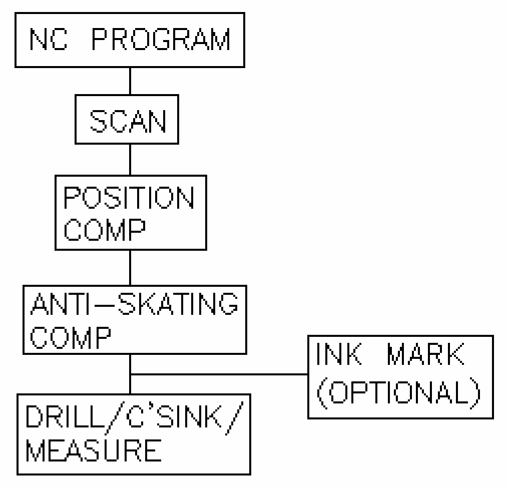


Figure 7. Hole Probe

PROCESS FLOW

The diagram below shows the basics of the TEF drilling process from start to completion:



The system process begins with the off-line generation of NC programs. The Cell Control executes NC programs that are generated with custom software built around IGRIP, a robotics simulation and off line programming software package available from Delmia Corp. The TEF is then loaded into the holding fixture.

Holding Fixture

The fixture consists of a "picture frame" rotisserie held by two large piers on either end (figure 8). Rotation of the frame is made by the manual rotation of a hand crank. There are three pinned angular positions for the frame enabling the machine to access all of the ~1400 locations. One of the two piers is on a sliding unit to add flexibility in the width of the frame for future applications. The drilling test coupon stand is positioned on the fixed pier.

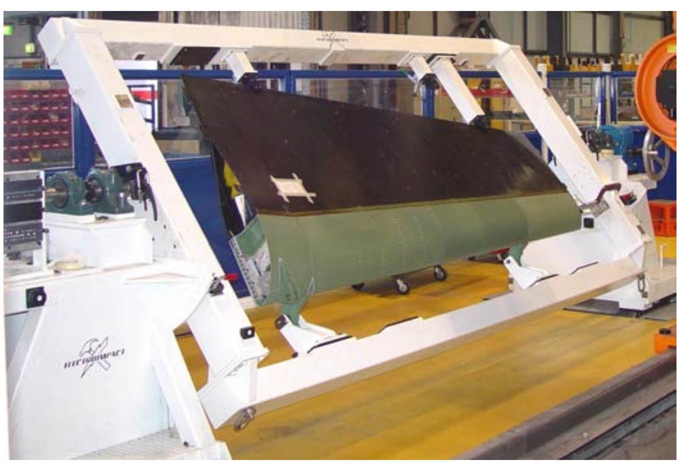


Figure 8. Holding Fixture

The program is executed and begins with a scanning sequence of the work piece.

Scanning (Resynching)

Predetermined, tightly controlled holes, edges, etc. are used for the visual scanning process. The machine drives to a nominal target position and the MFEE presents the resync camera. The camera display is superimposed with a crosshair and is viewed by the operator. If a deviation between the target and the crosshair exists, the operator jogs the machine parallel to the panel surface until the two are aligned. The actual position of the target is then captured and stored. Multiple target locations, as directed by the NC program, are used to shift the drill location to maintain critical hole to part relationships. Following the scan process, the operator can choose to start the program or ink mark the work piece in all or some of the locations.

Ink Marking

Ink marking is usually performed when a new NC program is being run, or if other factors that may contribute to variability are suspected. When ink marking, the system will perform every step short of drilling. The robot will move to its fully compensated position(s), the MFEE will clamp, and a special pen marking tool loaded into the drill spindle will feed forward and place an ink dot on the work piece (figure 9). This ink mark gives the precise location of where the part will be drilled. The positions of the marks are then measured to ensure proper location.

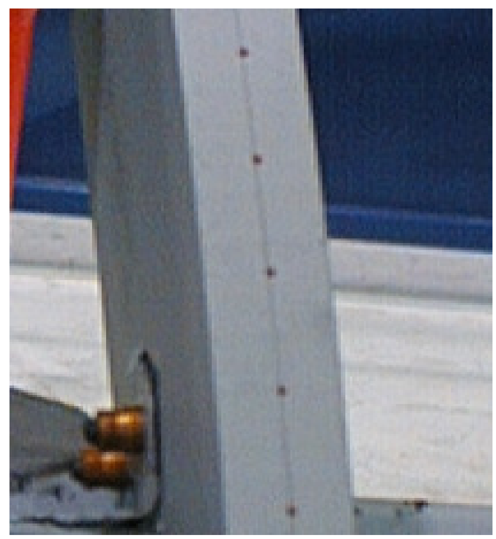


Figure 9. Ink marking

Test Coupon

At the start of a program, following a tool change, and/or after a change in the top stack material, a test hole is drilled in a coupon to verify proper hole size and countersink depth before moving on to the actual work piece. There exist 3 separate coupons, one of each material type (figure 10). The coupon material drilled will be the same as the next top material (usually the skin). The reason for this is because the drastically different material properties between the aluminum, titanium, and composite yield slightly varying countersinks. Should the countersink be off, the depth is adjusted and another hole is drilled and checked. When results are satisfactory, the machine will continue to the work piece.

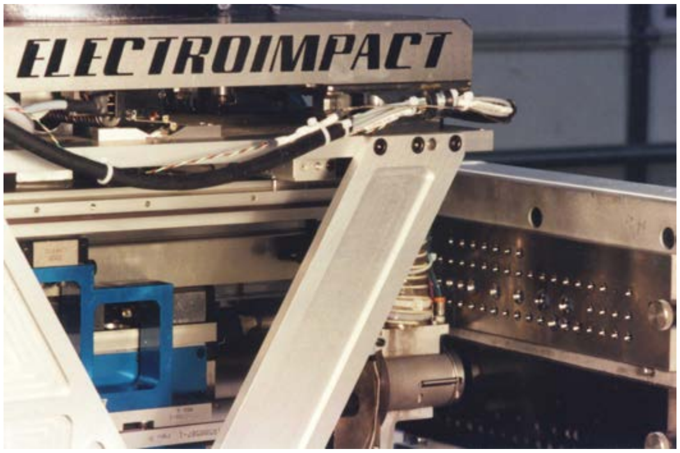


Figure 10. MFEE drilling test coupon

Drilling/Countersinking/Measuring

The standard hole tolerance for the TEF application is -0.000/+0.003" with a countersink depth accuracy sufficient to provide an installed fastener flushness of +0.001/-0.009. An Electroimpact patent pending panel touch-off process is used to achieve the high countersink depth accuracy. Following clamp up on the work piece, the spindle is fed forward until the panel is touched. When panel contact is made, the feed position of the spindle is captured yielding the exact position of the panel. This process eliminates the variability caused by clamping on swarf, clamping on slightly protruding tack fasteners, tool thermal growth, etc. The main requirement is that the clamp load be sufficient enough to remain in contact with the panel throughout the duration of the drilling process. Following the drilling operation, the hole probe tool is presented and measures the diameter of the hole at predefined depths set for each hole by the program parameters. Figures 11 and 12 show the system actively drilling and resulting finished panel.

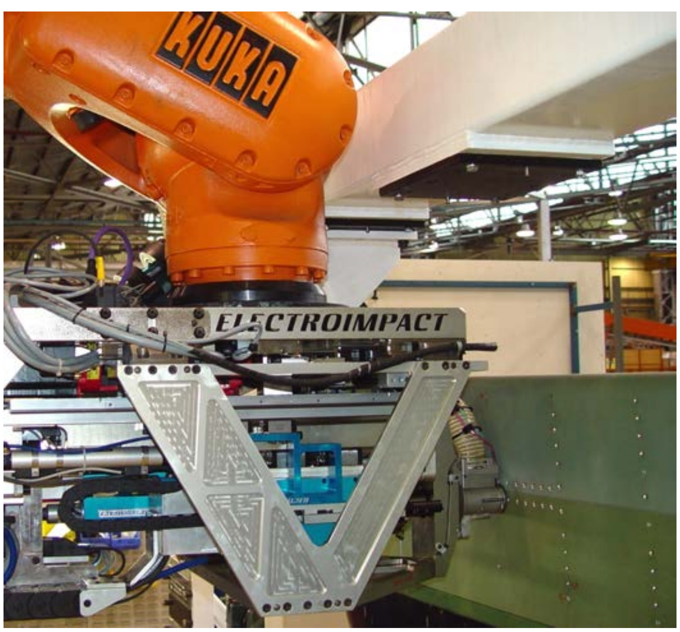


Figure 11. Drilling in process

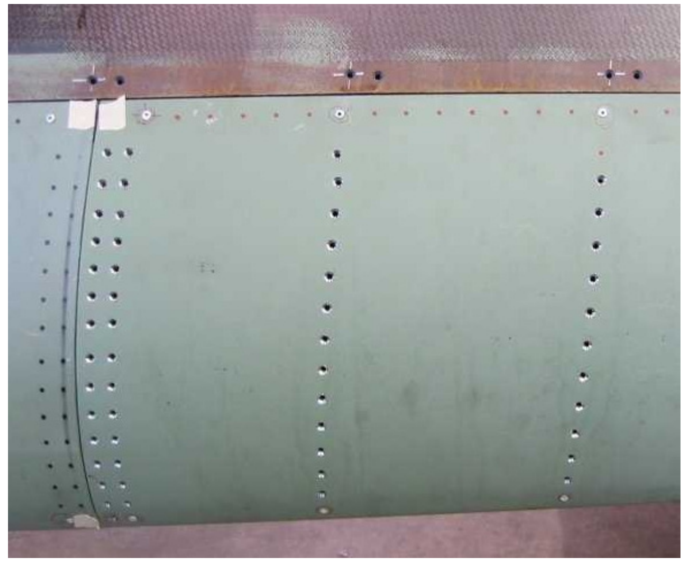


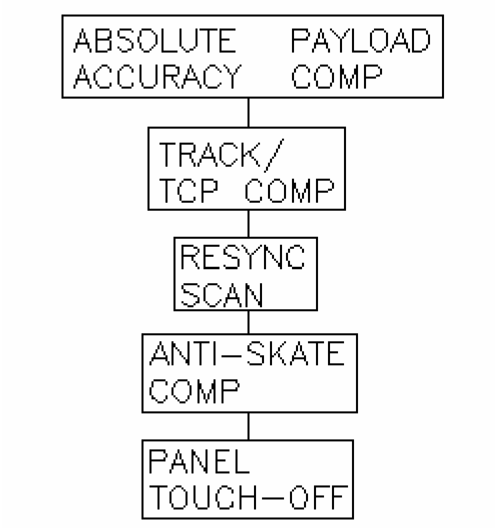
Figure 12. Upper leading edge holes

The drill/countersink bits are custom designed to optimize cutter efficiency and extend cutter life for this specific TEF application. The cost of cutters was one primary consideration in cutter design. Larger diameter holes use a tool configuration with separate replaceable countersink and drill cutter parts. The thinner aluminum structures required a one-piece combination drill countersink tool that provides a more stable cutting action. All the cutters can be re-sharpened up to five times before reaching the end of their useable life.

The actual cutter life can be difficult to predict when the structure includes different materials and covers a wide range of thickness. While cutter life is tracked by the cell control, the hole probe measurements provide the operator with constant hole quality data. Provisions in the cell control will allow increasing the tool life by as much as 50% on individual cutters to further maximize use.

COMPENSATION

The use of an articulated robot for performing machine tool-type applications has given rise to various complications, the largest of which being positional accuracy. Deviations result from the addition of inaccuracies during positioning the robot at the desired location and movement, or "skating" while panel contact pressure is established. A flow chart showing the levels of compensation used is shown below*:*



Unclamped Positional Accuracy

Positional accuracy is hindered by numerous factors: imperfect kinematic model, payload droop, misaligned robot mounting, uneven track rail, flawed TCP (tool center point) definition, imperfect gear ratios, backlash, etc. As mentioned above, the robot used for this system included an accuracy package that better defined the kinematic model of the robot. Further, the robot control also takes care of, to some degree of accuracy, deflections caused by the payload (in this case the MFEE).

The cell control software handles the remaining factors found to be primary contributors to inaccuracy. A best fit of the robot mounting and the spindle centerline TCP transforms are automatically calculated based upon laser tracker data as part of a calibration routine. The inaccuracies in the robot track are compensated using a six-degree of freedom transform that is a function of track position. Test results show that the compensated volumetric accuracy of the robot/track system is +/- 0.032" at a 99.7% confidence level.

Skating Reduction

Each axis position on the robot is measured at the back of the servomotor via a resolver unit. Consequently, any deflections forward of the feedback device (e.g. shaft torsion, belt stretch, etc.) are not accounted for. As static pressure is applied to the work piece, moments are created about each of the six (6) robot axes, the axes deflect slightly, and the result is movement, or skating, of the tool tip across the panel surface. The magnitude and direction of this skating is dependant upon the position of the robot and the applied force vector. At full clamp load, 400 lb., this skating can be as much as 0.070" - immediately throwing the machine position out of tolerance.

To prevent this problem, Electroimpact developed a patent pending anti-skating compensation. This process involves predicting the deflection of the robot, given the robot's position and the applied force vector, and compensating for this deflection in an equal and opposite manner. Compensation motion is triggered as panel contact is established. The result has been the reduction of skating by 80-100% in all positions regardless of panel to nose tip friction, robot orientation, and clamp load. Calculations are made on the fly and are completely transparent to the operator and programmer.

CONCLUSION

With the increased functionality available in today's off-the-shelf industrial robots, their use as a motion platform in the aerospace industry is fast becoming viable. Teamed with the multifunction end effector and software compensation, the system becomes a low cost, flexible, and very functional automation solution as proven by the ONCE system which is successfully in production.

ACKNOWLEDGMENTS

Electroimpact would like to acknowledge Boeing/HdH. Hawker de Havilland (formerly ASTA Components) designs and manufactures commercial and military aircraft aerostructure components. They make parts for Boeing aircraft, as well as for Lockheed Martin, Bombardier, and Airbus aircraft.

Electroimpact would also like to acknowledge Boeing Phantom Works in St. Louis.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CNC: Computer numerical control

KRL: KUKA robot language
LVDT: Linear variable-differential transformer
MFEE: Multifunction end effector
NC: Numerical control
ONCE: One-sided cell end effector
PC: Personal computer
TCP: Tool center point
TEF: Trailing edge flap