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Composite Automatic Wing Drilling Equipment (CAWDE)

Benjamen Hempstead, PE
Brent Thayer
Electroimpact, Inc

Stephen Williams
Airbus UK

ABSTRACT

A custom 5-axis machine tool is constructed to enable fully automated drilling and slave-bolt insertion of composite and metallic wingbox components for a new military transport aircraft. The machine tool can be transported to serve many assembly jigs within the cell. Several features enhance accuracy, capability, and operator safety.

INTRODUCTION

Figure 1 CAWDE Machine In-Jig

The CAWDE (Composite Automated Wing Drilling Equipment) is designed to produce holes for final fasteners in a wing box assembly jig. The wing box components include composite wing covers to be drilled and bolted to composite spar assemblies and metallic ribs. In addition, metallic components such as engine pylon reinforcings are drilled off by the machine.

The machine features include:

- Fully automatic CNC control and data collection
- 5-axis positioning within the entire wing skin envelope, 30m x 5m x 1m
- Machine transporter to move the machine from jig to jig
- Servomotor/ballscrew joint pressure from 900-9000N during drilling and fastening.
- Drilling and countersinking holes for 1/4” to 3/4” diameter bolts through multi material stacks of carbon fiber, aluminum, and titanium.
- Automated hole diameter measurement of 1/4” to 5/8” diameter holes.
- Automatic detection of manually installed slave bolts prior to drilling.
- Automatic insertion of 1/4” to 5/8” diameter slave dowels for temporary fastening during the build.
- Space on the process shuttle table for a future process tool.

The drilling process is supported by though-bit and external flood coolant systems and chip vacuum with coolant recovery.

The wing structure shape and component locations differ from the nominal CAD data due to thermal expansion, part manufacturing tolerances, and sub assembly tolerances. The machine is equipped with sensors and synchronization tools to help align the machine with varying geometry components. These include:

- Normality Sensors- Ball contact sensors track the surface of the wing skin and provide feedback so the machine’s CNC can position the head normal to the actual surface.
- Resync Camera- A video image is displayed for manual resynchronization
- Renishaw Touch Probe- A radio-frequency probe fits in the drill spindle. Software routines allow the

machine to find the center of holes, the z position of a pad, or the edge of a part with this tool.
- Thru Skin Sensor- magnets are placed in pre-drilled pilot holes in the wing structure behind the wing skin. This sensor looks through the wing skin and finds the center of the magnetic field.

MAJOR MACHINE COMPONENTS

The basic configuration of the machine is a traveling column post mill with a 5 axis head. The head provides gap-closing pressure and shuttles process tools to the toolpoint during drilling and fastening cycles. The machine travels the length of the wing assembly jig. The wing box is tooled in the jig with the forward spar and pylons located near the floor. After completing processing of one surface the machine is transported to the opposite surface of the wingbox.

The machine is discussed in 6 sections:

- X axis rails, drives, and bases
- Y axis column and A-B pivot
- Machine head and process tools
- Operator platform and console
- Controls and software
- Machine transportation and resynchronization

X AXIS RAILS, DRIVES, AND BASES

The machine travels on pairs of rails on beds installed below the factory floor. There are 2 wing jigs currently installed; each jig has a port and starboard fixture; in each fixture there is a machine line to process each surface, making 8 machine lines in the current installation. A third jig may be installed at a later date to accommodate production rate increases. Walk-on way covers cover the bed trenches, while a machine base spans the distance between rails. The way covers pass through the base of the machine on rollers, eliminating the need to use rollup canisters or spools carried with the machine. While the machine is not present on a line the floor presents no obstructions. Infill boards take the place of the machine way covers on lines where the machine is not currently running.

The rails are precision roller profile rail, with several runner blocks under the machine sled. The drive is via tandem servomotor with reduction gearboxes with pinions on helical rack to eliminate backlash in X. To enable high accuracy in X axis position, an optical linear tape scale in a sealing extruded housing is fitted to the master rail. Filtered purge air provides IP 64 protection for all optical scales. The X axis motors, gearboxes, scale readheads, and X axis cars all are mounted to a machine base on each line.

Each wing surface line has a set of rails and an X sled. To move the machine from line to line, a transporter lifts the entire machine off the base and moves it to the next line. Hydraulic over-center ball locking clamps and locating pins provide repeatable and secure connection to the base.

Figure 2 – X Axis Base with Waycover

Figure 3 – Flush Factory Floor – Machine Absent, Infill Boards Removed

Y AXIS COLUMN AND A-B PIVOT

The machine column extends from a rectangular base vertically, allowing 5 meter Y axis travel. The column is a steel weldment. Y axis rails are precision roller profile rail. The Y axis sled is positioned with a ballscrew and servomotor through a reduction gearbox. The screw has a 40 mm lead to enable fast traverse rates while keeping screw RPM low to prevent screw whip. The servomotor has an integral electric safety brake. A thrust bearing and air brake are fitted to the top of the screw, and the bottom end of the screw is supported with a radial bearing and a second air brake. Positioning feedback for the Y axis is via optical tape scale in a sealing extruded housing.

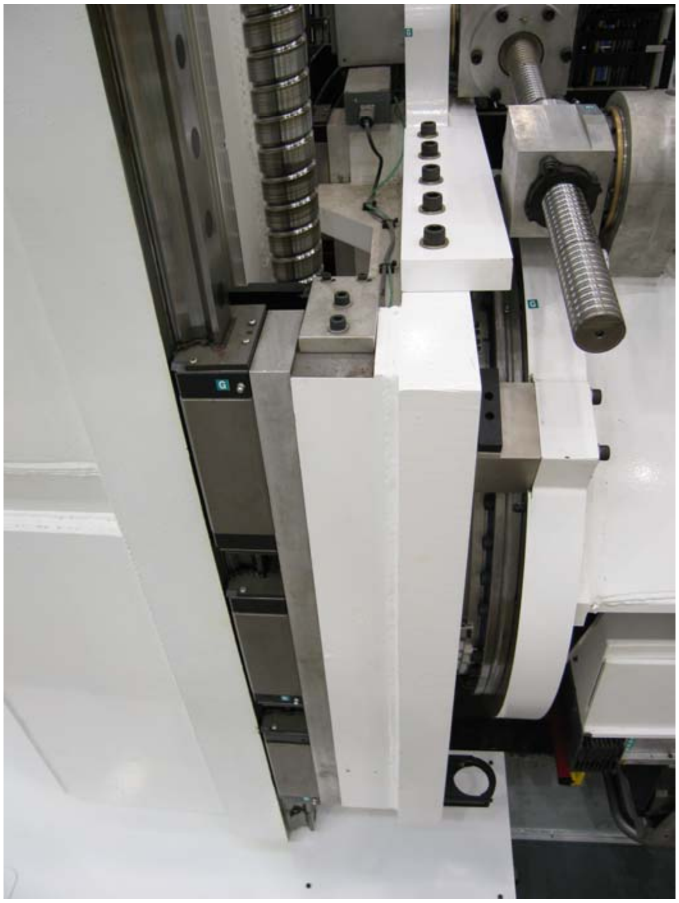

Figure 4 – Y Axis Sled

The Y axis sled joins together several runner blocks and the Y ballnut along with the scale readhead into a rigid assembly. To this sled is fitted an axial/radial rotary table bearing. This bearing has an axis parallel to X and provides a rotation in A, to handle chordwise curvature of the wing cover. The range of motion of A is 31 degrees, optimized for the total curvature of the cover envelope. The drive for A is via offset preloaded ballscrew and servomotor with reduction gearing. Feedback is via magnetic scale applied to the outside diameter of the bearing. A similar setup is employed for rotation in the B axis, around an axis parallel to Y. B axis rotation totals 12 degrees, corresponding to the span-wise curvature of the wing box. The A and B axis and drives are connected via a steel weldment called the A-B pivot.

Figure 5 – A-B Pivot

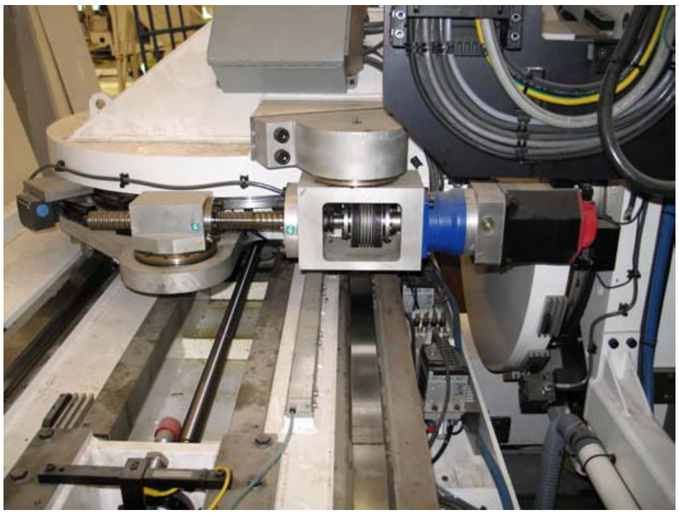

Figure 6 – Rotation Axis Drive

MACHINE HEAD AND PROCESS TOOLS

U Axis

The machine head hangs below the A-B pivot. The machine head consists of several process tools arranged on a steel weldment. The machine head contains a U axis, which at A=zero is parallel to the orthogonal Z axis. The U axis rotates with A and B and brings the pressure foot to bear on the cover surface, with 1 m of stroke. The thrust axis U of the head is just below the A bearing centerline. The U drive is a preloaded ballscrew with a servomotor and torque-limiting coupling. A loadcell is fitted to the ballnut on the screw, and provides force feedback to the CNC for applying pressure to the wing components. The torque coupling prevents overload to the drive or wingbox components in case of programming or operator error. The U axis rails are precision roller profile rail. Pneumatic-release safety brakes are employed on the U axis rails, clamping on the rails when the machine is in e-stop or in case of loss of air or CNC control.

Pressure Foot and Integrated Systems

On the front of the machine head, a deep pressure foot transfers pressure to the wing cover via a nosepiece. The large depth of the pressure foot allows the head to access the wing in proximity to skin straps and other obstructions on the wing surface. The nosepieces are quick-change and incorporate external flood coolant which sprays radially on the cutter to remove swarf. The nosepieces and pressure foot fully enclose the drilling operations. Swarf is evacuated via a vacuum system incorporating rigid pipe-work and a water separating canister. A resync camera is located below the toolpoint. A second camera looks into the nosepiece to provide a close-up view of the hole production and slaving process. Lighting and protection for the toolpoint camera are integrated in the pressure foot. Also integrated with the pressure foot is a Balluff chip reader which interrogates each toolholder while in the spindle. Data recorded on the chip include cutter setup information, feeds and speeds, number of holes drilled since change, etc. A proximity sensing cutter measuring device accurately confirms the length of cutters fitted while protecting delicate diamond and carbide cutter tips from impact damage. The ball-contact normality sensors are arrayed around the nosepiece, while the thru skin sensor is integrated in a slide mechanism above the toolpoint. A general view camera provides an overall look at the panel area surrounding the toolpoint in case of brackets, dowels, or other obstructions protruding from the wing surface. The thru skin sensor system is a machine adaptation of a commercially-available magnetic sensing array. It is deployed automatically when requested by part program, and allows the operator to locally resync on internal components to maintain edge margin without back drilling.

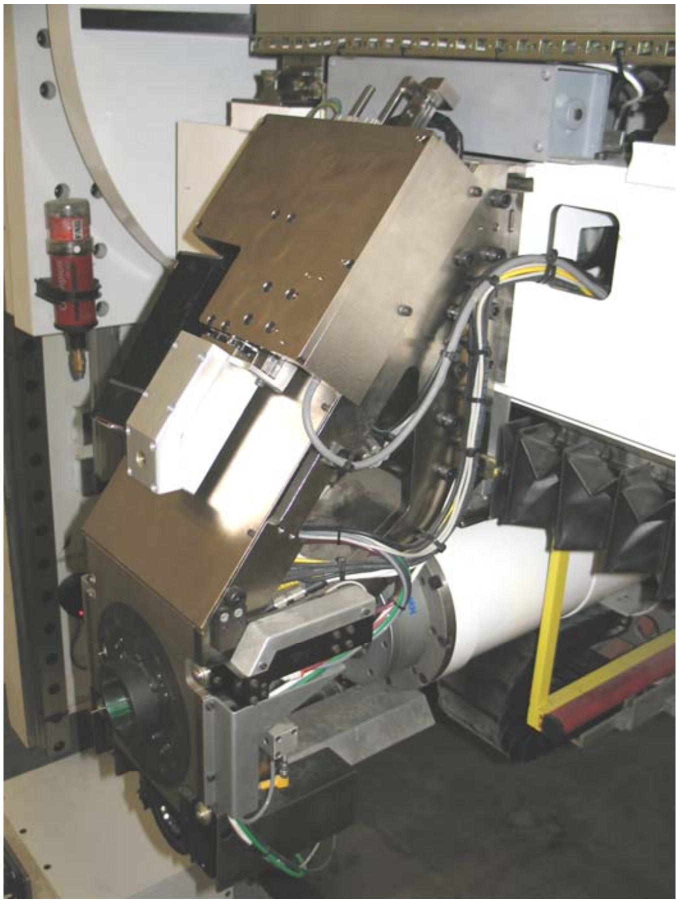

Figure 7 - Pressure Foot and Systems

Shuttle Table

On the underside of the head are several process tools used in the hole production process. The tools operate in turn as required by the CNC, and are shuttled to align with the nosepiece by a linear motor system. The linear motor enables very high repeatability and velocity of positioning, has low system inertia, and has very good mechanical packaging. Several linear ball profile rails support and guide the shuttling table and tools. Position and commutation is by glass scale feedback. Ball runner blocks with elastomeric ball separators are used to enhance service life, lubrication interval, smooth running, and reduce noise. Dowel pins in the table surface interface with bushings in the individual tool baseplates to assist in repeatable mounting following service. This general system has been in use in other wing production equipment for a decade.

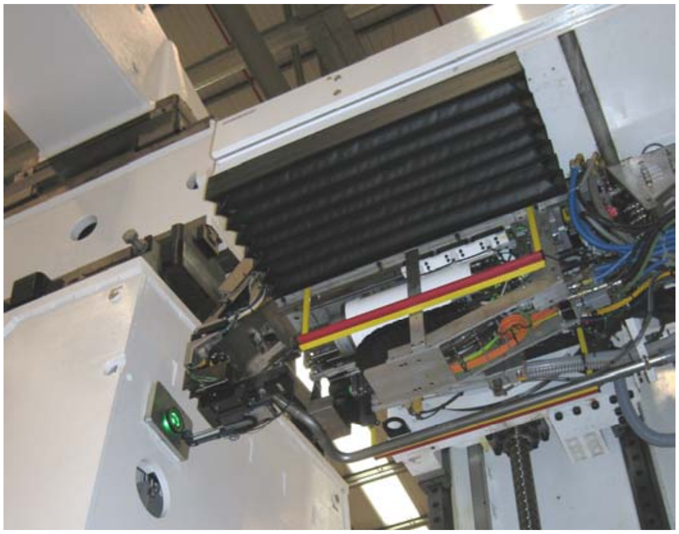

Figure 8 – Shuttle Table with Tools

Process Tools

The major tool on the shuttle table is a servo-servo drill spindle. The water-cooled GMN cartridge integrates an HSK63 toolholder with hydraulic drawbar and grease bearings. Spindle speeds range from 80-8000 RPM. Thru-bit flood coolant with air purge is supplied through the drawbar and rotary union. Servo feed of the spindle is via ballscrew with glass scale feedback and is guided on precision profile rails. The cartridge and feed system are easily removed from the machine for maintenance via quick disconnect services and dowel locators.

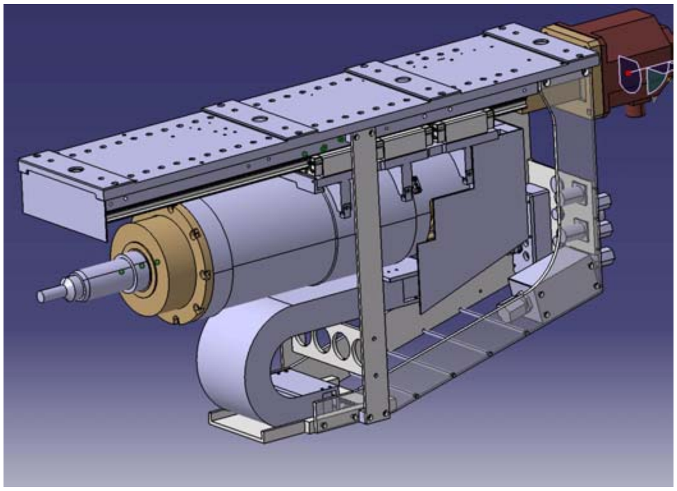

Figure 9 – Drill Spindle

Adjacent to the spindle on the shuttle table is a slave bolt detection tool. In case of manual slaving, the location of slaves may not be known to the machine. In areas suspected of using manual slaves, the slave detection tool is extended through the nosepiece prior to a drilling cycle. The tool employs a sensor to detect blank panel surfaces, empty drilled holes, or installed bolts. This detection allows the machine to alter the drill cycle as needed.

Next over is a hole diameter probe. Using mature 3-point gaging technology, this probe can measure diameter at many part-program specified depths in drilled holes, typically at each material or component layer in the stack. Hole probe data is recorded in an onboard Data Collection System in the machine control. Frequency of probing is program controlled. Probe tips are easily changed by the operator and have a large range so as to cover multiple hole nominal diameters.

For cycles requiring automatic slaving, a drop tube system prompts the operator for the grip to be dropped and feeds the fastener to a bolt insertion tool on the shuttle table. A small quantity of bolts can be pre-fed for immediate selection by the machine. The bolt inserter can, via a scale-reading air cylinder, confirm the expected length of the bolt and insertion depth in the panel. The tool can hold the bolt head while an operator manually runs a nut on the back side. Automatic ejection and refeeding is engaged in case of feed errors. The bolt feed tooling is quick-change and covers a range of ¼" to 5/8" diameters.

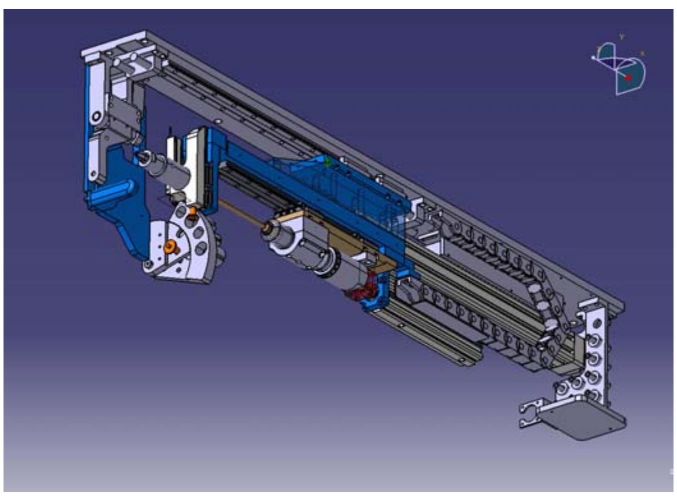

Figure 10 – Bolt Inserter

An extra space for a 5th process tool is provided on the shuttle table. This supports future development such as a sealant inserter to enable permanent fastener installation, etc.

Vacuum is supplied onboard the head via a regenerative blower pulling vacuum on a chamber enclosing the toolpoint. The coolant system provides underwater cutting of carbon materials to reduce airborne dust contamination risks. Effective cooling of carbide cutters processing titanium is also provided. Swarf is collected in an easily-emptied bucket with a chip basket for metallic swarf and a filter bag for carbon mud. Thru-bit and external coolant are both collected with very high efficiency. The coolant is filtered and recirculated through a reservoir system and back to the toolpoint and drill spindle.

OPERATOR PLATFORM AND CONSOLE

The operator has a ride-on platform to reduce fatigue. The platform is close to the toolpoint to enable good visibility of the machine operation. To minimize the machine envelope during transport, the platform folds up. A touchscreen HMI provides context-sensitive interaction with the control for the operator, reducing information overload. Additionally, pertinent CNC information such as toolpoint position, operator messaging, and part program viewing are displayed on a second LCD monitor. A third display shows the camera views. Software for the camera system displays all views in split screen or zooms to magnify the optical resync camera view to full screen for best resolution. Other features at the operator station include shadow boxes with space for all tooling that is changed out by diameter, and the fastener feed drop tubes. A hold-to-run pendant may be used to jog the machine and start/stop part programs.

Figure 11 – Operator Station

CONTROLS AND SOFTWARE

The machine control is a Fanuc 30i CNC. The HMI is a dedicated PC, and there is a PC for to support the Data Collection System (DCS) software. There is a touchscreen button panel with context-sensitive buttons for operator input/output. All pertinent information from the CNC is pulled out for display on a custom interface. Position, offsets, messages, and part program are all displayed simultaneously. Part program download is via a Tablet PC with a cradle integrated with the machine. Standard M and G codes are supported, along with custom codes specific to the machine architecture and capability. To enhance machine accuracy throughout the work envelope, software axis compensation is used to correct for gravity and process-induced deflections in machine components, and deviations in the foundation.

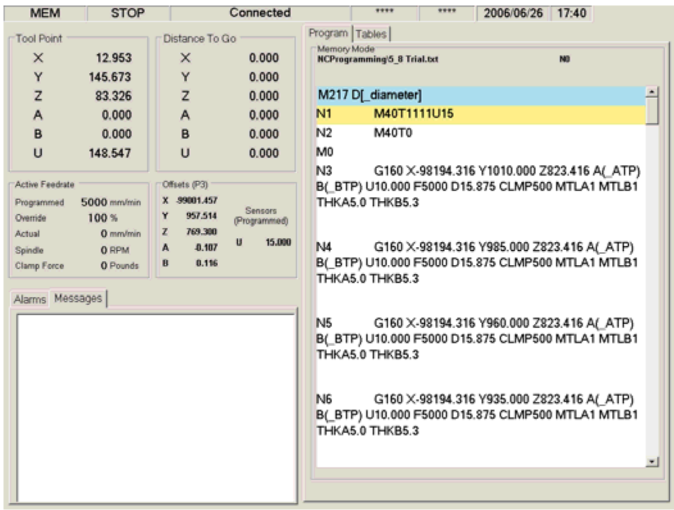

Figure 12 – Custom Operator Interface to 30i CNC

MACHINE TRANSPORTATION AND RESYNC

Transportation

During the wing box build process, the total time required for automated drilling of rib feet, spars, pylons, and other parts is only a portion of the build timeline. Many other manual operations such as component loading, detail setting, cleaning, sealing, manual bolting, etc. occur in-jig. To enhance machine utilization, leverage capital investment, and provide good access to the wing for manual work, the machine can be transported from surface to surface and jig to jig. Only one machine is needed to service 3 jigs (6 wing boxes in build). For transport, the machine is jogged to a machine transfer area at the end of the jig. Machine power and pneumatic services are quick-disconnected at the machine base. A purpose-built transporter crane attaches to the top of the machine and lifts it off the machine base. The machine may then be carried to any other line or surface requiring automated processing. Operation of the transporter is straightforward; no special heavy gang is required to move the machine. The machine may also be parked in the transport area for service, so that it is not blocking wing access.

Figure 13 - Machine in Transporter

Resynchronization

When the transporter sets the machine down on a base, dowel locators and clamps engage the base. Since unknown contaminants could potentially impair the repeatability of connection, pitch and roll checks are undertaken before drilling commences. Known details on the jig endgate are probed by the machine to confirm machine postion. As a baseline the machine must be oriented to the jig coordinate system. The resync camera or touch probe is used to locate a bushing that is valued in the jig reference system. The coordinates of this bushing are thus known to the machine, and the machine offsets can be updated to the X, Y, and Z values for the reference bushing on each line. To confirm or correct the A and B angle references, the normality sensors on the machine are used to normalize on a known surface in the jig reference system. The sensors are internally calibrated to the machine spindle axis, and so the machine spindle axis can be compared to the angular position of the jig. Once these calibrations have been performed, a part program using the axis system for that jig may be run by the machine. As noted earlier, the wing components may not be located precisely in the jig reference system due to part tolerance, loading tolerance, etc. To follow the actual contour of the wing surface, the normality sensors can roll along the OML. The Thru Skin Sensor may be used to locate out of column rib feet. The touch probe may be used to locate panel edges, pylon components, previously drilled reference holes, etc. The resynch camera may also be used to synchronize the machine on a local hole feature. These tools allow precise location of holes local to a feature on the wing which might be loosely toleranced relative to the jig. These techniques also allow for a reduction in excess material required to maintain edge margin with conventional back-drilling techniques. This results in a weight savings for the entire wing box.

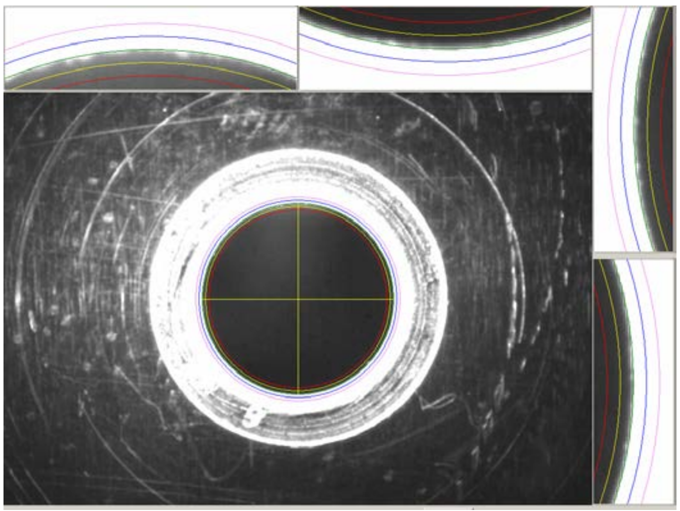

Figure 14 – Optical Resync Image, Viewing Countersunk Hole

CONCLUSION

Through the use of precision components, advanced software, the latest sensing technologies, robust drilling capabilities, and automated fastening, the CAWDE machine enables the automated drilling and temporary fastening of the latest designs in composite/metallic wing box assemblies.

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CONTACT

Brent Thayer and Benjamen Hempstead, PE are both mechanical engineers with Electroimpact, Inc. in Mukilteo, WA. For more information about this and other custom machine tools for aerospace automation, contact the authors at benh@electroimpact.com and brentt@electroimpact.com. The Electroimpact web address where this and other machines and tools can be viewed is at www.electroimpact.com.

ADDITIONAL SOURCES

High-quality components used on this machine include:

Heidenhain Encoders	www.heidenhain.com
Sony Encoders	www.sonypt.com
Proxistor Sensing Systems	www.halosensor.com
Alpha Gearboxes	www.alphagetriebe.de
Sensotec Force Transducers	www.sensotec.com
IKO Linear Products	www.ikont.com
INA Table Bearings	www.ina.de
Bosch-Rexroth Linear Products	www.boschrexroth.com
Zimmer Rail Clamping Systems	www.zimmer-gmbh.com
GMN Spindles	www.gmn.de
GE Fanuc Controls	www.gefanuc.com
Balluff Tool ID	www.balluff.com
Renishaw Probing	www.renishaw.com
Nilfisk Vacuum	www.nilfisk-advance.com