Automated Riveting of C-130J Aft Fuselage Panels

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Burton Bigoney
Electroimpact Inc.

Nicholas Huddleston
Lockheed Martin Aeronautics Co

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Abstract

Electroimpact and Lockheed Martin have developed an automated drilling and fastening system for C-130J aft fuselage panels. Numerous design and manufacturing challenges were addressed to incorporate the system into Lockheed Martin's existing manufacturing paradigm and to adapt Electroimpact's existing line of riveting machines for manufacture of these legacy aircraft parts. Challenges to automation included design of a very long yet sufficiently rigid and lightweight offset riveting anvil for fastening around deep circumferential frames, automated feeding of very short, "square" rivets in which the length is similar to the head diameter, creation of part programs and simulation models for legacy parts with no existing 3d manufacturing data, and crash protection for the aircraft part from machine collisions, given the uncertainties inherent in the model and the unique geometry of the aircraft parts. Additional challenges were overcome in integrating the system into Lockheed Martin's existing manufacturing methodology, while avoiding disruption to ongoing production activity and delivery schedules. Innovative and novel solutions to all of these problems were found and implemented. The result is successful automation of the drilling and riveting work on the aft fuselage, with corresponding improvements in manufacturing quality and production cost, and development of new technology that will have application in future automation systems.

Introduction

The introduction of automated fastening to the manufacture of legacy aircraft is often desired in order to provide improvements in quality, production cost, and worker ergonomics, among other factors. Special challenges to automation are frequently encountered in these applications.

- Automation must work around aircraft structures that were not designed with automation in mind. This means that part geometry may be very difficult for machine tooling to work around, leading to challenges for fastener accessibility; furthermore, fastener types that do not lend themselves easily to automated installation may be used.
- 3d datasets for older aircraft may need to be created from existing parts and tooling, making programming more difficult and limiting precision.
- This limit in programming precision, as well as possible limitations in the precision of the legacy processes used to build up parts prior to the fastening stage, means an increased risk of collisions between the automation equipment and the aircraft part.
- Original tooling and manufacturing processes were established for a fully fastened part. For the C-130J aft fuselage, the framing process needed to be redesigned to allow for 70% - 80% automation of fastener installation.
- Legacy processes for the manufacture of riveted aircraft structures typically involve locating rivets by means of pilot holes in the substructure. Removal of pilot holes for automation is required, with some means of efficiently locating holes for tack fastener installation by hand.
- Limited fidelity models can create a need for an extended pen plot trial to be performed on each assembly to adjust for collisions and verify rivet installation location.
- Methodology for automated drill depth and fastener selection may need to be adapted to accommodate the inaccurate models.
- Well-established manufacturing processes need to be adapted to incorporate the new system.

All of these issues needed to be addressed for the automation of the C-130J aft fuselage to be successful.

Electroimpact developed the E7000 line of riveting machines for the role of high-speed automatic fuselage riveting [1]. Tooling and machine systems had been designed around parts for the Airbus A320 and similarly constructed fuselage panels. The construction of the C-130J is considerably different, and necessitated new design concepts for several machine components.

Lockheed Martin has invested in automated rivet installation equipment for several assemblies on the C-130J, but the E7000 was the first fuselage riveter installed on the C-130J production line. As a traditional stick built aircraft, the manufacturing methodologies and tolerances are tailored to being built by hand. In most machining applications, large tolerances make it easier and cheaper to manufacture parts. For a mechanic or a machinist this is true. However, for a CNC machine that locates from one feature or fastener to place the subsequent fasteners and dodge obstacles, this lack of repeatability can be problematic.

A complete redesign of the manufacturing process prior to the auto-riveter was necessary to adapt the 40 year old manufacturing process to automation. This included generation of part models and simulations, part configuration changes, and a unique programming strategy to adapt to the open build tolerances. The result was a process which automates 65% - 75% of the fasteners installed in the aft fuselage reducing build cost and quality defects.

Figure 1. C-130J E7000 machine.

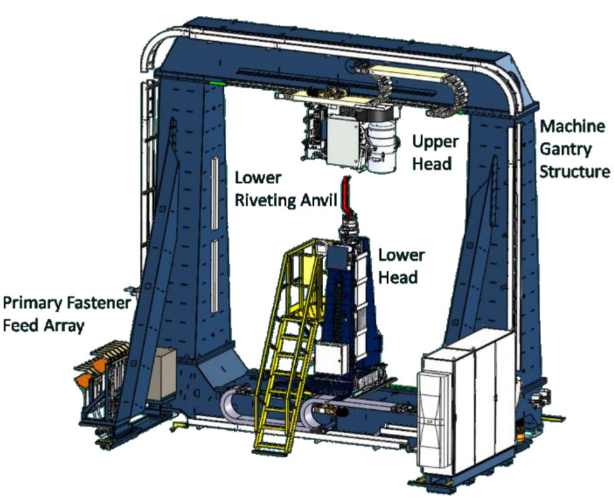

Figure 2. E7000 machine layout.

C-130J Aft Fuselage Construction

Unlike many modern commercial aircraft, the structure of the C-130J fuselage consists primarily of circumferential frames. Longitudinal stringers are not used. The circumferential frames are fastened directly to the skin. Many of the bulkheads that make up the frames consist of multiple pieces. Both the skin and the attach flanges of the frames are typically made of fairly thin aluminum. Minimum stack thickness where automated fastening was to be done is approximately 2mm.

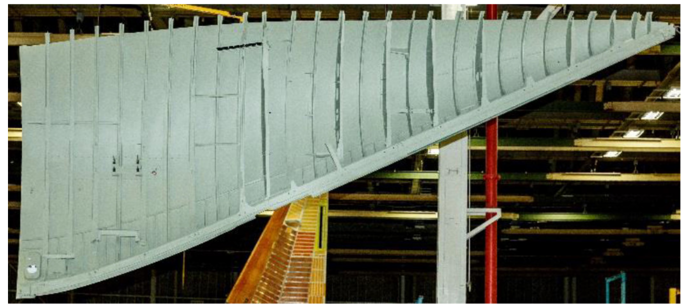

Figure 3. Right side panel of C-130J aft fuselage with structure visible, showing deep circumferential frames that must be fastened directly to the skin.

Lower Anvil Constraints

Rivets must be installed around a variety of frame geometries, all with tight clearances. Some circumferential frames have depths in excess of 500mm, making access difficult for an automated riveting anvil. Furthermore, the shapes of the frames are such that most rivets require an offset anvil.

In order to streamline production and simplify part programming, design of a single riveting anvil that could access all fasteners was set as a goal early in the design process. This meant that the shape of the riveting anvil was highly constrained by the various features within which it needed to be able to work.

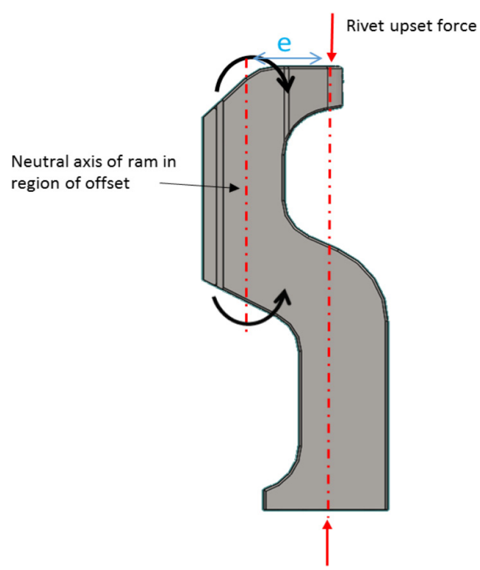

Figure 4. Illustration of internal bending moment applied to offset riveting anvil ram.

The size of the anvil is limited in every dimension due to accessibility considerations, and is also limited in weight, due to manual handling concerns. As with all offset riveting anvils, there is an internal moment applied to the anvil body, due to the eccentricity between the line of action of the upset force and the neutral axis of the anvil body at the offset (Figure 4). This moment tends to deflect the anvil laterally, and excessive lateral deflection will result in “smearing” of the rivet tail. Because of the very long anvil length and the tight size and weight constraints, this was a major concern for the anvil design.

Design

Through previous experience, Electroimpact has found that it is possible to limit lateral deflection through the use of carefully placed pockets in the offset ram [2]. FEA software is used to predict the ram lateral deflection, and through iteration, the cutout can be sized to reduce the lateral deflection to an acceptable level. However, the large length-to-depth aspect ratio of this anvil meant that deflection control on an especially large scale was necessary.

An initial analysis of the anvil ram found lateral deflection at the location of the riveting die would be approximately 1.6mm[.063”], an unacceptably large amount. Previous Electroimpact offset riveting rams have incorporated triangular pockets to balance out the ram’s smearing tendency. Because the deflection to be counteracted is so large in this case, analysis showed that a larger, more aggressive cutout was necessary.

Through iterative design and analysis, the theoretical lateral deflection of the ram was reduced to <0.025mm[.001”]. The design tradeoffs for this reduced lateral deflection are:

1. A slight but possibly significant increase in axial deflection, since the cutout reduces axial stiffness. In order to achieve the required upset forces for a 3/16” rivet, the ram must deflect axially by .75mm[.030”] with the cutout, as opposed to 0.65mm[.026”] without the cutout.
2. Decreased lateral stiffness of the ram. This relative lack of stability means that the ram is less able to stabilize the rivet tail during formation, which could increase the tendency of the tail to shift sideways, inducing buckling.

Results

An offset anvil was built using what was determined to be the optimal cutout geometry for minimum lateral deflection. Testing of the anvil for 3/16” rivet installations showed that rivet tails consistently had less than .050mm[0.002”] of eccentricity. This eccentricity is far below any cause for concern from a process quality standpoint.

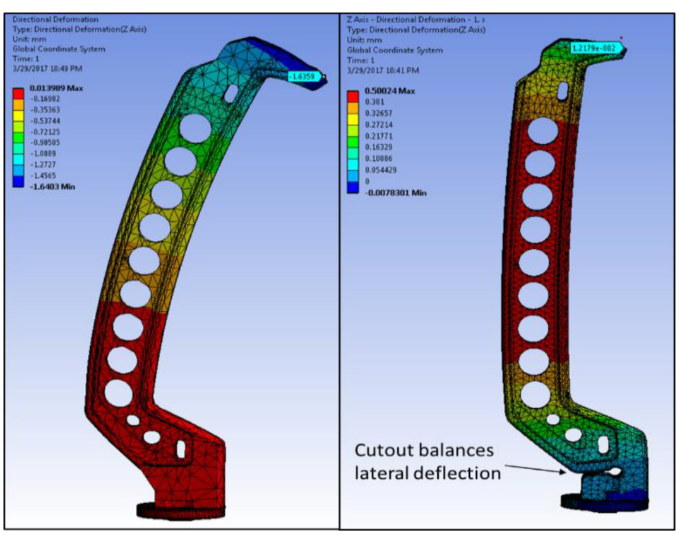

Figure 5. Comparison of lateral deflection in conventional offset anvil ram versus ram with optimized cutout.

Testing showed that within normal grip ranges, induced sideways buckling was not a concern. However, when excessively long grips were installed, substantial smearing of the tail was observed in some cases. This smearing was judged to be due to the induced buckling phenomenon, and this judgment was verified by examining video recordings of the upset. Because this only occurred with rivets much longer than the ideal grip for a given stack, it was not a cause for concern.

Feeding of Short Rivets

Fastening very thin stacks requires very short rivets. In the legacy manual installation process, rivet grips as short as 4.5/16” are used. For a 5/32” diameter MS20470 universal-head rivet of that grip, the head diameter is very nearly as large as the overall length of the fastener.

This is typically a problem for riveting machines, since it is common for fasteners to be fed from a remotely-located fastener feed system through one or more feed tubes to fastener injectors at the point of installation. Ideally, the tubes are sized such that it is impossible for the rivet to turn sideways within the tube. This becomes impossible to do when the rivet diameter approaches the length, since tube manufacturing tolerances and the potential for wear also must be factored in. A rivet that turns sideways may become stuck, stopping production and creating a potentially time-consuming maintenance problem.

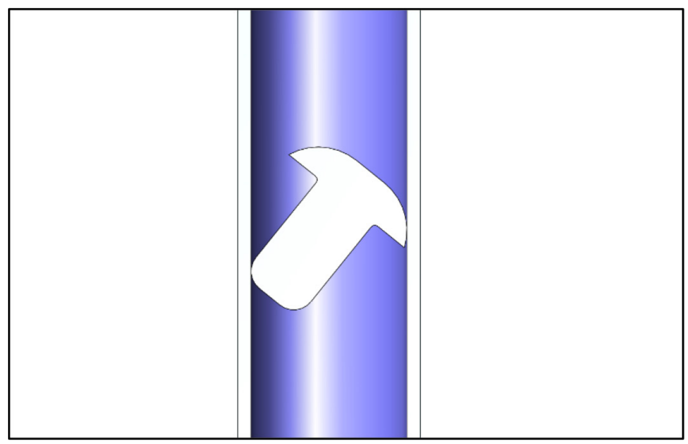

Figure 6. MS20470AD5-4.5 rivet turning in nominally-sized feed tube.

On the other hand, smaller, semi-automatic riveting machines often feed rivets from hoppers that are located directly adjacent to the riveting head. No feed tube is necessary, so this arrangement has no difficulty with feeding “square” rivets. However, it is impractical to fit more than a small number of hoppers directly on the head. Sixteen different fastener type and grip combinations are required for fastening the C-130J aft fuselage, with a dedicated magazine for each, so locating all of them on the head was not a viable option.

Solution: Hybrid Injector Array

A concept was developed for a hybrid design, combining both fastener injectors and hoppers on the head. This arrangement allows hoppers placed local to the head to be used for the shortest, most problematic fasteners, while a fastener magazine feeding a large array of fastener types can still be placed remotely.

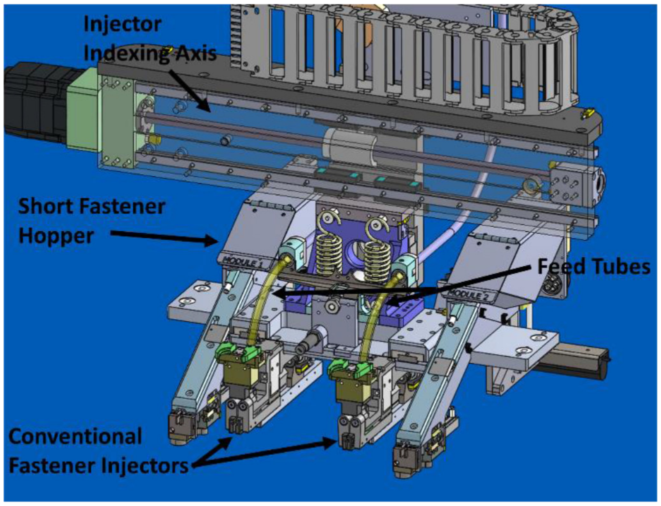

Figure 7. Injector array showing combined hoppers and fastener injectors.

In this way, the hoppers effectively act like additional injectors on the head. Based on the fastener type demanded for a particular hole, the machine controller identifies the source as either a hopper on the head or the remote fastener magazine, and shuttles the injector indexing axis accordingly.

Data Uncertainty and Part Protection

The usual method of part program creation using offline programming software and 3d datasets containing information on the parts to be produced, fastener locations, and tooling was followed. However, there was an unusually large degree of uncertainty in machine positions relative to features on the aircraft parts, and therefore a larger risk of machine crashes and resulting part damage. There were two main reasons for this:

1. 3d datasets were created from scans of actual parts. Using scanned data contributes to uncertainty in two ways:
   a. Accuracy tolerances inherent to the scanning process must be added to the overall stackup of tolerances when relating the 3d model to an actual part.
   b. There is no guarantee that feature locations on the parts that were scanned represent the "mean" locations of those features on other parts. In other words, any of the scanned parts may have been at one end of the manufacturing tolerance band compared to some future part.
2. The very deep circumferential frames increase the potential for collisions in the event of slight positioning or normality errors. For example, for a 500mm deep frame, a 1-degree error in either panel normality or in the frame itself would result in the free flange of the frame being out of position relative to the machine by almost 9mm. With the very small clearances required for fastener installation, this could result in a machine crash.

Crashes with the lower riveting anvil on the bottom side of the panel were of primary concern, as opposed to crashes between the upper head and the top of the panel (OML). All of the structure that must be avoided is on the bottom side, and furthermore, normality sensors enable the upper head to maintain a consistent distance to the skin OML, providing some protection.

Riveting machines such as the E7000 typically use pneumatic clamping on the bottom side of the aircraft panel. This means that a machine crash in the vertical direction may be limited by the pressure in the clamping cylinder. However, there is no protection in any other direction. There is additional risk when using an offset riveting anvil, because the anvil may be "hooked" around structure when attempting to retract.

Solution: Magnetic Crash Base

An electromagnetic interface for the lower riveting anvil was developed. The electromagnet provides the primary mechanical connection between riveting anvil and the machine. This allows the lower anvil to separate at the magnetic interface when a relatively small lateral or tension force is applied the anvil. In the event of a crash, the force that the anvil can excerpt on the aircraft part is thus limited. Sensors detect the separation of the anvil and immediately stop the machine. Because the holding force of the magnet is controlled by the applied voltage, it is also possible to increase the retention force at certain times, such as when forming a rivet [3].

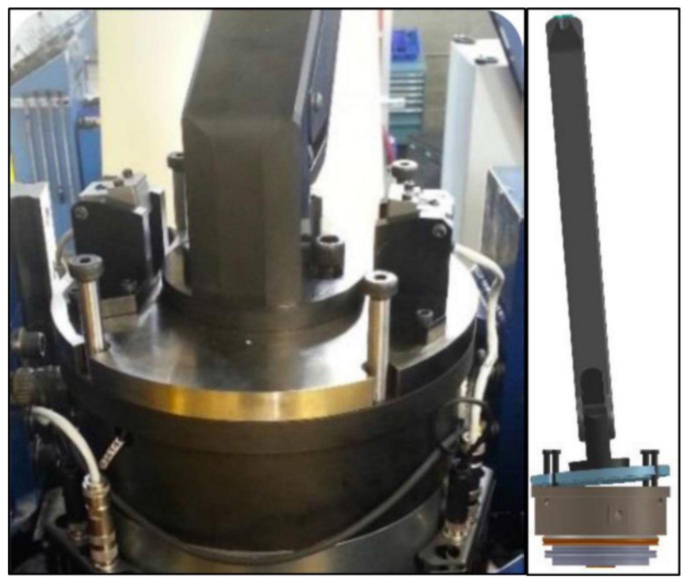

Figure 8. Magnetic lower riveting anvil connection allows separation in the event of a crash.

Low Confidence in Simulation Data

Like most fuselage riveters, the E7000 has the ability to use local features such as a fasteners head to apply offsets to locally realign the part. On many panels designed for fuselage riveter assembly, arbitrarily assigning a tack fastener every 12 or 14 inches would be acceptable practice due to few collision obstacles and single piece bulkhead caps. Most of the bulkheads that make up the frames in the fuselage panels on C-130J are made of multiple pieces. The large manufacturing tolerances and variability in the bulkhead build made it especially critical for realignment fasteners to be assigned to each individual part on each bulkhead assembly, with the machine only referencing fasteners common to that part on the bulkhead. Because of the number of possible collision areas on each bulkhead, it was important to try to keep the tack fasteners common to the collision areas where the machine cannot access, so that hand installed fasteners were minimized. The image below shows the part with the original pilot holes as an illustration of the locations of the fasteners. Parts without the pilot holes are used in production with the E7000.

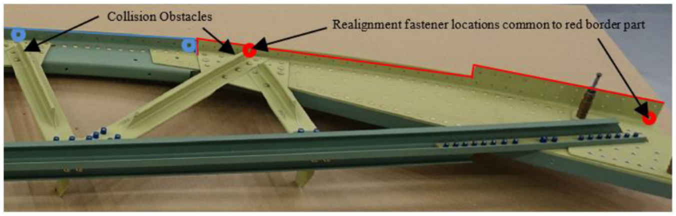

Figure 9. Example of multi-piece bulkhead on C-130. Realignment or resync fasteners are selected for each part.

Solution: Pen Plot Program Simulations

Legacy tools based on paper drawings are the controlling media for the majority of C-130J parts and assemblies. If any 3d models exist, they are reference models and cannot be relied on for accuracy. Reverse engineered models were generated through white light scanning to get fastener locations and basic obstacles shapes. The fidelity of the models was not fine enough to rely on for complete collision analysis and fastener location analysis. The refinement of the part programs was developed in two steps.

1. Simulation software was developed for checking bugs in the post processor and basic machine path.
2. A fully fastened part was loaded into the auto-drill and a pen loaded in the machine spindle was used to mark on the completed panel.

Pen plotting a complete part served as the simulation to give confidence to the quality engineers that the programs were correct. The marks of the auto-drill were compared with the locations of the installed fasteners and the lower anvil travel was observed and corrected anywhere collisions occurred.

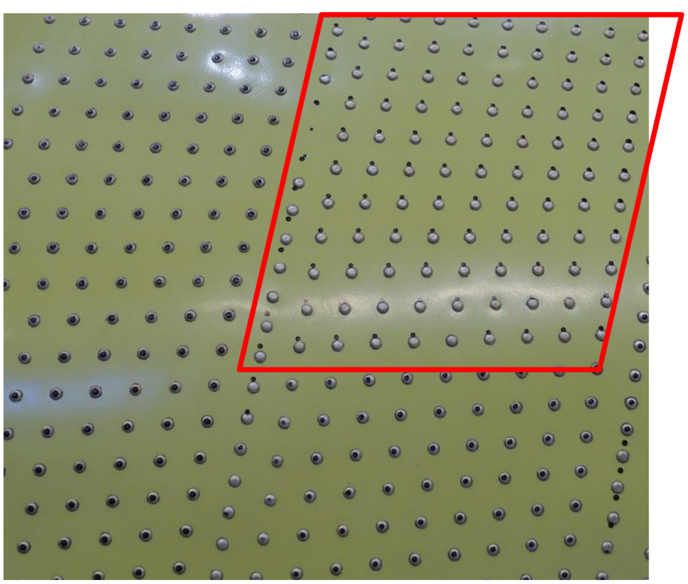

Figure 10. This example of an array of fasteners show areas that needed adjustment (in red) and fastener locations that were correct found during pen plotting.

Old/New Process Compatibility Issues

The legacy process for building fuselage panels involved a mechanic using the pilot holes in the substructure frames to locate parts and fasteners. The new auto riveting process could not tolerate existing holes in the substructure. Selective removal of pilot holes to the final configuration was not possible without accurate simulation models due to the high number of collision obstacles and uncertainty for fastener access. In order to get the most out of the new process, all pilot holes common to the skin surface were removed to allow for process flexibility. With all the previous tooling references removed, the mechanics would not know where to locate parts and fasteners.

Solution: Sheet Metal Template Development

Sheet Metal Templates (SMTs) have long been used as drill templates. SMTs are typically made out of spring steel and are between 0.040” and 0.050” thick. All of the holes in the SMT are sized to fit a bushing or some sort of bushed drill.

Figure 11. Example of SMT used in manufacturing process development.

A special set of SMTs were developed with markings to show part alignment and tack fasteners. Each hole on each SMT had a unique numeric identifier that tied that hole to a point in the program. After the pen plot on a complete part and approval was released to drill the first part, the SMTs showed the assembly mechanics which holes to drill prior to the E7000. This process allowed for quick process and program refinement without having to send all the changes continually through the supply chain. This also allowed flexibility to add or removal fasteners from the program due to collision or manufacturing process needs.

Low Confidence in Layer Data

The E7000 was designed to drill to a programmed depth which is generated from the simulation models. This would allow the manufacturing engineers to set drill speeds for each layer the drill penetrates in a stack. The majority of the C-130 aft fuselage is made up of aluminum so there is not a need for a varying drill speed. In addition, the simulation models did not have the fidelity to support model layer analysis. Since stack thickness directly impacts the cutter and fastener selection, a solution was needed for assigning a nominal stack thickness.

Solution: Drill to Measured Stack, and Record Actuals

For setting up the initial part programs, the only option for assigning part thickness for each location was the rivet grip length. Acquiring a 3d scan of the parts with accurate thickness data was cost prohibitive and analyzing every material stack at every fastener location would have been exceedingly time consuming. The expected rivet grip for each location was collected from the assembly mechanics and compiled in the manufacturing engineering model. That data was used by the post processor to assign an average stack thickness value for each rivet grip. This gave the initial variables for the machine to assign cutting tools and rivet grip.

After the first run of each part program, the data log was downloaded and used to correct the programmed rivet grips in any area the collected rivet grip information was incorrect. This corrected grip data also corrected any tool selection errors in the program. The controller was then reprogrammed to drill to the measured stack thickness rather than the programmed stack tolerating more mismatch of the programmed and actual stack.

Summary/Conclusions

Much of the drilling and fastening work on the aft fuselage section of the C130J aircraft has been automated successfully, leading to a reduction in costs and improvements in quality. The new technologies and methods developed for this process are likely to be applicable to future automation projects, and particularly for those involving other legacy aircraft components.

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Contact Information

Burt Bigoney is a mechanical engineer and project manager at Electroimpact, Inc. in Mukilteo, Washington.

Nick Huddleston is an applications engineer and project manager in Manufacturing Technology for Lockheed Martin Aeronautics Company in Marietta, Georgia.

Burt Bigoney, P.E.
Electroimpact, Inc.
burtonb@electroimpact.com

Nick Huddleston
Lockheed Martin Aeronautics Company
nicholas.huddleston@lmco.com

Definitions/Abbreviations

e - Eccentricity

OML - Outer Mold Line

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