Technical Improvements to the ASAT2 Boeing 777 Spar Assembly Cell

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Scott Hogan, Paul Haworth and Jason Rediger
Electroimpact Inc

Richard Wilkes
Boeing

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ABSTRACT

Electroimpact and Boeing are improving the efficiency and reliability of the Boeing 777 spar assembly process. In 1992, the Boeing 777 spar shop installed Giddings and Lewis spar machines with Electroimpact Inc. EMR(1) (Electromagnetic Riveting) technology. In 2011, Electroimpact Inc. began replacing the original spar machines with next generation assembly machines. The new carriages incorporate a number of technical improvements and advancements over the current system. These technical advancements have facilitated a 50% increase in average cycle rate, as well as improvements to overall process efficiency, reliability and maintainability. Boeing and Electroimpact have focused on several key technology areas as opportunities for significant technical improvements.

INTRODUCTION

The Boeing 777 ASAT2 (Automated Spar Assembly Tool) spar line, located in Everett Washington, is comprised of four assembly jigs and four automated fastening machines made by Giddings and Lewis in 1992, each dedicated to one of the four 777 spars. Electroimpact is implementing four new fastening machines to replace the existing units. During this process several opportunities for technological improvements were highlighted.

As part of the spar assembly process, the machines must traverse a radial portion of the box-way which follows a bend, or 'kick' in the 777 spar. The legacy machines are unable to traverse this section at the standard cutting traverse of 400 Inches per Minute, and instead must slow considerably during the kick motion. The new machines utilize the high speed positioning capabilities of the Fanuc 30*i* controller, as well as using a kinematic routine written by Electroimpact to facilitate motion through the kick of at least 400 IPM.

Machine accuracy during spar assembly is highly critical, especially in areas where reference holes (or 'K' holes) are drilled and later used to position aircraft components. Compensation accuracy, and more importantly, flexibility was a key focus during the project. In addition to this, the new carriages take advantage of a linear magnetic distance coded scale which provides exceptional accuracy, reliability and flexibility, enabling the operator to home the machine anywhere along the 30m long spar jig.

Finally, a critical development goal was to use the latest technology to enhance the usability of the new system in an attempt to improve overall process efficacy. These enhancements include a high resolution digital camera system and an advanced graphical Human Machine Interface.

The new ASAT2 carriages produced by Electroimpact can be seen in Figure 1.

Figure 1. Next generation ASAT2 machine.

THE SPAR ASSEMBLY PROCESS

The 777 spars are assembled from three primary structural components, two cords (longitudinal L shaped sections) and a web that spans between the two chords, along with other stiffeners and rib posts. Each spar is fastened with approximately 3,500 fasteners in a mix of slug rivets, threaded bolts with nuts and bolts with swaged collars. The Electroimpact machines are comprised of a pair of carriages running on the existing box-way, and are equipped with a 20K RPM Fisher MFW-1412 drill spindle, EMR's, EMB (Electromagnetic Bolting Tool), hole-probe, nut runner and BUCA (Back-up Clamp Assist) probe.

A typical machine process consists of synchronized motion of the two carriages to the fastening location, sensing of the spar position using the BUCA probe, clamping, drilling of the hole, measurement of the hole diameter, insertion of the fastener, swaging of the fastener in the case of a rivet, swaging of the collar in the case of a lockbolt or torquing of a nut in the case of a threaded bolt.

The current ASAT2 fastening machines can achieve an average cycle rate of 4 fasteners per minute. This figure is averaged across the range of different fastener types installed by the machine. In testing, the new ASAT2 machines have achieved an average rate of 6 fasteners per minute, an increase of 50%.

Figure 2 and Figure 3 show the twin fastening heads of the new carriages aligned, as well as the process tools (EMB, Drill, EMR from left to right). Also note the elongated nosepieces which reach past structural components of the spar to access fastener locations.

Figure 4 demonstrates how the fastening heads interact with the spar components, in this case the upper and lower chord, and the web.

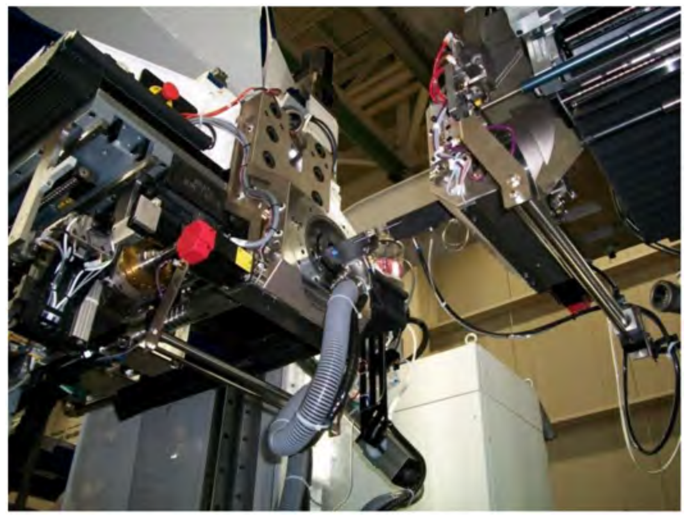

Figure 2. Fastening heads of the ASAT2 machine.

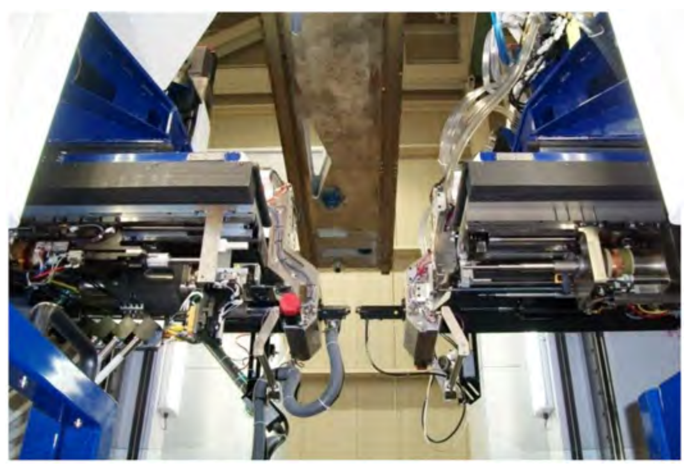

Figure 3. Fastening heads of the ASAT2 machine.

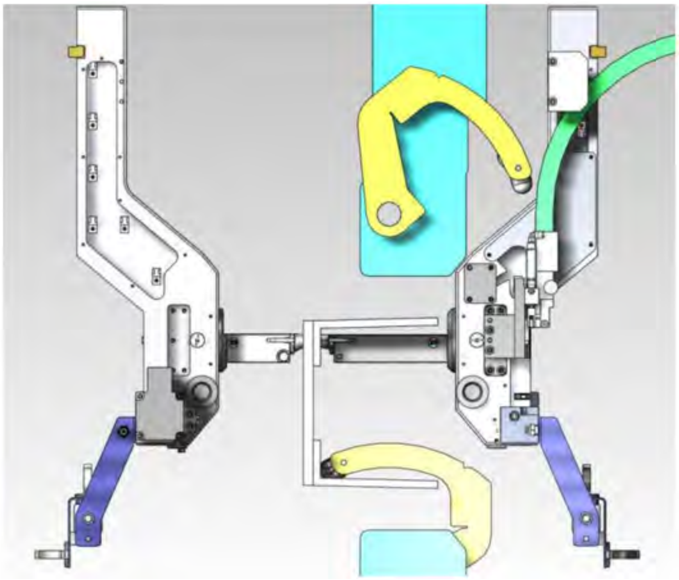

Figure 4. Fastening heads interacting with the spar components.

KICK NAVIGATION

The Boeing 777 front spar has an 8.3 degree inflection point at approximately 1/4 of the way from the wing root end. This inflection or 'kick' presents some kinematic challenges for the machine that fastens the components of the spar together. Giddings and Lewis opted to use a curved section of rail which bends through the same angle as the spar itself, and subsequently the new carriages would have to navigate the kick using a mechanically similar system.

The challenge for the new system was to improve speed, accuracy, and reliability of the carriage motion through the bend. A key requirement was that the new system would be able to traverse the bend at an increased speed of 400 Inches per Minute.

The motion of each carriage through the bend is controlled by a pair of linear servo trim axes referred to as "Beta" axes. These servo axes are capable of moving the corners of the machine as it traverses the bend. The motion through the kick has essentially three modes. Firstly, the machine enters the kick but the tool point is still located in a straight portion of the spar. Here a single Beta axis moves in order to keep the machine straight. The second mode occurs when the tool point enters the kick. Both Beta axes now move to rotate the tool point through a 740mm long, 8.3 degree radial path. The third mode happens when the tool point has completed its path along the curved part of the spar, but the lagging corner of the machine is still in the kick. In this mode, one Beta axis moves to keep the carriage straight until it has completely moved out of the kick. Figure 5 demonstrates how the Beta axes move from their nominal positions in the straight portion of the spar, to a different position when moving through the kick.

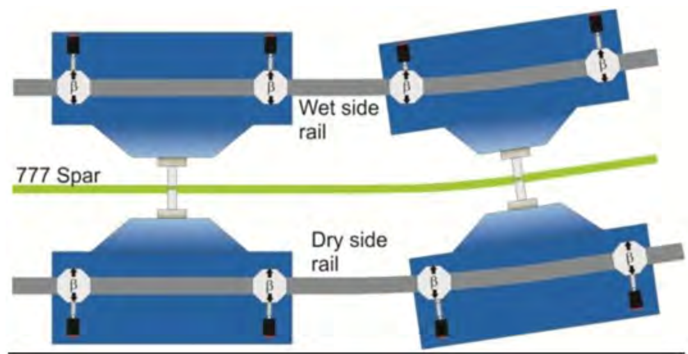

Figure 5. Dry and wet carriage transition through the spar inflection.

The paths followed by the beta axes are each governed by five piecewise functions. The closed loop form solution of these equations is very complex, involving dozens of terms. It was found that these functions could be approximated by lesser order polynomials with a high degree of accuracy. A second order polynomial approximation of the beta axes motion yields a result that matches the theoretical path by within 0.001″.

The positions of the beta axes are governed by these quadratic polynomials. A software routine developed by Electroimpact running on the CNC processor continually reads the position of the machine along the spar (X axis) and using these quadratic equations it provides updated positions for the two Beta axes. At higher X axis speeds however, this algorithm was insufficient to keep the Beta axis positions from lagging behind. This resulted in poor tool path control and the potential for damage to the structure and bearings.

In order to achieve high traverse speeds through the kick, a 'look ahead' function was used to predict the required Beta axis position at some time in the future depending on the current X axis traverse speed. This look-ahead feature is also used to establish how fast the Beta axes need to be moving in order to arrive at the correct location, at the correct time. A differential smoothing function was used to prevent small fluctuations in measured X axis position from creating instability in the velocity control loop. This control methodology enabled the machine to smoothly transition through the kick at up to 400 IPM.

COMPENSATION PARADIGM

Effective and flexible machine alignment is critical on any modern aircraft assembly tool. The need for accurate tool-point positioning is further magnified on a machine which uses independent positioning systems for each head, as is the case for the ASAT2 machine.

Development of the compensation and alignment system on the new ASAT2 carriages presented some unusual challenges. Firstly, when the dry side carriage moves through the kick, the X axis position must be actively scaled as the machine moves through the transition. This is due to the radial path of the tool-point being shorter than the radial path that the machine moves through at the drivetrain. The wet side carriage has a similar problem, instead here the tool-point moves through a longer radial path than the machine itself. In both cases, the difference is ~88.6mm. Secondly in addition to the general accuracy requirement for the spar envelope, Boeing had an additional requirement for tighter demonstrable accuracy at key locations along the spar, where holes are drilled which are later used to locate other key structural components ('K' holes). This requirement resulted in a need for a compensation system which supported non-equidistant compensation locations.

To meet these nonstandard requirements, a bespoke three axis compensation routine was written for the ASAT2 machines. Figure 6 demonstrates how the compensation system was engineered. An array of compensation 'stations' is defined over the machine *x, y* envelope. Each grid point has an *x, y* location and a compensation amount for the *x, y* and *z* axes. It should be noted that the *x, y* station location intervals can vary across the travel of the machine. Compensation values were established using a laser tracker, where the errors in *x, y* and *z* were measured at positions which corresponded to compensation locations. The compensation software reads the current *x, y* location, finds the nearest four grid locations in the compensation table (seen in Figure 6 as x_1, y_1 etc;) and then utilizes a bilinear interpolation calculation to establish the required three dimensional compensation at that precise *x, y* coordinate based on the compensation values at the four compensation grid points (shown in Figure 6 as xc_1, yc_1 zc_1 etc;).

Since the compensation locations can be defined individually, compensation intervals do not need to be fixed. Also, since the compensation values are not bounded by any internal limit this system can be used to compensate for the radial motion of the tool-point through the kick. Post compensation verification results have demonstrated accuracies of better than 0.005″ in X, Y and Z throughout the kick. This exceeds the required accuracy in the Boeing specification.

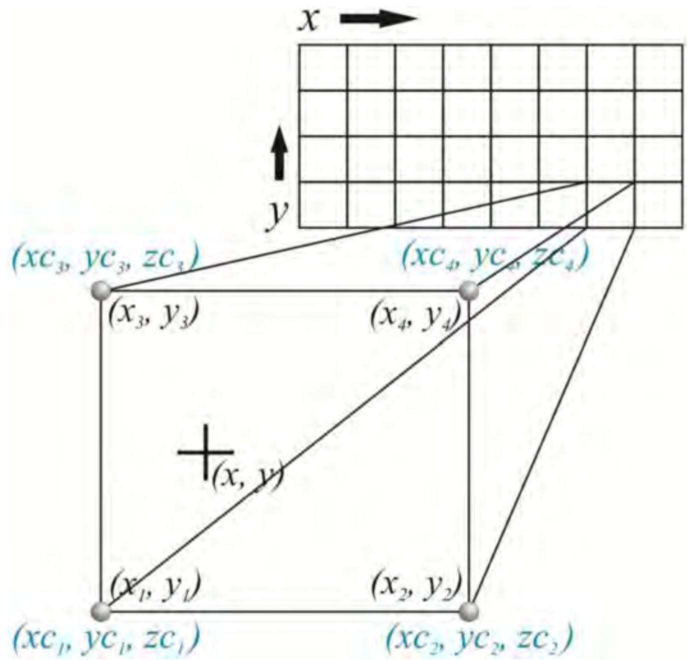

Figure 6. Pictorial representation of the compensation array, and the structure of a single element.

X AXIS MAGNETIC SCALE

The use of external feedback for linear and rotational servo controlled axes has several benefits, primarily that of improved accuracy and repeatability. However, the additional complexity and potential for maintenance issues can be a significant drawback. Therefore, external feedback systems that are robust, while possessing the required accuracy specification, are preferred. The external feedback system used on the X axis of the legacy carriages was highlighted as an area where significant improvements in reliability could be made.

The new system is comprised of a linear magnetic scale tape (LM-10 produced by Renishaw, UK) mounted on a steel backing spar. The read-head is mounted on a bracket which uses a roller in contact with the X-axis rails to maintain the correct fly height (the gap between the linear scale and the read head). The new scale has several advantages over the current system. Firstly, the fly height requirement of the LM-10 is between 0.1mm and 1.5mm in comparison with the 0.150mm to 0.350mm requirement of the legacy system. The significant increase in allowable fly height greatly improves the resilience of the scale to factors that lead to variations in fly height - such as debris, undulations in the machine bed and movement of the read head over time.

Secondly, the LM-10 used on the new ASAT2 system uses distance coded marks for reference return, as opposed to 2 discreet homing locations used on the current system. Distance coded marks allow the CNC to complete the homing sequence for that axis anywhere along the length of the spar by measuring the position of 3 consecutive distance coded marks.

Finally, the new system is designed to be completely non contact where the read head passes by the scale tape. This is a crucial design feature which ensures that debris cannot be caught and trapped in any alignment mechanism located adjacent to the read head. Instead, the roller guide that keeps the scale aligned is positioned in an area where debris ingress is unlikely, and of little consequence. Figure 7 shows the placement of the rail follower, away from the read head which does not contact the scale.

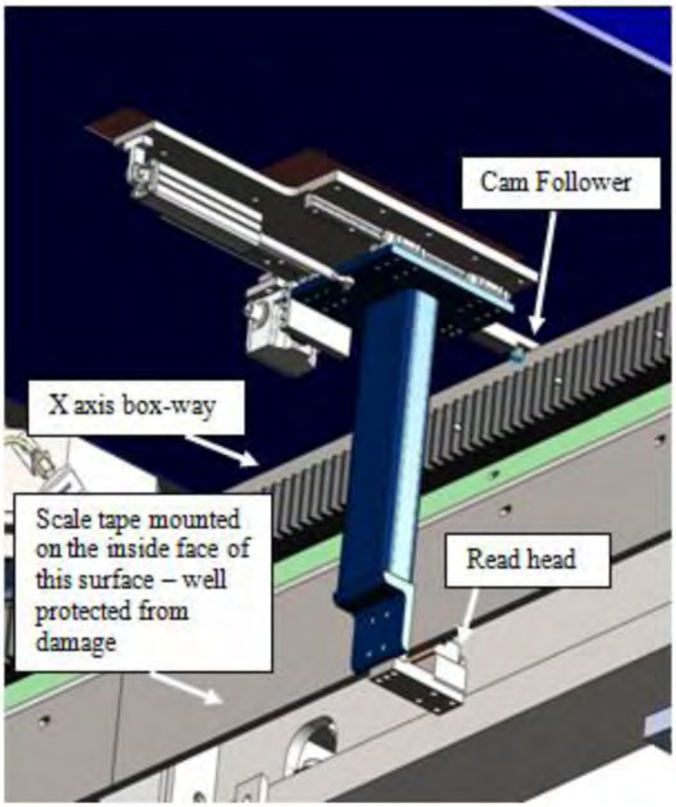

Figure 7. Diagram showing the read head mounting, and rail follower.

HUMAN MACHINE INTERFACE AND VISION SYSTEM

Operator workloads and effectiveness are key concerns during the development of any machine tool, particularly so on a system with the level of complexity found in an ASAT machine. The control system architecture, and in particular the design of the human machine interface (HMI or MMI), plays a key role in determining operator efficiency.

The HMI development environment available for the Fanuc series of controllers, known as 'Fanuc Picture,' affords machine tool designers with an opportunity to create advanced user interfaces with custom features that enhance machine operability.

The new ASAT2 carriages use a custom interface written using Fanuc Picture, and this interface includes several features developed specifically to improve operator efficiency. Firstly, the main operating screens are designed to incorporate all the data that the operator needs on a single screen. This removes the requirement for the operator to navigate through multiple screens to find pertinent machine data during operation, thus reducing workload.

Secondly, Electroimpact has incorporated a maintenance operations screen which allows operators and maintenance personnel to access key machine functions directly without the need to navigate through the logic programming within the CNC. In addition, the new ASAT2 machines also include a graphical process status screen, which diagrammatically describes the status of the machine fastening cycle. If the cycle is halted for some reason, in addition to error messages, the operator or maintenance person can see where the machine has progressed to in the cycle, and this information can be used as a starting point for diagnosis. This ability is key to rapid diagnosis of machine stoppages, particularly if there is a lack of familiarity with the core machine software.

Figure 8 is a screen shot from the cycle status screen displayed on the CNC. The flow of operations in the cycle is clearly visible, and color codes indicate processes that are in progress (yellow) or completed (green). Each process step number is indicated (e.g. Fastener Feed step number two), and this information can be used in conjunction with the machine operating manual to determine the machine state.

In addition to an enhanced HMI, the new carriages take advantage of the latest advances in machine vision technology. During spar assembly, there are several fastening locations that are closely adjacent to aircraft components, and this presents a challenge for operators as checking part clearances can be extremely challenging in such a confined space. To aid this process, the current machines have an analog video system which is comprised of 4 cameras and an analog video screen. For the new carriage, Electroimpact has enhanced this approach by implementing 4 high resolution digital gigabit Ethernet cameras (Allied GC1020C) displayed on a high resolution digital LCD screen (Siemens Flat Panel Monitor PRO 19″).

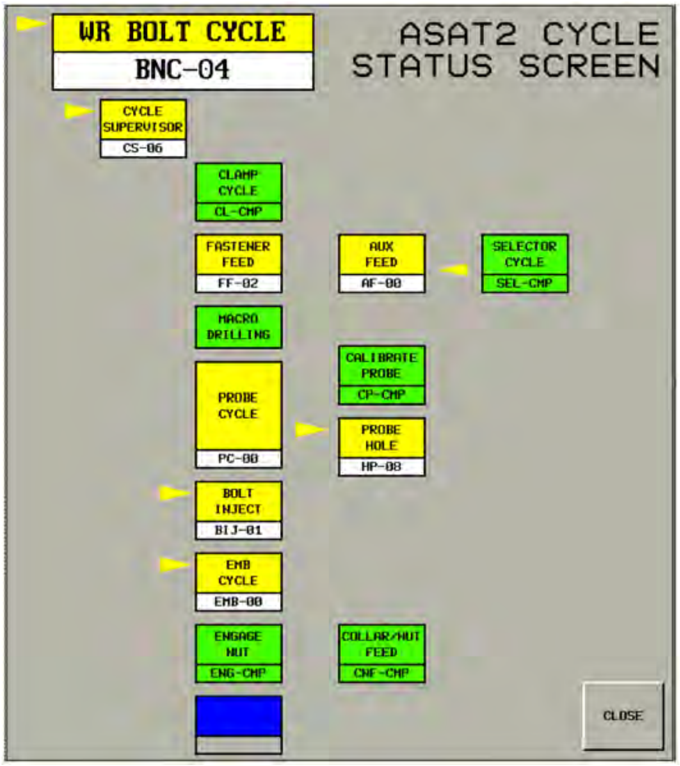

Figure 8. Screen grab from the ASAT2 cycle monitoring screen.

Digital cameras in industrial applications offer a number of advantages over their analog counterparts. Firstly, signal degradation due to noise introduced by nearby sources on the machine is a significant problem on analog systems installed on industrial machines; however digital systems are virtually impervious to this problem and consistently provide clean, clear images.

The digital cameras used on the new ASAT2 carriages have the ability to automatically adjust exposure settings on the fly, which allows for consistent brightness levels on the screen despite varying ambient light levels in the factory (largely due to obstruction of overhead lighting, and reflection of machine lighting on aircraft parts.) This prevents a commonly witnessed phenomenon in some analog machine vision systems where images are either too dark, or too bright to be of any practical use to the operator.

Digital cameras offer high resolution (1024 pixels wide by 768 pixels tall in the case of the model used on ASAT2) and using modern data compression and a high speed network, frame rates of up to 30 FPS can be achieved. Figure 9 shows the flat panel display in use on the right hand rear ASAT2 machine displaying 4 digital camera views.

Figure 9. The four camera digital display used on the new ASAT2 system.

CONCLUSIONS

The new Boeing 777 automated spar assembly tools (ASAT2) have demonstrated how the strategic implementation of advanced technology can improve process efficiency, reliability and maintainability. Average cycle rate has improved by 50%.

A linear magnetic distance coded scale produced by Renishaw UK, can be operated with a generous fly height range of 1.4mm whilst maintaining a resolution of 0.001mm, which was a key factor in achievement of machine accuracy requirements, while significantly enhancing reliability. The use of distance coded marks greatly reduces the time is takes to complete a reference return compared to traditional incremental scales with discrete homing marks.

Advanced graphical interface features have enhanced machine operability and aided maintenance activities, and a high resolution (XGA - 1024×768) fast response (30 FPS) digital camera system has provided ultra sharp images of hard to access fastening locations, which further enhances operator effectiveness and efficiency.

Advanced servo control technology and kinematic software allows navigation through the spar inflection at an increased speed of 400 IPM, thus requiring no reduction in feedrate compared to the straight sections of the spar.

Lastly, a bespoke three-dimensional flexible compensation system including non-equidistant compensation stations allowed for more compensation points to be allocated near critical positioning locations, such as K-Holes, and has facilitated accuracies of better than 0.005″ in all three positioning axes (X, Y and Z).

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CONTACT INFORMATION

Richard Wilkes is a Project Manager in the Equipment Engineering Automated Tool Group at the Boeing Aircraft Company.

Richard.Wilkes@boeing.com

Scott Hogan is a Mechanical Engineer and Project Manager, Paul Haworth is a Controls Engineering Manager, and Jason Rediger is a Mechanical Engineer at Electroimpact Inc.

ScottH@electroimpact.com

PaulH@electroimpact.com

JasonR@electroimpact.com

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DEFINITIONS/ABBREVIATIONS

EMR
Electromagnetic Riveter

EMB
Electromagnetic Bolting tool

BUCA
Back up clamp assist

CNC
Computer Numerical Control

BETA
Trim axis used to control machine motion in the spar kick

FAJ
Final Assembly Jig

FOD
Foreign Object Debris

MBPS
Mega Bits Per Second. 1000MBPS = 1GBPS, referred to as GIGE

IPM
Inches per minute

FPS
Frames per second

LCD
Liquid Crystal Display

HMI/MMI
Human/Man Machine Interface

ASAT2
Second Automated spar assembly tool, used for 777 spars

KICK
Inflection point in the spar

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

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