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# Slug Rivet Machine Installs 16 Rivets Per Minute Drill-Rivet-Shave

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## ABSTRACT

A new wing panel fastening machine, the E6000, has been designed with a focus on speed and reduced weight. A unique kinematic arrangement of the independent, four-axis fastening heads allows full CNC control of head alignment without a connecting structure. Short process tool travels and high-speed drive components contribute to fast cycle times. A custom CNC interface simplifies machine operations. The machine installs slug rivets at a rate of 16 per minute in a drill-upset-shave cycle.


Figure 1. E6000 riveting machine.

## INTRODUCTION

The E6000 is the latest in Electroimpact's line of Low-Voltage Electromagnetic Riveting (LVER) machines. It is being built for a customer in Xi'an, China where it will fasten wing panels for the ARJ21 regional jet. The machine is built to accommodate slightly larger wing panels, in the size range of A320 and 737. Its configuration can be scaled to other panel sizes.

The E6000 was designed from the ground up as a fast riveter, with an emphasis on light weight and high speed. Independent fastening heads are aligned through software control, eliminating the yoke structure which carries the heads on previous LVER machines. Cycle time improvements are achieved through high-speed process tools, short process tool travel to the workpiece, and non-contact sensors.

Compared to previous LVER machines, the E6000's light weight (70-80% weight reduction) and a new machine bed design significantly reduce foundation requirements. A custom CNC interface with mode-specific displays and controls helps the operator run the machine efficiently.

## MAJOR MACHINE STRUCTURE

### INNOVATIVE KINEMATICS

The E6000 is a traveling gantry structure with two independent 4-axis fastening heads. The heads operate on the skin and stringer sides of the wing panel assembly, which is oriented vertically in the fixture. Each head has a vertical axis, a clamping axis, and rotary "A" and "B" axes. Servo- and pneumatically-actuated tools perform drilling and fastening operations, mostly from the skin side. The concept of independent fastening heads working in tandem has been proven on other Electroimpact machines. A system in production at Kawasaki Heavy Industries (KHI) drills holes and installs slave bolts and collars for frame-to-fuselage attachment on Boeing 787 fuselage barrel sections.

Through kinematics software in the CNC, the heads are commanded to rotate as if mechanically connected. Software compensation corrects small deviations in head alignment. To effect “A” rotation around the toolpoint, each head rotates independently around its own A pivot bearings. This causes a change in the Y position of both heads, which is compensated by differential motion of the heads’ Y axes to maintain constant toolpoint Y position.

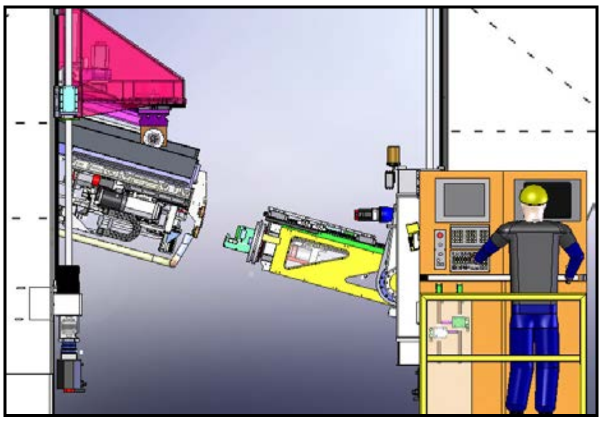

Figure 2. Coordinated head motion at A = -15°.

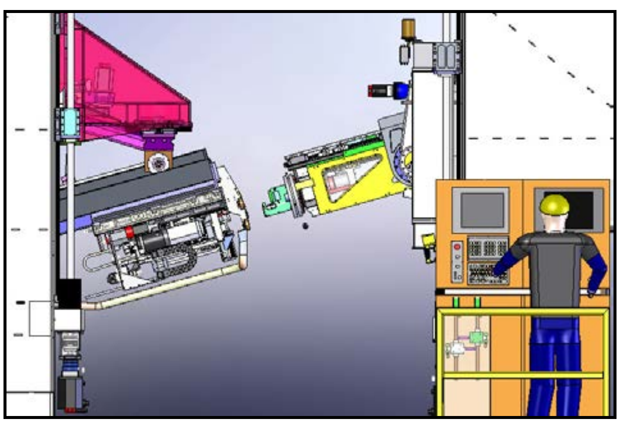

Figure 3. Coordinated head motion at A = 15°

Synchronized “B” rotation relies on a different bearing arrangement. The skin side head pivots on a rotary bearing, and the stringer side heads travels on curved rails concentric with that bearing. Because the heads rotate around a common center, there is no differential X motion, and therefore no need for sliding joints in the gantry. The gantry’s contiguous structure and support directly below each leg make it extremely rigid. The entire gantry travels in X to compensate for the change in toolpoint position during B rotation.

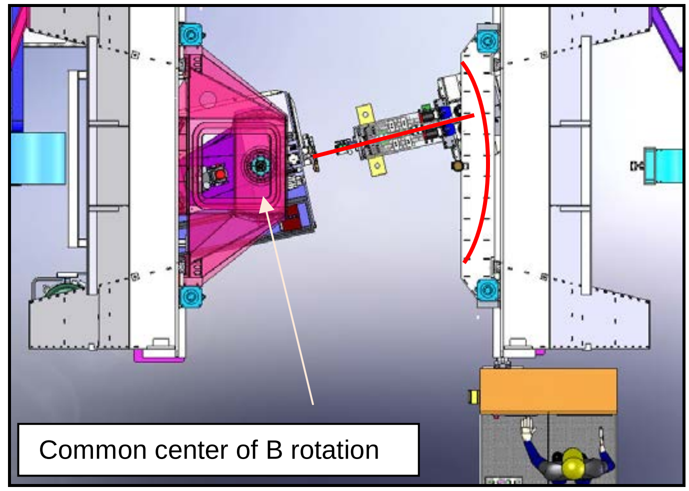


Figure 4. Coordinated head motion at B = 12°.

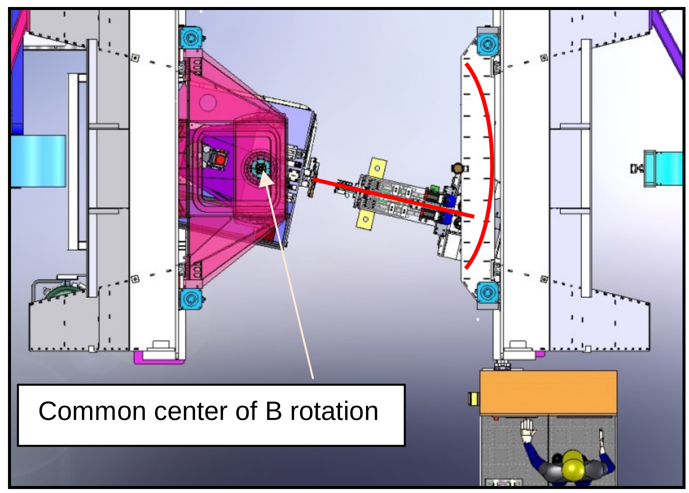


Figure 5. Coordinated head motion at B = -12°.

Major axis travels on the fastening heads are as follows:

| | |
|---|---|
| Y (vertical) direction | 3 m |
| A (rotation around X) | ±15.5° |
| B (rotation around Y) | ±12° |
| U (clamping on skin side) | 700 mm |
| V (clamping on stringer side) | 950 mm |
| Working range between heads | 350 mm |

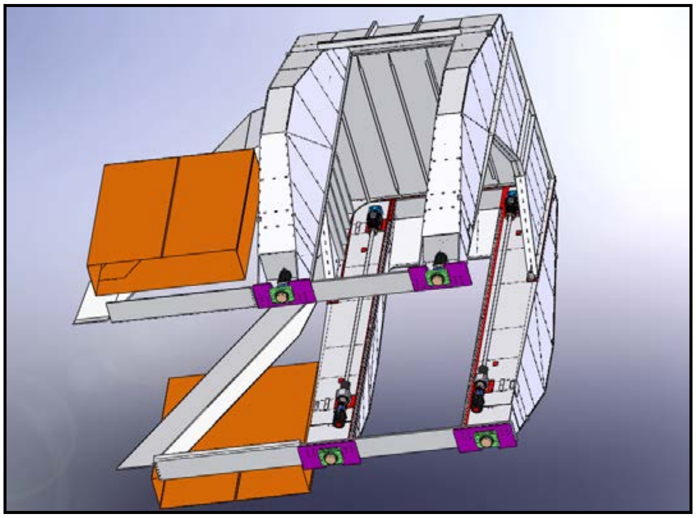

**Figure 6. Rigid gantry structure.**

MACHINE LOADS

The LVER process delivers high forces to the fastener while minimizing reaction forces in the surrounding machine structure. The main loads considered in the E6000 design were gravity, inertial loads due to acceleration, and process loads, specifically clamping and drilling.

To minimize inertial loads, machine structures and process tools are designed to be as light as possible, while still providing acceptable deflection under external forces. Designers used finite-element analysis extensively to optimize material thicknesses. The structure incorporates symmetric, redundant load paths wherever possible. This minimizes moment loads that would otherwise require large sections for rigidity. Examples include tandem Y drives and multiple pivot bearings on both fastening heads. On the skin side head, curved-rail bearings concentric with the skin side B pivot help resist clamping and tool-shuttling loads. On the stringer side head, the clamping axis is centered on paired A and B bearings. Clamp loads are imparted to the bearings radially, the direction of greatest rigidity.

The independent-head configuration and attention to load paths and structure weight yield dramatic results. The E6000's traveling weight is approximately 50,000 lb, compared to 250,000 – 300,000 lb for other LVERs. This weight reduction provides corresponding benefits in reducing in the size and cost of steel, bearings, and drive components.

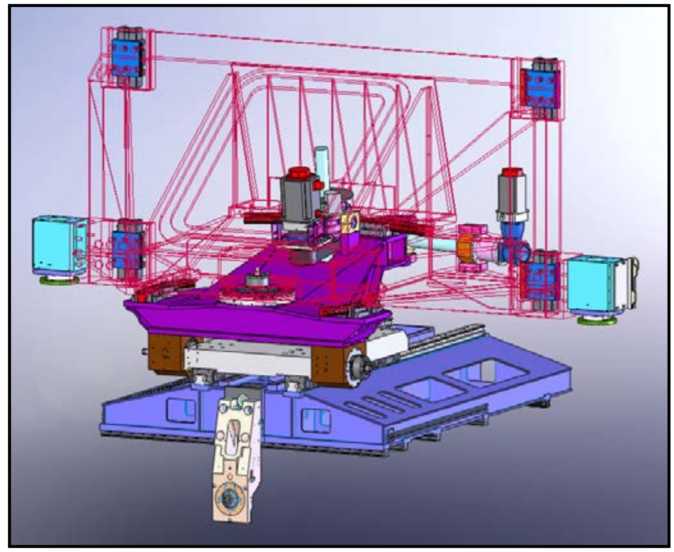

**Figure 7. Skin side Y-A-B-U assembly, process tools not shown.**


**Figure 8. Stringer side Y-A-B-V assembly.**

MONOLITHIC BED

Previous LVER machines have a relatively wide footprint (5-6m) and travel on separate, parallel machine beds. Wing panel fixtures are supported on base units between machine beds.

In contrast, the E6000 gantry is designed to be as narrow as possible, while providing sufficient dynamic stability and personnel access between the towers and wing panel. Distance between X bearing rails is 2.9 m. The machine's small footprint and light weight prompted the development of a monolithic bed structure to support both of the machine's X rails, as well as the wing panel fixtures in between. Bed sections are 3 m wide and 6 m long, and are joined lengthwise to create a continuous base. In the first E6000 installation, total bed length is 72 meters.

X-axis bearing rails and gear rack are mounted along the edges of the bed's top surface. Machine loads are transmitted through the reinforced side walls to jacking bolts directly below the rail centerlines. The bed's interior is a lightweight grid structure with a thin top skin. This structure supports the wing panel fixtures which impart relatively low static loads to the bed.

The combined bed structure has several benefits over previous installations:

- Reduced manufacturing cost and installation time.
- Less differential deflection between machine and fixture, in the event of foundation settlement.
- No alignment checks between one bed and another, therefore less time required for periodic fixture realignment.
- Significantly lower foundation costs, due to lower overall weight, and fewer features required to attach beds to the foundation.

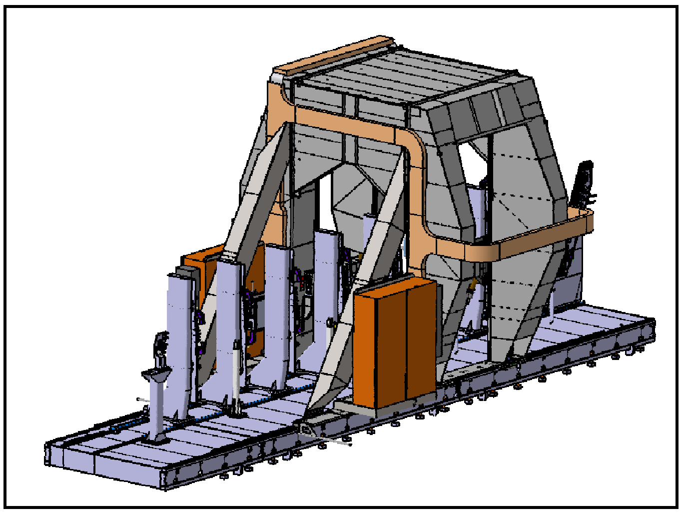

Figure 9. Machine and fixture on monolithic bed structure.

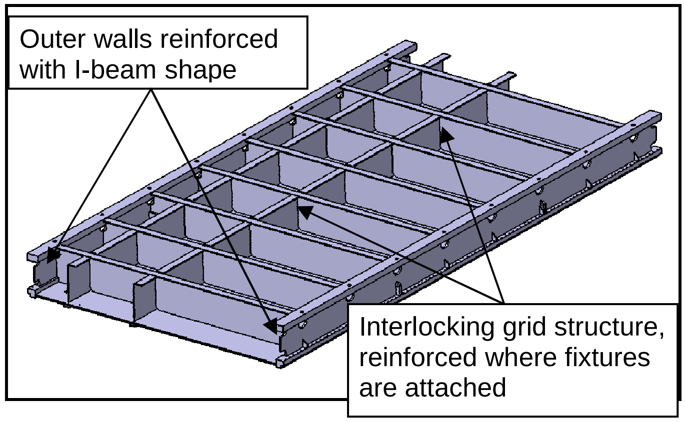


Figure 10. Underside of monolithic bed.

## FASTENING HEADS

### FAST PROCESS TOOLS

To a great extent, fastening cycle rate is governed by performance of the fastening heads, primarily the skin side head. Servo-driven axes include the clamping axis, the shuttle table, and main riveting process tools: drill spindle, shave spindle, and EMR or riveting tool (Figure 9). Making these components as fast and light as possible is a key factor in attaining high cycle rates.

The skin side clamp axis has a 4000 RPM servomotor directly coupled to a 40x10 mm ballscrew. This allows a top axis speed of 40 m/min (limited to 37 m/min by the ballscrew's DN rating), compared to 10-15 m/min on previous machines. The custom-designed bellows coupling between the motor and ballscrew has 40% of its corrugations removed to provide extra torsional rigidity while still allowing small misalignment.

A linear motor with 6000 N maximum thrust drives the shuttle table. With a payload of about 950 lb (4300N), this thrust produces an acceleration of 1.4G. Top speed is in excess of 2 m/sec, but most shuttle moves are too short to reach this speed.

Feed axes on the spindles and EMR use 6000 RPM servomotors mated to 10 mm lead ballscrews, for a top feedrate of 60 m/min, compared to 20-40 m/min on previous machines. EMR redesign trimmed the weight by 50 lb, to 200 lb. Drill spindle selection was based on the torque and power appropriate for ARJ21 and A320 fastener hole sizes. The spindles weigh 130 lb each, compared to 250 lb and up for other machines installing similar fasteners.

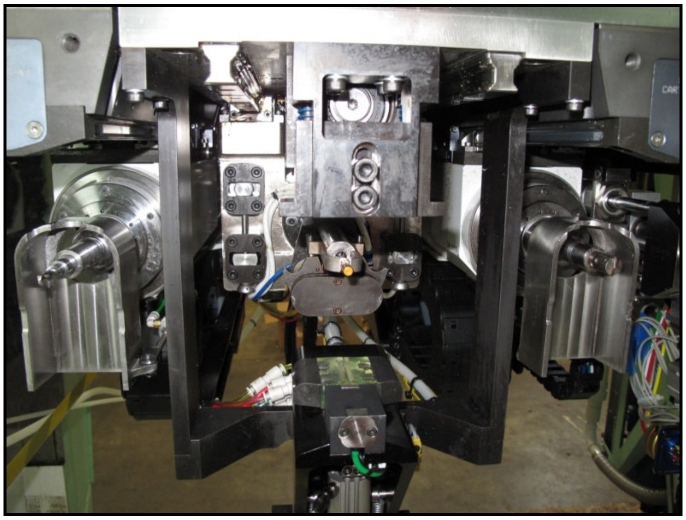

Figure 11. Drill spindle, EMR, and shave spindle. All are servo-actuated.

CLAMPING FOOT (HEADSTONE)

On Electroimpact's wing panel fixtures, an array of curved beams or "skin straps" maintains skin panel curvature until the assembly is tack-fastened. The skin side fastening head must avoid colliding with skin straps during the tack pass. This requires a clamping foot which is "taller" than the skin strap profile in the clamping direction, by a safe margin. It also requires that skin side process tools such as the spindles and EMR be outside the skin strap profile when fully retracted. The tools travel the depth of the clamping foot, known as the drop, to reach the panel from the retracted position. Previous installations have a 200 mm skin strap envelope and a clamping foot drop of 225 mm.

For the ARJ wing panel fixtures, new skin straps were developed with an envelope depth of 100 mm. This allows the E6000 to have a clamping foot with 125 mm (5") drop. The shorter drop reduces cycle time by (a) shortening the stroke of each tool, and (b) reducing overall tool weight, thereby increasing peak shuttle table acceleration. A possible side benefit, not yet measured, is an improvement in hole quality due to a shorter cantilevered portion of the spindle.

Another feature of the E6000 clamping foot is a ring-shaped load cell to detect clamp load. The ring is mounted in a sealed cavity behind the clamp pad. Process tools pass through the load cell's bore to operate on the panel. The combination of the ring load cell and a rigid, low-inertia machine structure behind the clamping axis provides a fast response during machine clamping. Approximate clamping times are 700 ms on older LVER machines, 450 ms on the most recently installed large LVER machine, and 350 ms on the E6000.

Figure 12: E6000 clamping foot and process tools.

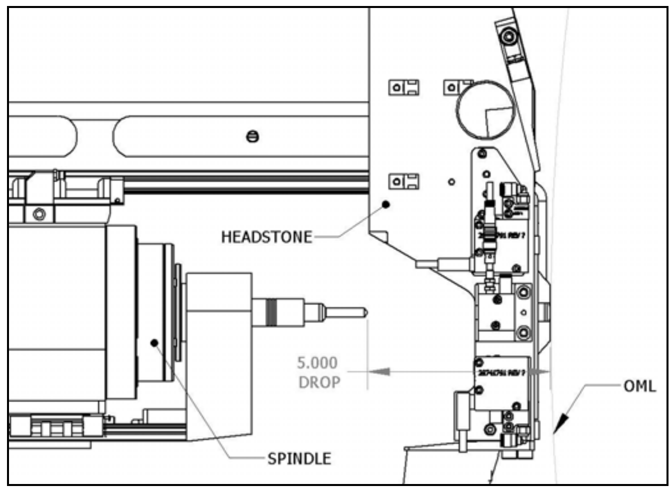


Figure 13. Depiction of 125 mm / 5" drop on E6000. Drill spindle, shown in retracted position, traverses this distance to reach the panel.

NON-CONTACT NORMALITY SENSORS

The E6000 incorporates laser normality sensors in a rectangular array on the clamping foot. The sensors have a 100 mm range, an improvement on the 35-40 mm for the mechanical sensors formerly used. The laser sensor housings fit within the thickness profile of the clamping foot, unlike the mechanical sensors which protrude behind the clamping foot and extend toward the panel when activated.

Although the laser sensors offer no direct increase in machine speed, they have several advantages which will improve machine utilization. Longer sensing range allows the machine to find the panel, normalize, and drive to programmed flying height more quickly when "Sensors On" is commanded. The lasers' small housing and non-contact operation greatly reduces the chances of collision with dowels, temporary fasteners, or other objects above the skin surface.

The rectangular sensor arrangement allows the machine to normalize even in locations where one or two sensors must be turned off under NC program control, for example at a panel edge or access hole. This feature is carried over from previous machines with mechanical sensors. However, unlike a mechanical sensor whose output changes gradually when it rolls off an edge, a laser sensor's output changes almost instantaneously. The E6000's normalizing routine exploits this characteristic by automatically "ignoring" the output of a sensor which suddenly falls out of the expected range. The machine continues to normalize with the remaining sensors. Since the lasers are always on, the CNC detects when the missing sensor has returned to the panel, and resumes using its output in the normalizing routine. This feature reduces operator intervention in situations where sensor drop-off is not anticipated in the part program.

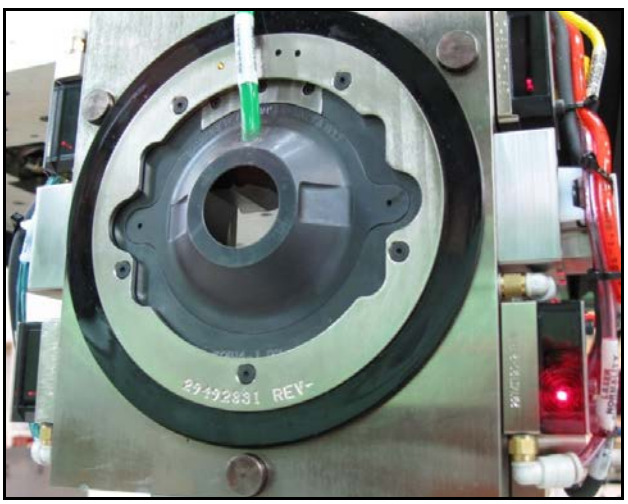

**Figure 14: Front of clamping foot with laser normality sensor array on the sides. Ring load cell is mounted in a pocket behind clamp pad at center.**

**Figure 15: E6000 machine with laser normality sensors follows a test panel's curvature.**

## CUSTOM CNC INTERFACE

The E6000's controller is a Fanuc 30i CNC with a customized user interface. The user interface on previous machines is PC-based. However in the high-vibration environment of a riveting machine, reliability is a concern. Even "industrially hardened" PC's have demonstrated shorter mean time between failures than CNC components, and a portion of machine downtime is attributable to PC maintenance.

The E6000 sidesteps this problem with a user interface operating on the Fanuc 30i. A development tool called Fanuc Picture allows the programmer to create customized screens, artwork, touch-screen buttons, and menus in the CNC environment. The E6000 interface gives the operator full control of normal fastening operations without reverting to the standard CNC displays and menus. Each control mode (MEM, MDI, JOG, etc.) has a custom screen which displays only the information, operations and menus specific to that mode. For example, the MEM mode display includes a navigable part program window, message and alarm windows, machine axis positions, status of interchangeable tooling, and real-time displays of machine parameters such as spindle speeds, clamp force, and selected fastener size.

The CNC-based E6000 interface offers improved reliability over a PC-based system. Mode-specific displays eliminate much of the clutter of hard-wired button panels, reduce the operator's work load, and contribute to efficient machine use.

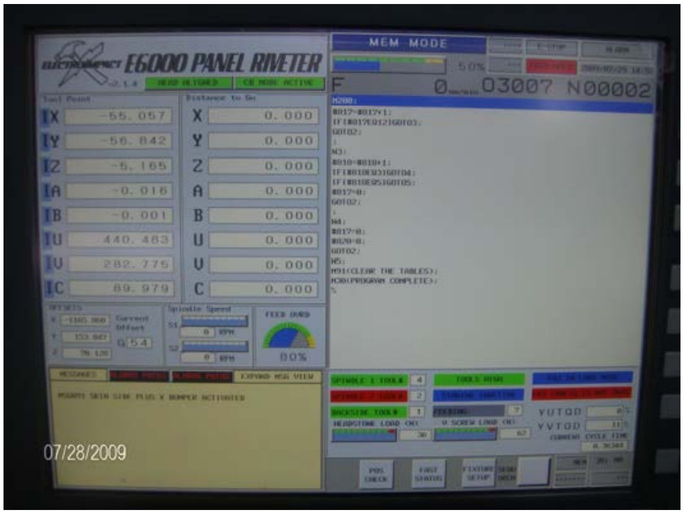


**Figure 16: CNC display in Memory mode.**

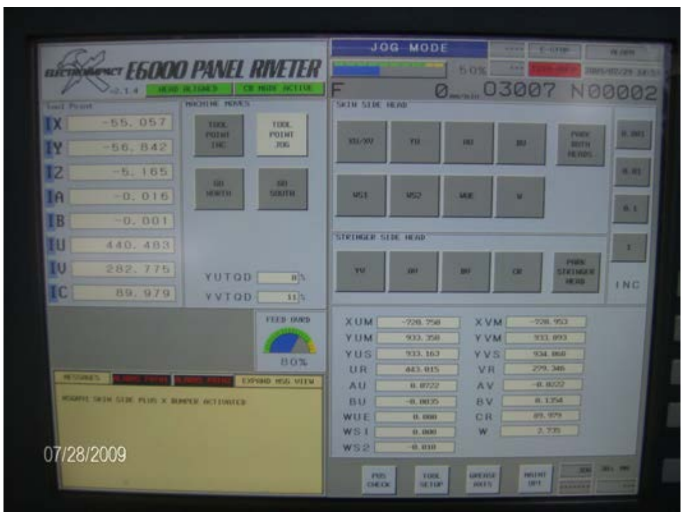


**Figure 17: CNC display in Jog mode.**

## CONCLUSIONS

The E6000 riveting machine incorporates independent fastening heads in a novel kinematic design which eliminates the yoke structure. The small, lightweight gantry permits the use of a monolithic bed to support the machine and fixtures, allowing the system to be installed on a minimal foundation.

Other improvements in process tool weight and speed contribute to high cycle rates. The E6000 installs slug rivets in a drill-upset-shave cycle at a rate of 16 per minute, compared to 8 per minute for older LVER machines and 12 per minute for the most recently installed large LVER. Non-contact sensors and an operator interface in the CNC environment offer long-term reliability.

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## CONTACTS

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

EMR: Electromagnetic Riveter. The riveting tool on an LVER machine.

LVER: Low Voltage Electromagnetic Riveter. A CNC-controlled machine tool which fastens wing panel assemblies.