

A Phased Approach to Optimized Robotic Assembly for the 777X

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Abstract

Low rate initial production of the 777X flight control surfaces and wing edges has been underway at the Boeing St. Louis site since early 2017. Drilling, inspection, and temporary fastening tasks are performed by automated multi-function robotic systems supplied by Electroimpact. On the heels of the successful implementation of the initial four (4) systems, phases II and III are underway to meet increasing production demands with three (3) and four (4) new cells coming online, respectively. Assemblies are dedicated to particular cells for higher-rate production, while all systems are designed for commonality offering strategic backup capability. Safe operation and equipment density are optimized through the use of electronic safeguards. New time-saving process capabilities allow for one-up drilling, hole inspection, fastening, fastener inspection, and stem shaving. Multi-function end effectors with dual spindles permits drilling and reaming within a single clamp, and hybrid cutting fluid delivery enables a no-compromise approach to process optimization. New automated health checks and calibrations limit the need for operators and maintenance personnel to access the equipment. The integration of these innovative technologies provides a high level of process control while the timely deployment of additional phases maintains a lean production system.

Introduction

The Boeing Company's 777X is supported by the mass production of assembly aerostructures produced at the Boeing facility in St. Louis, Missouri, a key supplier across this airplane's global supply chain. Final assembly of the 777X is conducted in Everett, Washington and the St. Louis work package primarily consists of fabrication and assembly of fixed wing edges, moveable trailing edges, new folding wingtips, and moveable empennage assemblies, comprising mostly of composite structures [1]. This new airplane is scheduled to make its debut test flight this year and at this time production units are in flow.

Current assembly automation processes include single pass drilling and countersinking of mold line and nut plate attach holes, comprehensive hole inspection, and temporary or blueprint blind fastener installation. This is achieved by the use of highly-accurate robotic arm positioning systems fitted with multi-function end effectors (figure 1). Current MFEE configurations include a 20k RPM HSK-40 servo spindle, hole inspection module, re-synchronization camera, [optional] fastener installation module, and [optional] 1k RPM HSK-40 pneumatic spindle (figure 2).

The articulated robot was selected due to its inherent ability to cover a large working volume with fastener normals in potentially all directions. The supplied Electroimpact accurate robot systems met or exceeded Boeing's requirement for very tight control on positional accuracy and repeatability. This not only enabled the systems to easily perform their existing work statements, but also removed a barrier common to robotic systems with regard to processes that require performance typical of bespoke machine tools. Tools can be added or subtracted, processes can be high or low force, and new

processes can be added such as milling or trimming if the need arises in the future.



Figure 1. Electroimpact MFEE coupled with Accurate Robot.

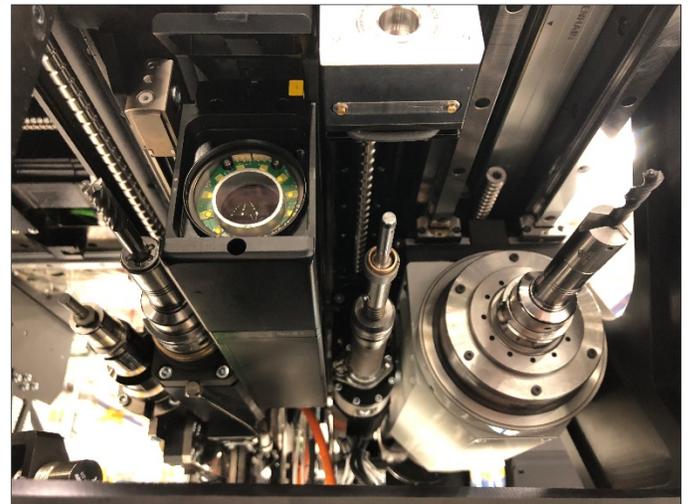


Figure 2. Inside view of Electroimpact MFEE (from left to right: Fastener Insertion, Secondary Spindle, Re-Sync Camera, Hole Probe, Primary Spindle)



Figure 3. The Electroimpact Accurate Robot offers a characteristic global accuracy of 0.2 mm (0.008 in) - equivalent to the thickness of two (2) pieces of paper.

Systems are designed and integrated just-in-time which enables a lean capital investment approach. Boeing partnered with Electroimpact, Inc. as the system OEM and integrator. As rate breaks are surpassed, the addition of right-sized systems into the facility allows for optimization of the cells and adjacent workspaces. The current deployment consists of three (3) systems, with four (4) additional systems beyond that currently undergoing manufacture. Future systems are identified for turnkey deployment to enable further throughput potential.

Production Phases

Low Rate Initial Production, Lessons-Learned

The current work scope remains a consistent 43 assemblies per shipset ranging considerably in size (Figures 4 and 5). More than 99 percent of all mold line holes are automated which, in total, is nearly 60 thousand holes per shipset. In addition, there are thousands of nut plate attach holes processed by the automation.



Figure 4. Processing a small component – in this case a fairing



Figure 5. Robot system working on a rudder which is one of the larger assemblies processed by the automation

The initial four (4) robotic systems have been utilized to process these 43 assemblies [1]. Procurement and implementation of the first phase was performed in parallel with aircraft design, tooling design, and process development. Though the majority of the requirements were known, it was not possible at time of procurement to fully define or be certain of exactly what processes and capabilities would be needed. The initial phase of systems enabled Boeing to automate the major assembly processes such as drilling and temporary fastening with low risk and minimal investment. This also provided an ideal opportunity to study the pros and cons and efficiencies/deficiencies of the systems to better specify future automation. There were lessons learned relating to process capabilities whereby technologies were added or modified to prevent the need to return to hole locations for further processing. Additional cutting lubricants and methods were specified to allow layer by layer drilling optimization specifically targeted for one-up assembly. Sensors were added and software implemented to perform real-time self-health checks to automatically ensure systems continue to perform as expected. Many subsystems that require fine tuning could be designed to be calibrated automatically, decreasing the need for operator or maintenance intervention. Lastly, to achieve full rate production given the factory floor space, the footprint of future automation cells had to be minimized.

Cutter Lubrication

Each robotic system utilizes a closed loop vacuum and “flood” coolant lubrication system for drilling various material types, stack, and drill size combinations. Initial systems had the capability to vary flood coolant rate and application could be through the drill bit and/or externally applied at the cutting pierce point through the nose piece tip. The coolant and swarf is contained within the nose and is extracted via vacuum, filtered, and recirculated with no external mess observed at the work piece. Due to the multitude of stacks and materials, the use of flood coolant was selected as it performs satisfactorily with most aerospace materials and is preferred when drilling structures with titanium. A desire for lubrication optimization was spawned during LRIP to better address composite only or composite over aluminum structures especially where one-up assembly was targeted. This was accomplished by integrating additional lubricant functionality. To complement the flood coolant system, a programmable oil/air mist system was installed. This enabled Boeing to choose, by layer, to drill dry, with air only, oil/mist, or flood coolant. Application rates are variable as is the application location, again all uniquely set per layer in the stack. Critical for one-up assembly as the fastening immediately follows the drilling process, composite stacks are drilled dry and metallic substructure layers drilled with minimal air/oil mist. This keeps the

prepared hole dry and clean. To keep the evacuation system clean from carbon build-up when drilling dry or with air/oil mist, a coolant jet was added downstream of the nose piece to enable the line to be washed.

Fastener Installation and Core Bolt Inspection

The phase 1 systems were designed to ensure the correct fastener is selected and retrieved at the end effector by automated measurement of the stack thickness, fastener diameter, and fastener length. During installation, real-time measurement of the installation torque and angle are used to ensure proper rundown. These integral validations are used for both temporary and permanent fasteners.

Additional data was desired by Boeing relating to the installation quality of permanent fasteners. Some of the subject assemblies utilize blind twist-type bolts which leave a short protruding stem at the head after installation is complete. The height of the stem can be used to inspect the installation quality as there exists a narrow acceptable band of about 2.5mm. For the phase 2 automation, systems were designed to enable measurement of the stem height post installation. This was accomplished by integrating a high-accuracy encoder into the axial compliance base of the hole probe. No additional process tools were required as the same tool that is used to measure hole and countersink diameter is subsequently used to measure the stem height.

The remaining fastener stems must eventually be removed (shaved) for aerodynamic reasons (figure 6). The shaved stem height is closely monitored for conformance to strict height near flush $\pm 0.1\text{mm}$ ($\pm 0.004''$). In addition to hole diameter and stem height measurement, the probe is utilized for the third process of measuring the height of the shaved stem. Testing has shown the measurement accuracy to be within $\pm 0.03\text{mm}$ ($\pm 0.001''$). Phase I systems incorporated a single drilling spindle, so shaving and subsequent measurement requires returning to the hole location post install. Follow on phases incorporate dual spindles to enable all processes to be completed in a single pass.

Dual Spindle Operations

Two purpose-designed spindles are utilized to accomplish machining tasks at locations that require two different setups. A common issue with twist-style blind bolts is the need to shave the stem in order to meet flushness requirements. Two spindles were identified to allow stem shaving after installation.

With the inclusion of a second spindle numerous operations can be completed whereas the same operations require at least two clamp cycles to fulfill with the previous one-spindle MFEE configuration. With the goal of minimizing overall cycle time, a systems approach is used to identify opportunities where processes can be performed in parallel and other instances where tool configuration provides the capability to realize improvement.

With the requirement to shave the core bolt of the blind bolt flush after installation, the ability to perform this task immediately following installation eliminates the need to perform a tool change and revisit each fastener location. This eliminates the need to re-clamp and normalize, as well as the time and distance traveling back to each location. Numerous studies were performed to quantify the time savings and with the inclusion of the second spindle, the same operation has a cycle time reduction of at least 30 percent. In addition to reducing the processing time for an assembly, this

ultimately provides additional machine capacity since the work is being performed faster.



Figure 6. Blind fasteners installed and shaved flush with the OML

Another viable use of the second spindle is for performing reaming operations. Based on the scope of the automation, reaming is limited to the stacks inclusive of titanium, which is commonly machined at a low speed. Since the second spindle is rated for 1k RPM it is ideal for performing this task. In this case a pre-ream hole can be prepared with the first spindle, and followed by a reaming operation with the second spindle. In this example, an approximate cycle time reduction of the same magnitude is realized on a one to one basis.

A new capability under study is the ability to utilize the MFEE's process tool shuttle table positioning ability to plunge axially with an eccentric offset induced and subsequently perform radial milling operations on core bolts. This is primarily to shave the core bolt on sub-flush fasteners while also improving shaved-stem quality. This has the potential to extend cutter life for setups that are currently axially plunged only. With an axial offset, and end mill can plunge while using the cutting edges in a more traditional milling operation.

Automated Mastering

All industrial robots incorporate some means for checking and setting the axes absolute positions, commonly referred to as "mastering". For a variety of reasons there are occasions when the absolute position of an axis is lost. Further, in many cases loss of mastering can go undetected and is only discovered if an accuracy issue is noticed or if manual verifications are performed on a periodic basis. With the dual encoder Accurate Robot supplied by Electroimpact, each robot axis can be automatically verified to be within tolerance, guaranteeing that positional accuracy is maintained. To accomplish, each motor is fitted with an absolute, safety-rated, encoder and each axis output is fitted with an absolute external encoder. Following first mastering when the system is commissioned, the robot is driven to a specific pose approached from a consistent direction to eliminate drivetrain backlash. At this pose, the offset between the motor encoder and external encoder for each joint is saved. Subsequently, any time the robot is moved to the mastering verification pose, the values can be compared. This can be completely transparent to the operation of the system and ideally is set up as a common waypoint to enable seamless and frequent verification. This health check can flag errors if only a few thousands of a degree in deviation is noted.

The operator or maintenance personnel are alerted via the HMI as to which axis is suspect and by its magnitude. Not only does this automated health check prevent defects on the production assemblies, but it also serves to minimize redundant manual mastering that is time consuming and normally performed as part of periodic maintenance activities.

Full Rate Production

All rate system design, configuration, and functionality follows the principal requirements and deliverables as seen on the initial phase of systems [1]. Standardization of systems is a fundamental goal while introducing future phases of automation within. This allows for commonality amongst systems, standardization of methods and training, which is highly desirable for the end users. Further, subsystems are arranged to provide for optimal assembly processing as well as operator and maintenance conveniences.

Full rate production logistics are highly considered relative to the planning and installation of future systems. In order to maintain capacity, new systems are scheduled for future deployments to meet demand. To protect for this capacity, the systems are primarily arranged by major assembly family, and the drilling cycle times per those assemblies.

A key element to the phased approach regards the deployment of future automated cells with minimal disruption to existing operations. Systems are deployed in rate-complemented batches to stay competitive with investments, and best utilize existing machining capacities of existing platforms. To support this strategy, the factory is designed for numerous automation phases enabling a batch of cells to be deployed increasing drill capacity (Figure 8). Systems are identified in order of deployment to minimize distance of assembly travel to initially shared systems based on weighted criteria such as assembly and tooling size. Due to this design the low rate cells offer a multitude of processing capabilities, mainly in cell size which is driven by track length and the selection of some robots to work on either side of that track. Where practical, adjacent systems supporting similar product families are arranged such that these systems can serve as a backup platforms if needed. System configuration decisions include cell provisions for assembly tooling, safety controls, NC programming, and resource flow.

Figure 8. Overview of in-work automation layout consisting of the first three (3) phases inclusive of 11 robots. Rn refers to the robot cell integration number. Robot cells sizes shown are relative.

The sizes of the automation cells are dictated by the processed commodities and safeguarding requirements. A natural inclination is to make the cells large to satisfy these criteria, however given a fixed available factory floor space, each cell's footprint must be minimized in order to maximize the automation density for FRP. Cell perimeter guarding is comprised of both physical fencing and electronic safeguards, in this case light curtains (figures 9 and 10). To address each product, the robots must exhibit a large amount of articulation including reaching high, low, outstretched, and so on. The main axes are hard-limited to bind their working volume as much as feasible. Though axes are not typically at their respective extents in combination, the cell safeguards must protect for this case. Reliance only on ingress safeguards does not sufficiently reduce the automation foot print. To minimize, additional light curtains were integrated to "cage" the robot and supply a sufficient no-contact buffer zone for personnel ingress and/or automation stopping distance. Further cell reduction is realized by balancing maximum traversing speeds to achieve reasonable stopping distances while maintaining rapid automated production activities, along with additional electronic safety controls integrated on the present tooling within the cell and robot base [1].

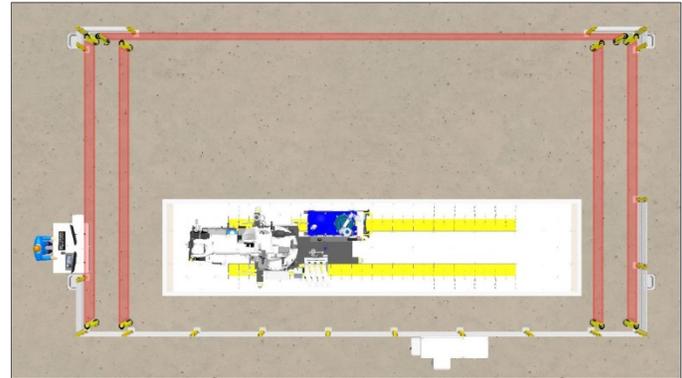


Figure 9. Overview of perimeter guarding.

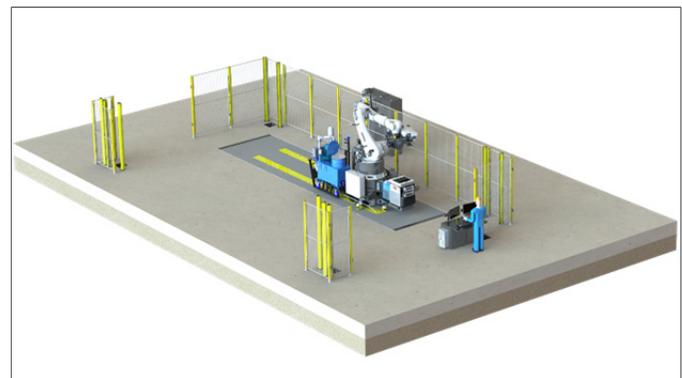
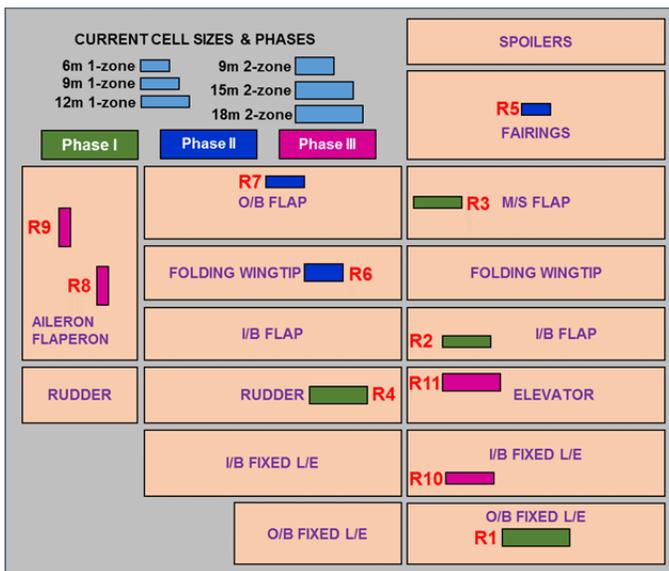


Figure 10. Overview of perimeter guarding.



Summary

Proven and cost effective technologies are progressively adopted by new and existing aircraft programs and operational facilities. Aligning these technologies to a structured production ramp up plan enables a low-risk approach to assembly automation. The latest

introduction of technology advances processing capabilities to minimize total run time and maximize system efficiency. Further system usage, such as flap carrier fitting hole preparation, is under evaluation on the path to full rate production to further automate additional processes.

References

1. Mir, R. and DeVlieg, R., "777X Control Surface Assembly Using Advanced Robotic Automation," SAE Technical Paper 2017-01-2092, 2017, doi:10.4271/2017-01-2092.
2. Saund, B. and DeVlieg, R., "High Accuracy Articulated Robots with CNC Control Systems," SAE Technical Paper 2013-01-2292, 2013, doi:10.4271/2013-01-2292.

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Definitions/Abbreviations

CNC	Computer Numerical Control
MFEE	Multi-function End Effector
OEM	Original Equipment Manufacturer
OML	Outer Mold Line
TCP	Tool Center Point