777X Control Surface Assembly Using Advanced Robotic Automation

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Abstract

Fabrication and assembly of the majority of control surfaces for Boeing's 777X airplane is completed at the Boeing Defense, Space and Security (BDS) site in St. Louis, Missouri. The former 777 airplane has been revamped to compete with affordability goals and contentious markets requiring cost-effective production technologies with high maturity and reliability. With tens of thousands of fasteners per shipset, the tasks of drilling, countersinking, hole inspection, and temporary fastener installation are automated. Additionally and wherever possible, blueprint fasteners are automatically installed. Initial production is supported by four (4) Electroimpact robotic systems embedded into a pulse-line production system requiring strategic processing and safeguarding solutions to manage several key layout, build and product flow constraints. Commonality amongst the robots was desired to allow each to effectively address any of the commodities which range from small fairings to very large empennage and leading edge assemblies that required the automation to work its way around from the upper to lower surface. Multi-function end effectors enable processes to be completed in one pass from initial hole preparation to installed fastener. Advanced safety systems are utilized which include programmable laser scanners on the robots and tooling that are automatically configured based on the present tooling. Operator access and part flow through the cell are paramount, driving the design of a flush floor rail system and the ability to operate robots in dual zones, further driving the requirement for flexible cell processing and safeguarding techniques.

Introduction

An affordable solution designed through strategic planning revealed the St. Louis Boeing facility as a main entity within the 777X aircraft's global supply chain. Across every stage of the aircraft program from design to build, St. Louis is primarily responsible for delivering most of the 777X control surface assemblies to Boeing's twin-aisle final assembly plant in Everett, Washington. On-site resident expertise, involvement with technologies that helped shape the current optimization of aircraft assembly processes and a phased-implementation approach would prove to be key in winning the work package and serving a new aircraft program from low rate initial production to the delivery of numerous airplanes per year.

Automated assembly systems were selected as the primary hole-preparation and fastener installation platform due to their high degree of process control and first pass quality by automating repeatable tasks that are often labor intensive and prone to ergonomic risks. In order to justify the inclusion of these systems a timely ROI had to be realized. Specified robotic systems delivered by Electroimpact were key in providing a low-cost approach to automate numerous processes across a variety of assembly sizes and geometries. Coupling this with a linear bedway drastically increased the work envelope at a marginal cost in comparison to traditional bespoke machinery.

Just-in-time manufacturing delivers detail parts to the assembly facility where the assemblies' structural build begins and ultimately processes through a series of stations. The production system is arranged to provide independent assembly lines that produce many of the airplanes fixed and moveable flight control surfaces including several wing and empennage edges, flaps, and the innovative folding wingtip assemblies. This work package (figure 1) is comprised of materials consisting primarily of CFRP and where necessary, aluminum and titanium.

Figure 1. St. Louis 777X control surface assembly work package

The assemblies are transported through the production system to various stations in transportable assembly tooling. The production system is based around lean concepts including single-piece flow. A pulse-line allows for the product to be processed among balanced stations that pulse at Takts designed around given customer demand. The processing begins in the first station that is typically reserved for structural build-up and component location in preparation of a second station, automated drilling and fastening (as identified), which is followed by a final station for cleanup and manual fastener installation.

A phased implementation plan provides for timely investments of these systems that perform as the primary resource for a majority of the work package's mold-line drilling applications. Four systems will support early manufacturing efforts while the facility has been designed for future systems to be phased-in as needed to match required capacity. For this reason, commonality amongst systems was foremost for servicing the diverse set of assemblies at startup whereas the systems would become partially or completely dedicated to any given assembly after production system maturation.

The end goal is to achieve one-up assembly on products where possible, typically those with close out skins and where field removal for inspection or maintenance is not a requirement. To achieve one-up assembly, a system and supporting drill processes are needed to demonstrate high degrees of capability and control. Several features make this possible from temporary fastening capabilities that allow for periodic and adjacent clamp up when needed. This allows for increased touch time per product and ultimately affords the production system opportunities to produce more product in less time.

Automation Process

The primary function of the subject automation is to prepare accurate holes and countersinks to enable fastening of structural components. In addition to this primary function, additional features are utilized whenever feasible, such as automated hole inspection, temporary and/or permanent fastening, and fastener stem shaving. The fundamental design philosophy is to complete as much as possible in a single pass, therefore the robot end effectors are multi-function and carry a spindle, hole measurement probe, vision system camera, and up to two fastening modules (figure 2).

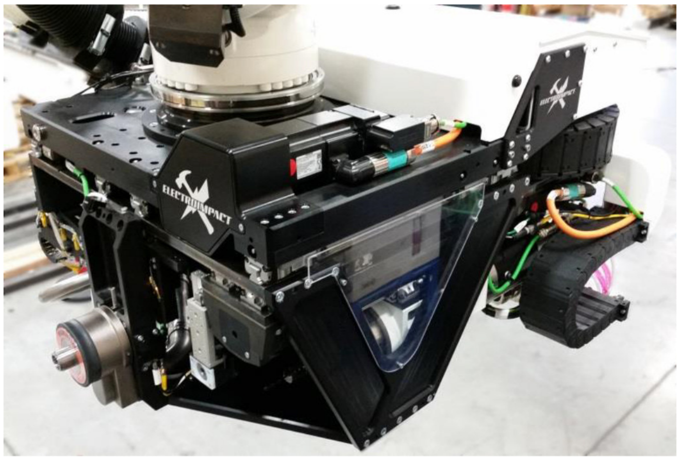

Figure 2. Electroimpact multi-function end effector

A typical one-pass, multi-function process consists of applying controlled pressure to the work piece, normalization, single-shot drill and countersink, hole inspection, and fastener installation. The noted functions are largely independent and generally run in a serial fashion as each tends to facilitate the next.

One-Sided Pressure and Auto-Normalization

Contact between the automation and the work piece is established prior to performing assembly operations and remains in contact until all operations are complete (figure 3). This initial step is critical for the following reasons:

1. The location of the work piece surface is known which facilitates accurate countersinking.
2. Contact provides an angular reference and enables the ability to auto-normalize.
3. Stability is significantly increased. As designed/implemented, the sum of forces remains constant at the work piece and at the robot even when applying significant drill thrust loads. A paramount feature for obtaining high-quality holes when using an articulated arm as the primary motion platform.
4. Gaps between structural components are closed (e.g. skin to spar/rib) preventing localized ingress of interlaminar swarf.

Figure 3. Automation "clamped" against [test] work piece

One-sided pressure, commonly referred to as "clamp", occurs between the end effector nose piece tip and the outer layer of the work piece. The nose piece is rigidly attached to the "clamp axis" of the end effector which actuates via servo control linearly and parallel to the spindle feed direction. A load cell is integrated behind the nose piece to provide force feedback and is used for closed-loop control of the axis when clamping. Once contact is established, the gimballing tip is passively forced normal to the contact surface, the 2DOF angle is detected via internal sensors, and the robot is closed-loop driven about the TCP to establish normality within 0.05°. In very high curvature regions such as the forward section of the fixed leading edge, a pneumatically-actuated multi-point lander is utilized to retain the ability to auto-normalize [1]. In addition to detecting the contact angle, the nose piece contains technologies to provide lubricant to the drilling point, provide blast air to clear chips from the drill flutes, and extract coolant and swarf.

Hole Preparation

Once clamping and normalizing are complete, drilling can commence. Material stacks are generally drilled from blank with the exception of occasional pilot holes or tack fasteners that require automated drill out. For the 777X control surfaces, material stacks can consist of any combination of CFRP, fiberglass, aluminum, and/or titanium. The spindle motor (figure 4) is configured to offer high torque at low speeds (> 200 rpm) for titanium drilling, yet still be able to spin at 20,000 rpm if needed for softer materials. In combination with the servo-controlled feed system, feeds and speeds are tailored for each layer in the stack to optimize cutting efficiency. Boeing has selected the use of 3-piece combined drill/countersink cutters for use wherever possible. The combination enables the hole and countersink to be produced in a single shot and 3-piece construction saves on perishable tooling costs. Boeing tailored processes using low flow coolant delivery at the TCP (~0.5 liters/min). The coolant serves to lubricate the cutting action, reduce heat, and wash away chips and composite. Swarf and coolant is collected from the nose piece via a remotely-mounted vacuum where the coolant is filtered and recirculated. The system is completely self-contained with no external leakage observed.

Countersink depths are controlled programmatically, therefore precise control is required of the feed system. The spindle process tool incorporates a servo-controlled quill axis with secondary encoder feedback enabling position accuracy of < 0.0025mm (0.0001"). The feed position is calibrated in relation to the tip of the nose piece since the tip is coincident with the panel when the system is clamped.

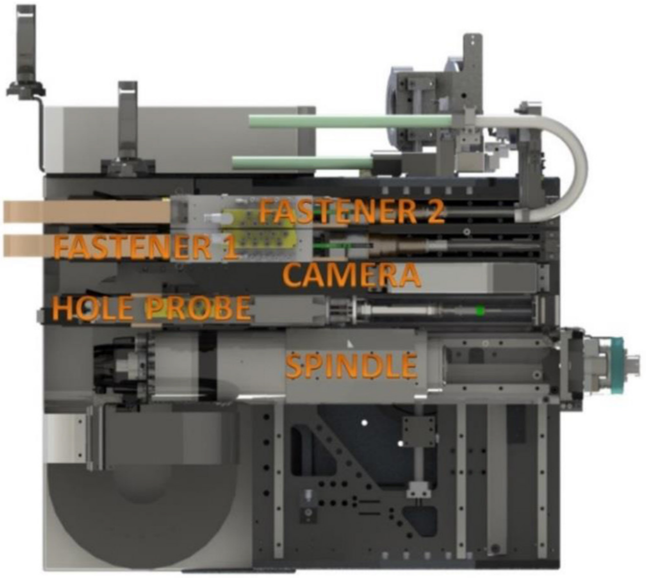

Figure 4. Bottom view of end effector with chassis hidden to show layout of process tools

In structures where nut plates are installed, the automation also drills the nut plate attachment holes. After the main holes are drilled and countersunk, the skins are removed manually exposing the substructure. The automation is programmed to return to the main hole, but assumes the substructure has moved and performs an automated "resync" using the vision system to accurately align. Using a specially-designed nose piece to allow shuttling of the spindle internally (figure 5), the end effector is aligned to the desired orientation of the nut plate and the two holes are drilled and countersunk in one clamp up pass. Nut plates are installed manually in the next stage of assembly.

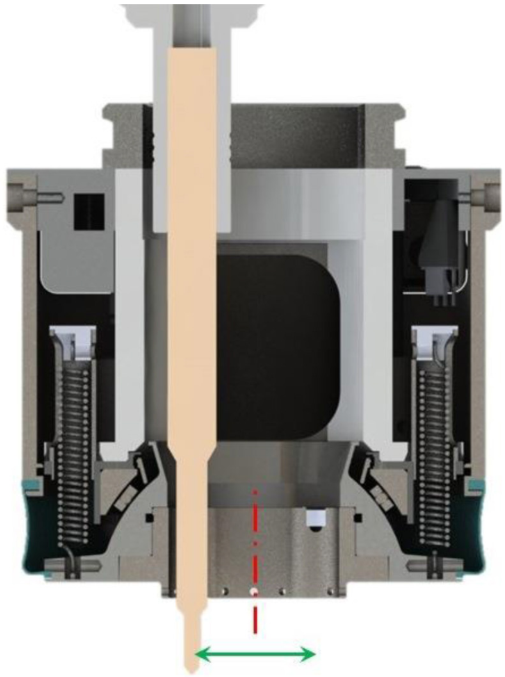

Figure 5. Cross-section of nut plate nose piece allowing internal shuttling of the cutting tool

Hole Measurement

Inspection of drilled holes is generally required and typically handled downstream of the drilling cell which adds an additional step to the production process. In cases where automation is limited to only drilling, the inspection step can be avoided until later although not desirable. If a fastener is to be installed with the automation, inspection of the hole is required, therefore the subject robot systems utilize integrated hole measurement probes. In-process hole measurement has the following advantages:

1. Measured features are linked to unique hole IDs and stored for further analysis. The need for manual measurement downstream is eliminated.
2. Out-of-tolerance conditions are immediately flagged limiting any quality issues to a single hole rather than a large aircraft section.
3. Grip measurement is used to select appropriate length fasteners - especially important in composite structures where ply thicknesses can vary significantly.

The hole probe process tool resides adjacent to the spindle (figure 4). The 6 second automated inspection routine returns three distinct measurements, namely the diameter profile at 0° and 90°, the countersink depth, and the grip measurement (stack thickness) [2]. The probe utilizes an off-the-shelf contact-style 2-point ball gage to reference the inside of the hole as well as the transitions from entrance to exit. The deflection of the balls passively actuates an internal shaft and the motion of this shaft is digitally captured using a high-accuracy linear encoder (figure 6). Measurement of the countersink depth utilizes the same encoder at a different region in its stroke. The probe is extended far enough to contact the countersink surface and the spring-loaded panel reference lander is pushed back. The relative position of the lander is captured by the encoder to report the countersink depth.

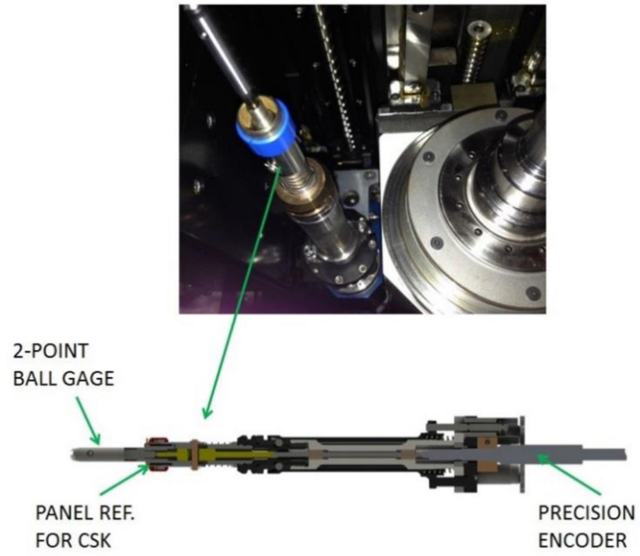

Figure 6. Hole probe process tool and cross-section of measurement gage

Fastener Installation

Fully-outfitted, the multi-function end effector is designed to install two fastener types - Centrix temporary bolts (figure 7) and BACB30VK permanent fasteners (figure 8) both with nominal shank diameters of 3/16” or 1/4”.

Figure 7. 3/16” and 1/4” Centrix fasteners (Centrix, LLC)

Figure 8. BACB30VK twist-type blind bolts

The temporary Centrix fasteners are used stabilize the structure as drilling progresses by providing both clamp up and dowel actions. These removable and reusable bolts are installed automatically at a frequency determined by Boeing (e.g. once every 10 holes). The fastening module (figure 4) contains both a feed axis to stake the bolt in the hole as well as a spindle (a.k.a. “nut runner”) to twist the core bolt to thread the fastener up to provide a clamping action. The final torque on the fastener, and thus preload, is precisely controlled via the nut runner controller. Once the automated drilling and temporary fastening is complete, the assembly is moved to the next station and the fasteners are manually removed to enable structure disassembly.

In structures suitable for one-up permanent fastening, Boeing is utilizing the BACBVK30 twist-type blind fastener for automated installations. Like the Centrix, the BACB30VK insertion module also requires a feed axis and spindle to run in the bolts. In contrast to the Centrix, however, the permanent fastener is twisted until the inner core bolt shears. The sheared “tail” of the fastener must be discarded which is accomplished by ejecting it into a vacuum tube that carries it to a collection bin (figure 9). The core bolt remaining in the installed fastener must be shaved flush. At the end of the structure’s assembly process, a shaving bit is installed in the spindle and stems are cut down to flush automatically.

Figure 9. Fastener stem collection bin

In-Process Validations

To ensure the automated equipment is performing the programmed tasks with high-quality and accuracy, internal validations and in-process error checking is utilized.

Prior to Drilling

When a new tool/structure is brought into the assembly cell, the location of key features such as datum holes or tack rivet heads are automatically scanned using the on-board vision system camera (figure 4). For maximized accuracy, the camera is positioned such that its view is through the axis of the spindle enabling scanning to occur in the same robot pose as used when drilling. The actual position of these key features determined by the vision system are used to register the part to the robot coordinate frame ensuring that holes/fasteners will be placed correctly.

Feedback Related to Drilling

Cutting tools are exchanged automatically. To ensure the proper tool is loaded in the spindle, an on-board RFID system is incorporated into the end effector to enable the ability to read/write on the end effector. After the tool data is verified, which includes data for the overall length of the setup, the length of the setup is measured via a sensor in the end effector and compared to the expected length. Any discrepancies are flagged and the automation is paused until remedied.

When drilling, a coolant flow sensor is used to ensure lubrication is being delivered as commanded and a vacuum sensor is integrated to detect proper swarf extraction. While cutting, the drilling thrust is being monitored real-time. This data is used to detect a worn or damaged cutter and is also used to track the cutter wear.

Prior to drilling on the aircraft structure, tools that have not been flagged as "qualified" are first drilled automatically at an integrated coupon stand. Holes are measured using the hole probe to ensure the diameter is in tolerance and the countersink depth is adjusted properly.

Feedback after Drilling

As previously described, the hole measurement probe is used immediately following hole drilling and countersinking. Any measurements of diameter, countersink, or stack thickness are immediately known to be in or out of tolerance.

Feedback Related to Fastening

To minimize cycle time, fasteners are pre-fed to the end effector based on the anticipated stack thickness. As fasteners are received, a gripping mechanism with position feedback clamps on the shank of the bolt (temp or permanent fastener) to measure the diameter. When transferred to the insertion module, the grip length of the bolt is measured yielding a complete inspection of the fastener. This is validated against the expected fastener dimensions and purged if incorrect. Additionally, if the hole probe reports a stack thickness differing enough from expected to warrant a different length fastener, the existing is purged and a new fastener is sent, inspected, and installed.

The spindles used to twist both fastener types incorporate angle encoders and torque transducers. Signature profiles of torque vs. angle are expected when running either type. Should the rundown of the fastener complete and not meet the specific criteria, a flag is raised and the machine is paused until remedied.

Hole Positioning and Motion Platform

The tool center point (TCP) of the system is located at the nose of the end effector and must be accurately presented to the work piece in 6DOF. An off-the-shelf articulated arm with 3.3m reach and 340kg payload was needed to handle the required working range and the mass of the end effector. An additional 7th axis was integrated to linearly increase the working range to address parts with lengths exceeding the reach of the robot. The additional (redundant) axis can also help to significantly reduce/eliminate robot singularities.

Accurate Robot

Boeing selected the use of Electroimpact's *Accurate* robot [3] which can meet the need for sub 0.25mm (0.010") global positional accuracy on part. This is critical for placing holes/fasteners accurately with or without datum features nearby. Additionally, high omni-directional repeatability of < 0.063mm (0.0025") is required for returning to holes for reaming operations.

In stock form, off-the-shelf robots will not meet the stated tolerances. To improve the stiffness and accuracy of these systems, high precision encoders are added to each of the robot's joints to read actual joint positions as opposed to inferred positions from the motor encoders. Use of this feedback yields greatly-improved repeatability enabling ideal conditions to pair with an optimized kinematic model to produce a motion platform of high accuracy and high stiffness. This provides a low cost, yet accurate positioning system that remains accurate for much longer than conventional robots since changes in stiffness/backlash in the axes due to wear over time is washed out by the additional encoders.

7th Axis

Each of the four systems includes a linear axis to increase the working volume. Based on the size of the commodities presented to each cell, the working strokes vary from 10.5m to 16.5m. All the ancillary components, less the main CNC controller, are carried along with the robot on the 7th axis "sled". This includes the automatic tool changer (ATC), spindle chiller, fastener feed system(s), vacuum, nut runner controller(s), and electrical junction box. Motion of the sled is dual servo-controlled running with "tension torque" to eliminate backlash. Power transmission is delivered through dual gearboxes/pinions to a helical rack.

The linear axes are designed for high stiffness and alignment stability. The bed is constructed from welded plate steel with the load path optimized to go directly from the robot to the foundation. Bed sections are constructed in standard lengths and mounted in series to produce desired working strokes. The beds are leveled and straightened using locking jacking bolts ("triplets") at a pitch optimized to yield negligible changes in stiffness as a function of sled position (i.e. no measurable cyclical deflection when traversed from end to end). The way system utilizes dual size 65 profiled roller rails with four bearing cars, one at each corner of the sled.

The linear axes run the length of the majority of the cell. When tooling is present, manual access between the bedway and tooling can potentially be tight and in some cases space constraints completely prevent access for items such as carts, steps, etc. For the installation at Boeing for the 777X control surfaces, the linear axes are mounted just below the factory floor level (figures 10) and a system of passive way covers are utilized to allow the robot/sled to pass just over the factory floor (figure 11). This allows easy access to the products/tools in the cell, eliminates trip hazards, and protects the ways and utility cable tracks.

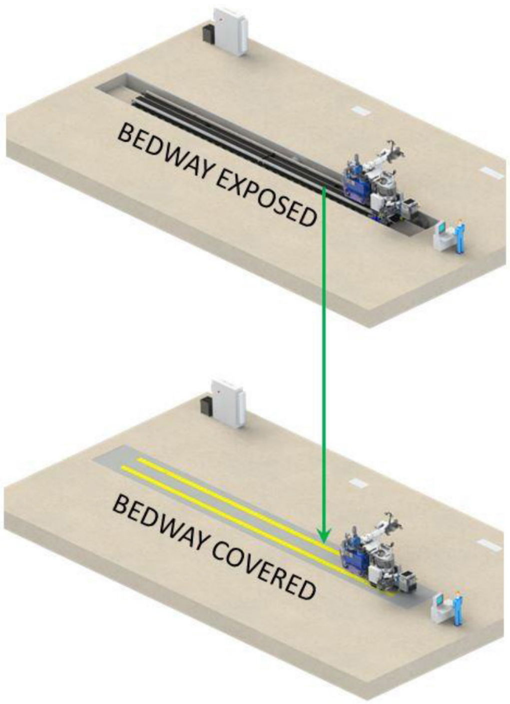

Figure 10. Bedways mounted below grade

Figure 11. Electroimpact flush floor bedway system with passive way covers

Safe Operation

Personnel safety was paramount while considering the design of the cell and selection of safeguarding controls. Compliance with recently developed company safety policies along with industry specific safety regulations - mainly ANSI's robotic safety standard (RIA 15.06-2012) - were met through the integration of numerous layers of controls ranging from ESPE to rigorous internal risk management processes. Physical building limitations, unique build requirements, and inner-plant assembly and tool flow were fundamental considerations in arriving at a unique solution that allows for universal cell safeguarding. With this approach, dual sided cells can serve tools on either side of their bedway and allow for the reutilization of safety hardware for any anticipated assembly that is scheduled to any given system. An added benefit is the ability to identify the active tool in the cell allowing for a cross check of program selection and positive verification prior to commencing operations.

Each cell is outfitted with a series of light curtain sets and fencing to provide for complete cell perimeter protection. This is complimented with inner-cell safety laser scanners that effectively create a protective boundary around the equipment, work part, and tooling. These scanners are resident on the motion platform as well as installed on any tool while processed within the cell. The tooling includes a circuitry system and universal hardware designed to offer interchangeable safety controls, offering a leaner and more cost-effective solution. The intent of this is to first keep personnel from entering the cell and second to detect any object that does not ordinarily belong within the cell. This added benefit also protects against inadvertent reset and operation once anything is beyond the projection plane of the light curtains. A typical cell layout is shown in figure 12. The ESPE equipment ultimately provides OSSD outputs to the controlled via the failsafe hardware coupled with software that is certified for managing these peripherals in a safe and programmatic fashion. Due to currently planned operations, manual intervention is not required during machine operation and further the operator is safely positioned outside of the cell's envelope at all times during operation. These controls combined with a cell monitoring system, awareness measures, training programs, etc., successfully mitigated or eliminated all potential hazards.

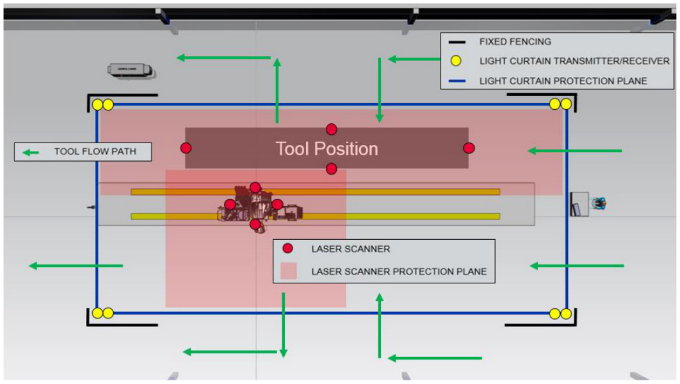

Figure 12. Typical cell layout at startup capable of serving many assemblies with identified safeguarding controls

Conclusion

The manufacture and delivery of control surfaces is made possible through a uniquely designed system capable of meeting the required throughput rates through all courses of the programs life. Turnkey automated system deployment proves to support demanding program and delivery schedules in an efficient manner while meeting all production goals. New technologies and processes are being examined for feasibility and inclusion in order to further drive affordability goals and cost targets. Future potential and safe operating solutions may enable worker-machine collaboration that could prove to offer even higher levels of productivity.

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Definitions/Abbreviations

CFRP - Carbon Fiber-Reinforced Plastic

DOF - Degree(s) of Freedom

ESPE - Electronic Sensitive Protective Equipment

OSSD - Output Signal Switching Device

ROI - Return on Investment

TCP - Tool Center Point

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