INTEGRATING ULTRASONIC CUTTING WITH HIGH-ACCURACY ROBOTIC AUTOMATIC FIBER PLACEMENT FOR PRODUCTION FLEXIBILITY

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Dan Wells
Adam Walker
Electroimpact, Inc
4413 Chennault Beach Rd.
Mukilteo, WA 98275

ABSTRACT

To create a flexible method for manufacturing flat carbon fiber reinforced plastic (CFRP) charges, a 4-axis Ultrasonic Cutting Gantry and zone-controlled vacuum table has been integrated with a high-accuracy Automated Fiber Placement (AFP) robot. The high speed cutting gantry is outfitted with a 30 kHz ultrasonic knife and is capable of maximum speeds of 76 meters per minute. In addition to final trim, the ultrasonic cutting gantry is equipped with a mechanism for automatically spreading backing film over the vacuum table, a vision system, table mapping system, and a part marking device. The robot is an off-the-shelf 6-axis KUKA Titan KR1000L750 riding on a linear axis with its positioning enhanced by secondary feedback at each of its joints. This robot is outfitted with Electroimpact's modular AFP head technology. Although unto themselves the ultrasonic cutting gantry and the AFP robot function as separate machines, each running a dedicated Siemens 840Dsl CNC, Electroimpact has developed collision detection and safety software using position information from both machines. This allows for the creation of two distinct work zones. Beyond the advantage of layup and final trim occurring on the same table, the ability to switch from a full-table work zone to multiple work zones allows for the flexibility of having workers access the finished goods in one zone while the robot continues operation in the other, further increasing utilization.

Figure 1: Ultrasonic Cutting Gantry, Vacuum Table, AFP Robot.

1. INTRODUCTION

Building on its vast experience as an aerospace automation systems integrator, Electroimpact has combined its accurate robotic AFP system with a high speed 4-axis Ultrasonic Cutting Gantry (UCG) and zone-controlled vacuum table. This system is optimized to produce kits of single-ply flat CFRP charges whose layup time is similar to the time required for their precision trimming. The similarity in cycle times allows the machines to alternate between work zones and keep their utilization high, while the integration of both systems into the same table reduces handling and saves floor space. This style of system is in demand due to the fact that AFP can produce flat charges at near net shape and at higher rate than Automated Tape Laying (ATL). The increased productivity and dramatic reduction in waste of the integrated AFP/UCG system results in a fast return on investment when replacing an ATL flat charge system. In addition, the use of steered AFP layups has a distinct engineering advantage. Even in complex shapes, stress analysts and aerostructure designers can specify the tensile direction of fibers in each ply and create more efficient composite components.

Near Net Shape Example: Representative Fuselage Frame Flat Charge Kit

- 4.26m x 2.29m bounding box shown in green.
- Box has an area of 9.8m^2. This is the total area of wide tape or fabric required to produce this kit.
- Layup area shown in black is 3.9m^2.
- Result: 60% Wasted material

Continuous 1/4” (6.35mm) tows are steered along the length of the profiles. 1800mm minimum radius of curvature is pictured.

Figure 2: Near Net Shape Layup Efficiency Calculation.

Figure 3: Steered Fiber and Neat Net Shape Layups.

2. SYSTEM OVERVIEW

The integrated cell is comprised of three major components: the ultrasonic cutting gantry, accurate robot with modular AFP heads, and the vacuum table. Because this system alone will be supplying pieces to multiple downstream operations in the future, it has been designed to maximize throughput. The 16m (52ft) work surface of the vacuum table has been divided into two major work zones. To start production, the backing film is manually placed the "load position" in Zone 1. The operator will then instruct the UCG to pick up the end of the film and advance it to the end of the work zone. In the table, the vacuum will ramp up sequentially as the gantry traverses the table, helping to alleviate wrinkling. The gantry will then move to other work zone as the AFP robot begins work. As the rough charges are laid by the robot in Zone 1, the gantry can be spreading film in Zone 2. When the robot is finished, the UCG will enter the zone and begin precision trimming and part marking while the robot crosses back to Zone 2 to begin layups there. Workers can then remove the finished goods from Zone 1 and prepare the table for another layup kit while Zone 2 is being cut.

The table can also be configured as a single work zone of any length up to 16 meters. The operator has the option to command the gantry to advance the film over just the required number of table segments to produce a layup of given length.

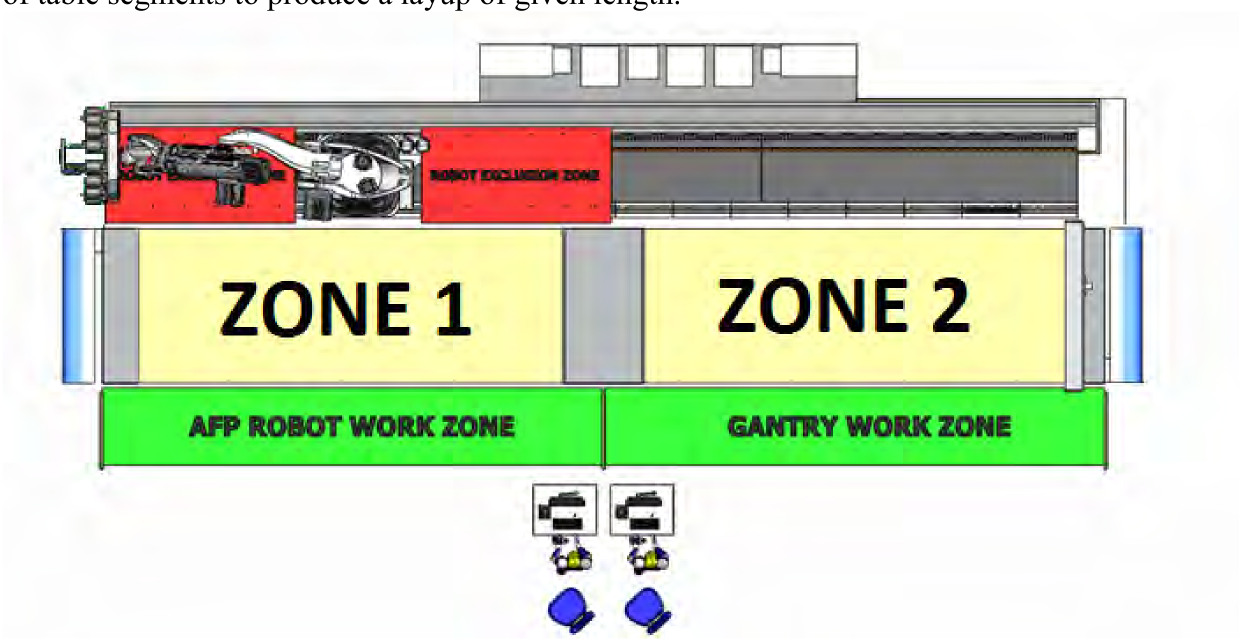

Figure 4: Work cell divided into two zones.

2.1 Multifunction Ultrasonic Cutting Gantry

The ultrasonic cutting gantry is a lightweight machine capable of speeds in excess of 76m/min (3000in/min) on its long and cross axes. Both light and stiff, it is outfitted with Siemens Automation servo motors with Multiturn Absolute Encoders allowing it to hold volumetric positional accuracy of +/-0.38mm (+/-0.015in) and repeatability of +/-0.13mm (+/-0.005in). The low mass components allow the UCG to be driven by greaseless systems such as synchronous belts and fiber-reinforced plastic pinion gears; a very important consideration when operating over uncured composites. At the heart of the machine is the ultrasonic knife stack. The custom iQ series 30,000Hz system is supplied by Dukane Intelligent Assembly Solutions and features a one-piece solid titanium horn and an 18mm carbide blade for precision trimming. At the top of the transducer, the ultrasonic signal passes through a sealed mercury contactor allowing the steering axis to rotate infinitely. The depth of cut is set by a precision ballscrew, compensated by data from the table mapping process.

Figure 5: Front view of Ultrasonic Cutting Gantry showing main process head.

Figure 6: Rear view of Ultrasonic Cutting Gantry showing backing film pickup mechanism.

Other tools carried by the gantry include:

- Film Pickup Mechanism: A vacuum assisted roller used to pick up the backing film from the table, trap it, and pull it to the desired location on the table.
- Table Mapping System: Used to precisely map the flatness of the table. To be used whenever the sacrificial vacuum/cutting surface is changed. The UCG will probe the

table in a raster pattern and record the data from the depth sensor on the probe arm. This data is added to the compensation table for the z-axis of the machine, improving the depth of cut accuracy to +/-0.075mm (+/-0.003in) at any point on the table. It can also be outfitted with a paint pen or marker and used as a pen plotter.

- InkJet Part Marker: High speed ink jet printing system supplied by REA-Jet. A small pressurized reservoir on the carriage supplies ink to the printing head.
- Part Location System: A contrast sensor is used to distinguish carbon from the sacrificial vacuum/cutting surface. This can be used to locate and trim parts not laid down by the AFP robot, further adding flexibility to the system.
- Toolpoint Camera: A wide angle camera is centered on the cutting knife and can see the operation of each tool. The images are transmitted to the operator station.
- Non-contact blade calibration: A recessed, subsurface laser at the end of the table measures both the length and orientation of the blade.

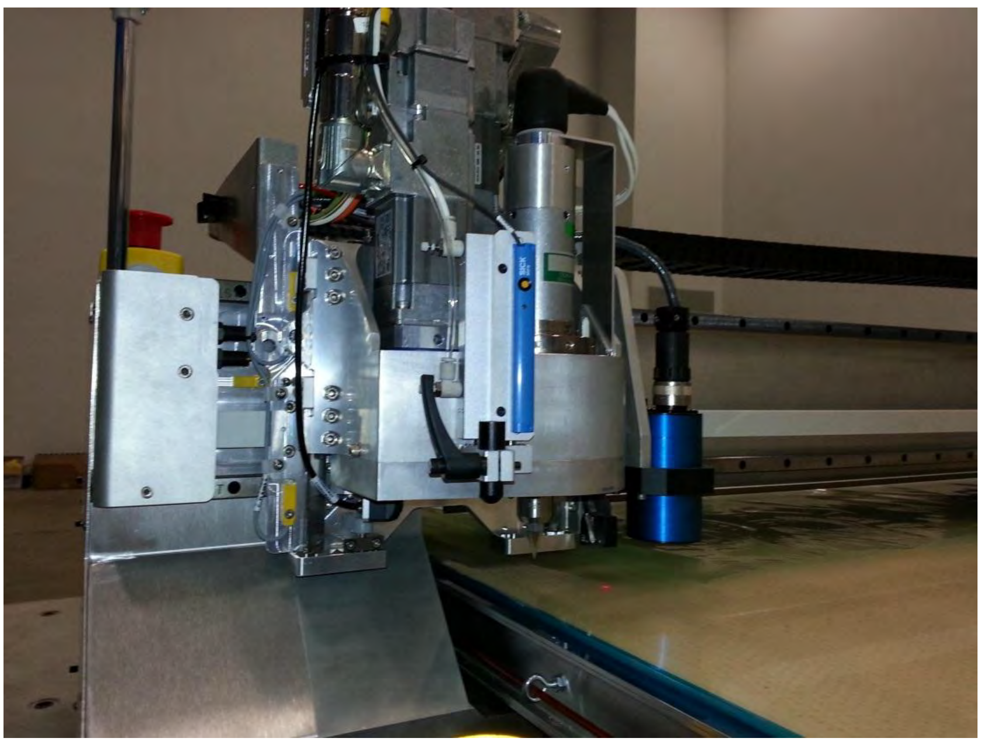

Figure 7: Close-up of process head. Tools from left to right: Toolpoint Camera, Table Mapper, Ultrasonic Knife, Contrast Sensor, Inkjet Printer.

In operation, the UCG trims single-ply layups consistently at 20m/min (800in/min). Thicker layups can be trimmed with a reduction in speed proportional to the thickness of the piece.

2.2 Vacuum Table

The cutting surface on the table is 16m (52ft) long by 2.5m (8ft) wide. At each end of the table are aluminum coupon plates for AFP tuning and an ultrasonic blade calibration station. That surface is divided into thirteen 1.2m (4ft) segments along its length which are serviced by four 4.5kW (6HP) vacuum blowers on controlled by variable frequency drives. The table segments are made of an aluminum honeycomb core with a perforated top surface. They are stiff enough to span the table and react the AFP compaction loads but still allow vacuum to be drawn through them easily. Each blower is capable of pulling 390m^3/hr (230ft^3/min) at 30kPa (120in of water) vacuum. On top of the vacuum segments is a continuous perforated sacrificial cutting surface which is tensioned at each end of the table and clamped tight on the edges. A creel is located at each of end of the table that houses the backing film. The creel features a tuned dancer system that maintains constant tension on the film as it advanced by the cutting gantry. It also has a braking system, tracking adjustment, and automated chuck to secure the film roll during loading. The table also serves as a base for the ultrasonic cutting gantry, housing its long axis linear components.

The table is controlled from the same operator interface as the gantry. From there, the operator can select which table segments receive vacuum and to what level they receive it. For example, the table can maintain a constant vacuum level in Zone 1 while ramping up the vacuum and sequentially activating segments to facilitate film spreading in Zone 2. This is accomplished using a series of pneumatically actuated gate valves mounted to the underside of each table segment.

Figure 8: Vacuum Table and Film Creel.

2.3 AFP Robot

For robotic automated fiber placement systems, the KUKA KR1000L750 was selected for its payload capacity and extended reach (see Figure 7). The robot arm utilizes large-section steel castings and a number of dual-drive servo axes to provide a payload rating of 750kg at a full reach of 3602mm. These features result in a system with high dynamic stiffness which helps maintain toolpoint positional accuracy while in motion on a complex path. To enhance positioning, Electroimpact has designed and installed optical secondary feedback at the joints, which feeds directly to the Siemens 840Dsl CNC.

Figure 9: Modular AFP Head on Accurate Robot.

Electroimpact has also developed a high-order kinematic model to enable high precision compensation of the toolpoint position. This kinematic compensation software is also executed on the Siemens 840Dsl CNC. The combination of optical encoders and software compensation allows correction of positional inaccuracies due to drivetrain deflections, drivetrain backlash, deflection due to payload, and deflection due to process force inputs. The secondary feedback also effectively stiffens the robot as it allows the CNC to react to positional inaccuracies due to either statically or dynamically applied forces during path motion.

In an AFP process, the inability to maintain path accuracy will result in course-to-course gaps, course overlaps, and tow end-placement errors. To prevent this low quality layup, feed rates must be reduced thereby reducing overall productivity. By utilizing the high payload robot with accurate robot technologies, the Electroimpact AFP Robot is capable of both the high speeds and high accelerations required to traverse a moderately contoured part while maintaining normality. The result is AFP layups that rival the speed, accuracy, and productivity of any non-robotic AFP machine.

2.3.1 Steering Axis Improvements on the AFP Robot

Electroimpact's latest generation of Accurate AFP robots now feature a high performance continuous steering axis (robot Axis 6). In many CFRP layups, productivity can be gained by performing bi-directional layups to reduce off-part motion. Typically a bi-directional ply would consist of a series of parallel courses. An AFP head would traverse a course, lift off the part, spin 180^{o}, then touch down on the part and traverse in the opposite direction on a parallel adjacent course. The higher the performance of the steering axis (commonly named the "C" axis), the faster the AFP head can spin and begin the next course. On a conventional industrial robot, Axis 6 is driven by a motor that is mounted near Axis 3 and utilizes a series of drive shafts and bevel gears to reach the end of the robot arm resulting in a low speed, high backlash drive. It is also necessary to route electrical cabling and pneumatic lines along the exterior of the robot arm to connect to an end effector. This cabling limits the useable travel of Axis 4 and 6, despite the fact that on the KR1000L750 they are mechanically continuous.

Electroimpact has developed a remedy to these limitations. The solution involves removing the stock Axis 6 gearbox and motor, and part of the Axis 6 drivetrain on the end of the robot arm. These components are replaced with a custom drive package that includes a servo motor, gearbox, belt drive, and crossed roller bearing (see Figure 8). The custom drive package also includes slip rings to transmit electrical signal, electrical power, and compressed air. The result is a high acceleration, high speed, continuous steering axis for an industrial robot AFP application.

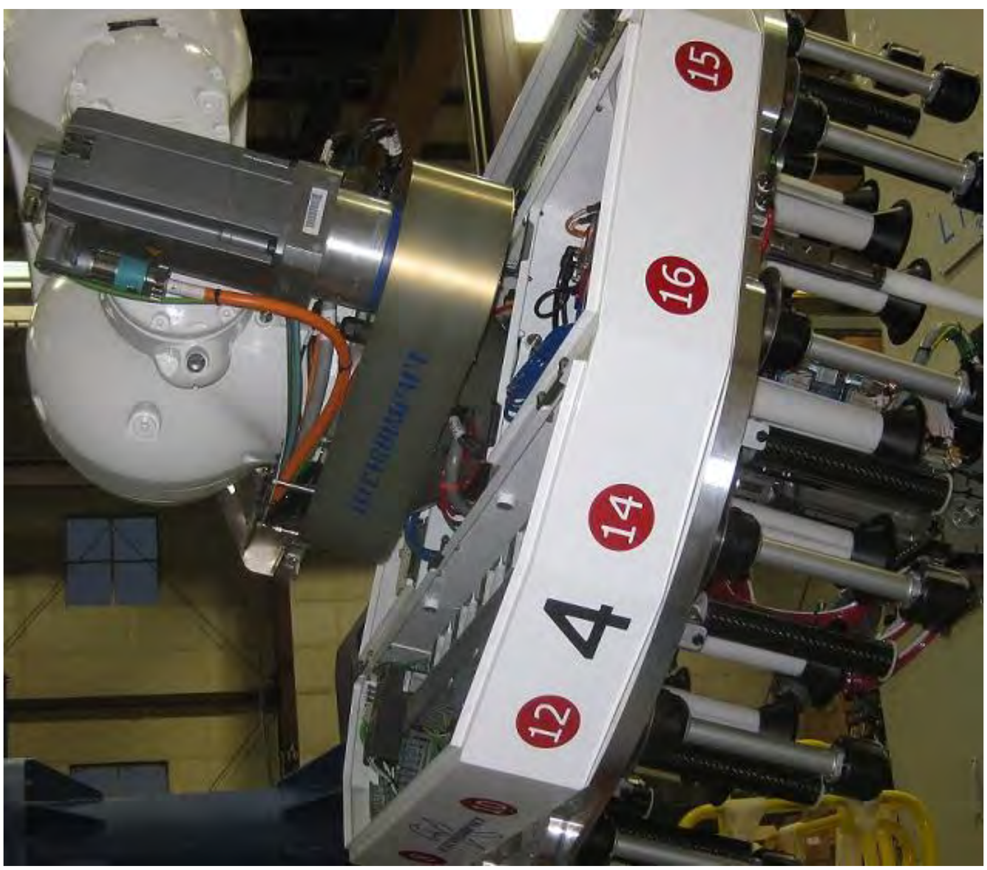

Figure 10: High speed Axis 6 (C-Axis) retrofit.

2.4 Modular Automated Fiber Placement (AFP) Heads

Electroimpact began development of AFP heads in 2004 for use in CFRP structure production for commercial aerospace. Several unique developments were made that improved the performance and reliability of automated fiber placement. Electroimpact AFP heads have been used in commercial aircraft production and have demonstrated high rate, high quality production. Some of the key characteristics of the AFP heads include:

- Robotic tool changer on the AFP head. This provides a quick-change interface allowing the entire head and creel to be moved offline. Typically a production cell will be paired with a set of “transfer stands” that allows AFP heads to be swapped in roughly 90 seconds. This enables the robot/ machine to maintain production while an AFP head is moved offline for cleaning and/or material loading. This interface also allows a quick-change of material forms, for instance, a single motion platform can utilize 1/8″, 1⁄4″, and 1⁄2″ tow AFP heads. Additional processes can also be introduced into the cell using this interface including ultrasonic cutting, automated tape laying (ATL), wide fabric handling, etc.
- Onboard creel. Every portion of the tow handling hardware and process is on the quick-change AFP head.
- Short, simple tow path. The simple short tow path minimizes the number of redirects and results in minimal threading time, elimination of tow twists on the part, and elimination of slit-tape tow overlap-splice breakage.
- No-tool access to areas that need cleaned. Eccentric cam latches are used to hold cut, feed, and clamp modules in place. The heater is retained with a spring loaded quick-release latch.
- Simplified tension system. The tension system is actively controlled to prevent slack tows in the creel.
- High speed add on-the-fly and cut on-the-fly. Actuators are designed to allow high speed tow add and cut without needing to stop or slow down toolpoint path motion.

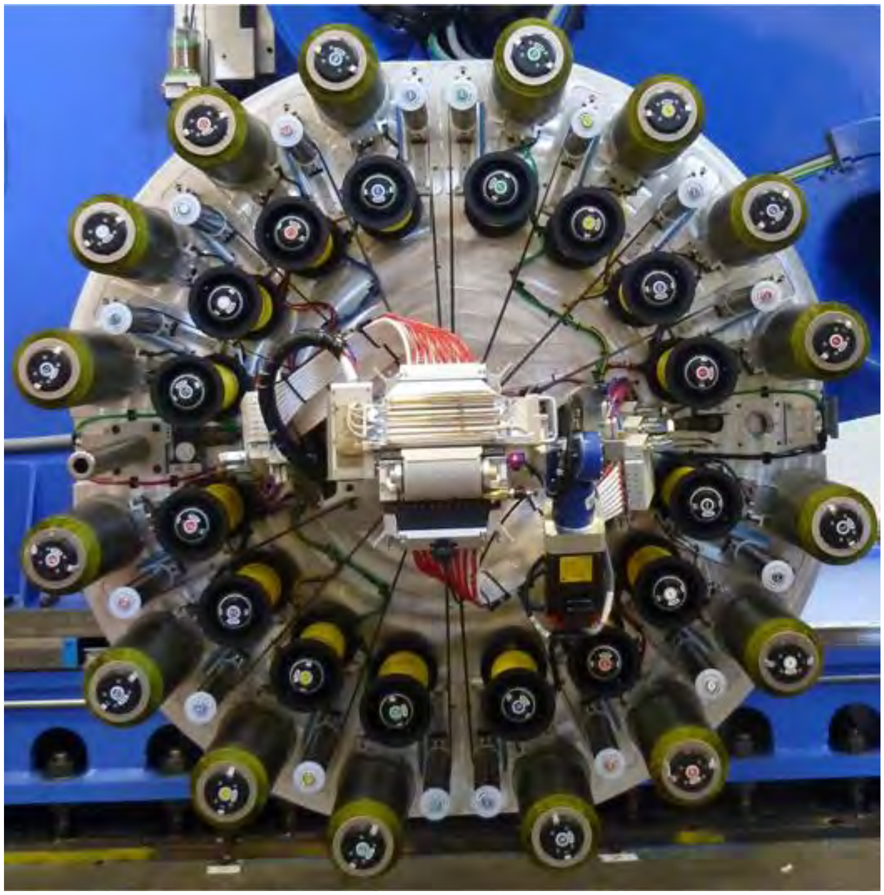

Figure 11: Electroimpact Modular AFP Head.

2.5 Safety

Having a single system combine multiple processes, both automated and manual, requires integrated safety and collision protection systems. As with all automation systems it delivers, Electroimpact has developed a safety strategy to protect both workers and the equipment. Though the AFP robot and the ultrasonic cutting gantry each have their own independent motion controller, a common coordinate frame is shared by both. The CNC of each machine exchanges position information with its counterpart allowing a number of safe moves to be programmed. Utilizing these safe moves makes machine-to-machine collisions virtually impossible. The robot cannot execute a program while the gantry is in its intended work zone and vice-versa. Also, the ultrasonic cutting gantry can be told the precise locations of the tows just laid by the robot.

Because the table is so wide, it is necessary for workers to have access to both sides in order to remove finished parts. For personnel safety, two laser scanners mounted on the front side of the table protect the active work zone from encroachment. Two more scanners mounted to the x-axis carriage of the robot guard the zone on the back side. When combined with audible warnings, light towers, long stroke bumper switches on the ultrasonic cutting gantry, and laser scanners, the CNC coordinated moves create an explicitly divided cell where people and automation can coexist safely.

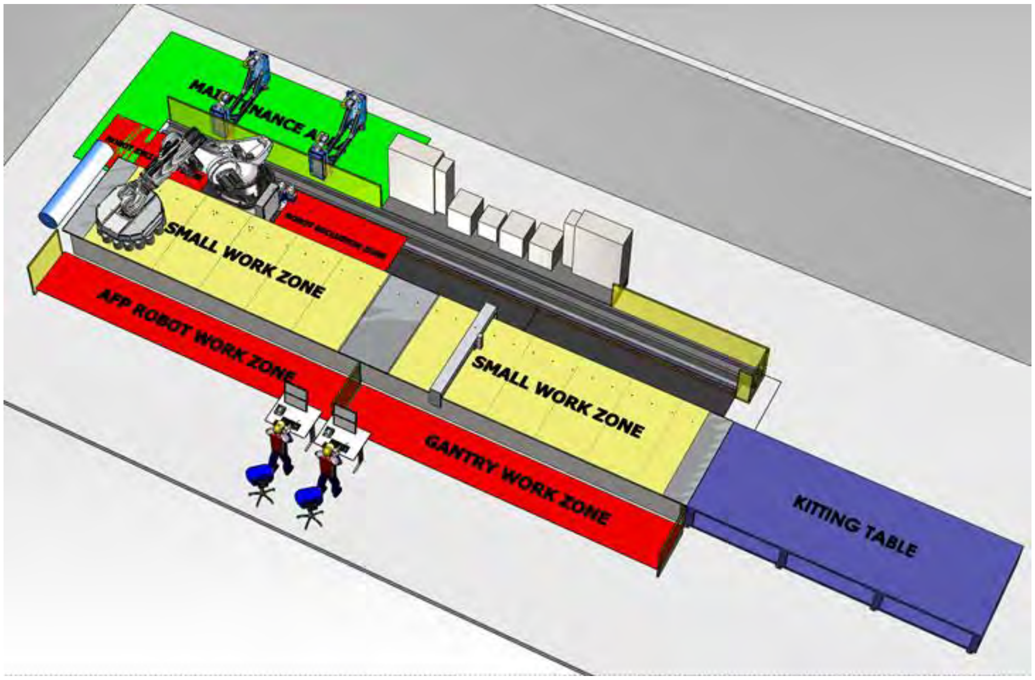

Figure 12: Example of safe zone configuration: Both Ultrasonic Cutting Gantry and AFP Robot working.

In the scenario pictured in Figure 10, both the robotic AFP zone and UCG zone are active. Operators cannot approach the table in either zone (shown in red) or the machines will feed hold. The operator, however, is free to access the spare AFP head in the maintenance area (shown in green). In Figure 11, both machines are parked giving operators access to all areas.

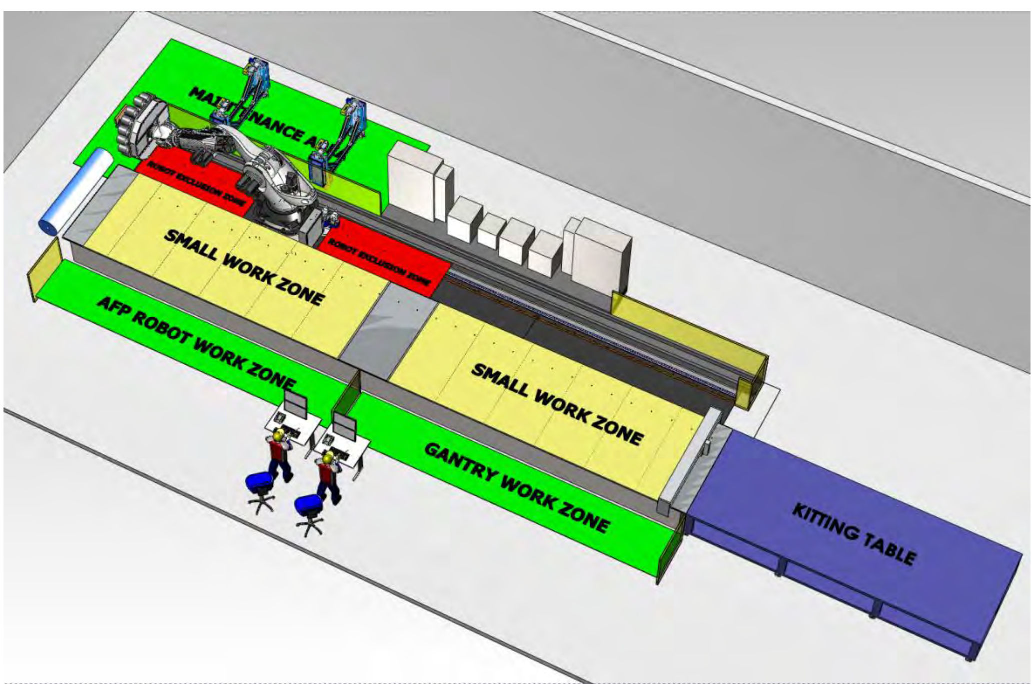

Figure 13: Example of safe zone configuration: Ultrasonic Cutting Gantry and AFP Robot Parked.

3. CONTINUED ULTRASONIC DEVELOPMENT

3.1 Combination Probing and Ultrasonic Cutting Head

The decision to pair an AFP robot and dedicated ultrasonic cutting gantry on a vacuum table is optimal when the CFRP layup time and precision trimming time are comparable. It allows the machines to alternate between work zones and have very high utilization rates. If, however, the layup time is very long (e.g. many plies thick) compared to the cutting time, a dedicated cutting system will have relatively low utilization in comparison. For this reason, Electroimpact has developed an ultrasonic cutting head. This head combines precision trimming with touch probing onboard a single multifunction device. A tool can be loaded into the cell and probed with the Cut/Probe head to establish its location and orientation. The machine will then switch to the AFP head for a multi-ply layup. When finished, the machine will swap back to the Cut/Probe head with the probe removed for the precision trimming operation. This arrangement saves handling time and floor space and reduces the need for a separate trimming machine. Like all Electroimpact modular heads, the Cut/Probe Head is outfitted with a robotic tool changer and is compatible with any Electroimpact AFP system.

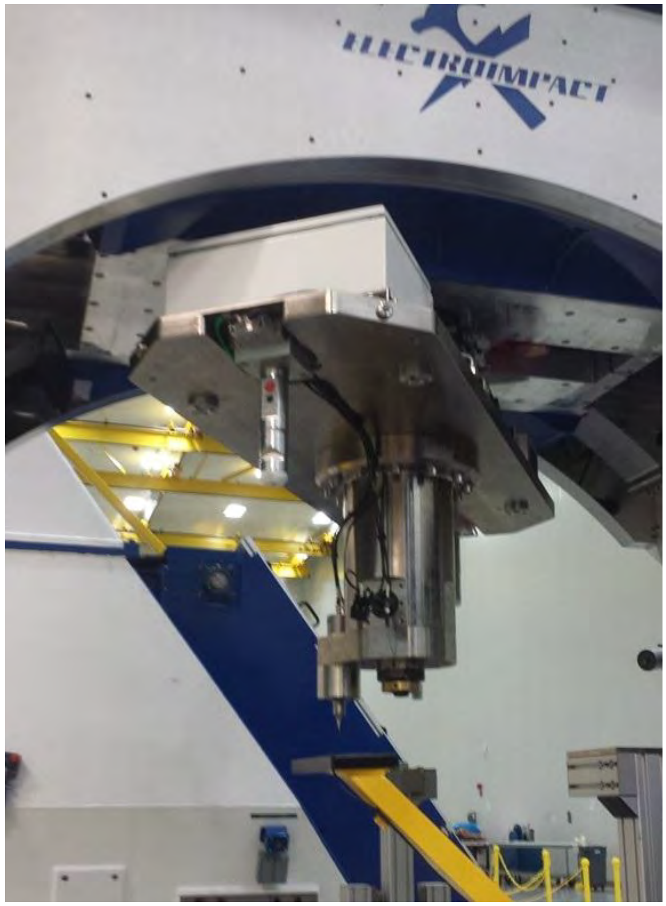

Figure 14: Electroimpact Modular Ultrasonic Cutting / Probing Head. Ultrasonic knife on the left, touch probe interface on the right. The touch probe itself is not present.

3.2 High Clearance Cutting Head

Currently under development at Electroimpact is a high clearance version of the modular cutting head. This head will have a smaller outer diameter and longer toolpoint length than the current Cut/Probe head offering. This will allow the head to make the very shallow angled cuts often required on complex aerostructures without interfering with the static tooling. The design goal is to operate between vertical and 30° from horizontal. As with Electroimpact's other modular heads, the high clearance ultrasonic cutting head will utilize quick change technology and will carry the ultrasonic generator and related components on board.

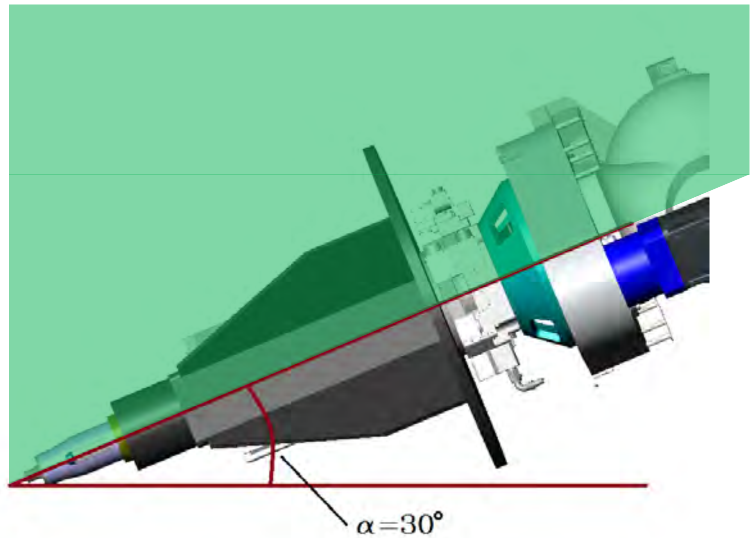

Figure 15: Rendering of High Clearance Ultrasonic Cutting Head at 30º from horizontal. Operating range shown in green.

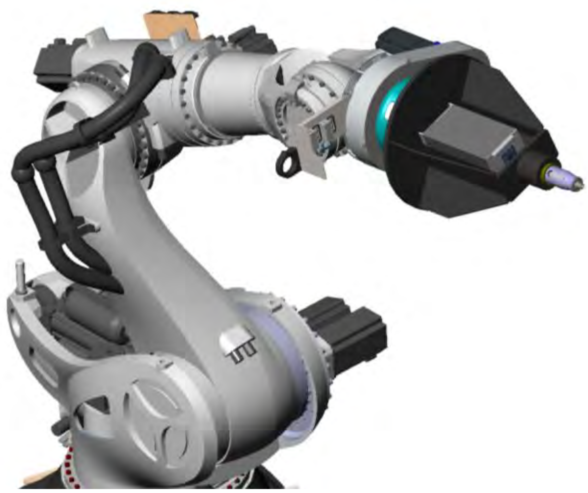

Figure 16: Rendering of High Clearance Ultrasonic Cutting Head on Accurate AFP Robot

4. CONCLUSION

The integration of a multifunction Ultrasonic Cutting Gantry and vacuum table with an Accurate AFP Robot is a system for producing flat charges which maximizes utilization and throughput. All operations from the application of backing film, AFP laydown, precision trimming, through part marking, are performed quickly and accurately on the same vacuum surface. The independent controls of the AFP robot and Ultrasonic Cutting Gantry provide the flexibility to run both systems simultaneously, while the tight integration ensures that they do so safely. Furthermore, the use of robotic tool changers and modular process heads ensures high robot utilization while allowing for expansion to different tow widths or processes as necessary in the future.

5. REFERENCES

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6. DEFINITIONS/ABBREVIATIONS

AFP - automated fiber placement
ATL - automated tape laying

CFRP - carbon fiber reinforced plastic
Slip Ring - an electromechanical device that allows the transmission of power and electrical signals from a stationary to a rotating structure
UCG – Ultrasonic Cutting Gantry