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Enhanced Robotic Automated Fiber Placement with Accurate Robot Technology and Modular Fiber Placement Head

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ABSTRACT

The process of robotic automated fiber placement has been enhanced by combining the technologies of an accurate articulated robotic system with a modular Automated Fiber Placement (AFP) head. The accurate robotic system is comprised of an off-the-shelf 6-axis KUKA Titan KR1000L750 riding on a linear axis with an option for an additional part rotator axis. Each of the robot axes is enhanced with secondary position encoders. The modular fiber placement head features a robotic tool changer which allows quick-change of the process heads and an onboard creel. The quick-change fiber placement head and simplified tow path yields terrific process reliability and flexibility while allowing head preparations to occur offline. The system is controlled by a Siemens 840Dsl CNC which handles all process functions, robot motion, and executes software technologies developed by Electroimpact for superior positional accuracy including enhanced kinematics utilizing a high-order kinematic model. Part programming and simulation are performed offline using CGTech VERICUT Composite Programming and VERICUT Composite Simulation. This combination of technologies results in a system that has high path accuracy and process flexibility at a lower cost than traditional fiber placement machines.

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INTRODUCTION

Electroimpact has developed accurate robotic technologies and modular automated fiber placement end effectors over a period of many years. Each of these technologies has reached maturity through use in multiple production applications. Recently Electroimpact combined their patent pending accurate robotic technology with their modular automated fiber placement head technology. This unique combination results in a low cost automated fiber placement solution that can be used for a wide variety of CFRP parts.

MAIN SECTION

Accurate Robotics

Industrial robots are used in many applications that require moderate levels of accuracy and repeatability. These applications include pick and place, light assembly, and welding. Traditionally the lower accuracy of articulated industrial robots has precluded their use in many aerospace applications due to the requirements for high positioning accuracy. Electroimpact developed a line of accurate industrial robots for use in aerospace applications. Most of the applications for accurate robotics have involved drilling and fastening of aerospace structures.

To achieve higher accuracy Electroimpact mounted optical encoders to each robot rotary axis near the output. The encoder signal is input into an industrial CNC (Siemens 840Dsl) which is capable of controlling each axis based on optical scale secondary feedback rather than the primary feedback on the servo motor.

Electroimpact 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. This combination of optical encoders and software kinematic compensation allows correction of position 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 whether due to statically applied forces or dynamically applied forces during path motion.

The improvement in toolpoint positioning accuracy was demonstrated by analyzing patterns of holes drilled by an accurate robotic end effector on representative work pieces. The radial position deviation of the hole parallel to the surface was examined. A standard industrial robot (non-accurate, without secondary feedback) was used to drill a pattern of 56 holes over an area of 3240 × 220 mm (0.71 square meters). The system demonstrated a 3-sigma hole pattern accuracy of +/−0.45mm. Then an accurate robot (with secondary feedback) was used to drill a pattern of 64 holes in an area of 1400 × 840 mm (1.18 square meters). The resulting 3-sigma accuracy was +/−0.08mm, conclusively demonstrating the toolpoint positioning accuracy improvement when using the accurate robot technology (see Figure 1) [8].

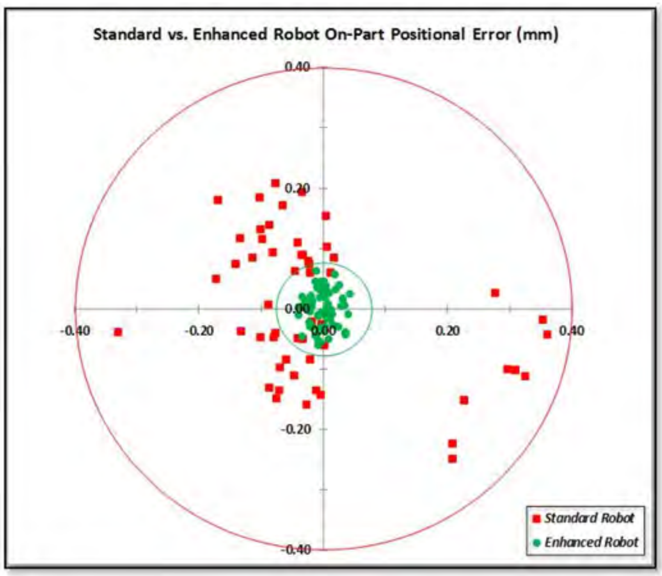

Figure 1. Accuracy comparison of standard robot vs. accurate (enhanced) robot.

For robotic automated fiber placement systems the KUKA KR1000L750 was chosen (see Figure 2). This robot provides a high payload rating (750 kg) and long reach (3602 mm). The robot arm utilizes large section steel castings. These characteristics of the robot arm result in good dynamic stiffness which helps maintain toolpoint positional accuracy while in motion on a path.

Path positioning errors in AFP result in course to course gap, course overlaps, and tow end placement errors. Note that high speeds and accelerations are required to traverse a moderately contoured part while maintaining normality. Inability to maintain path accuracy while traversing a contoured path will result in lower quality AFP layup or force a reduction in path speed, thereby reducing productivity. Utilizing the high payload robot with accurate robot technologies allows AFP layups that rival the speed, accuracy, and productivity of any non-robotic AFP machine.

Figure 2. Accurate Robot (KUKA KR1000L750) with optical scale secondary feedback installed.

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″, ¼″, and ½″ 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.

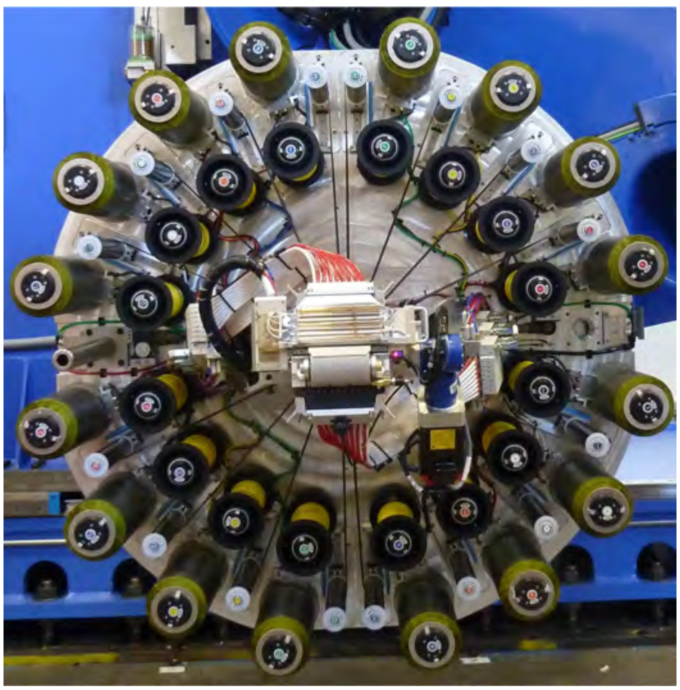

Figure 3. Automated fiber placement head with robotic tool changer and onboard creel.

Robot Axis 6 Improvements

Electroimpact AFP machines are typically designed with a focus on the performance of the last orientation axis that is used for AFP path steering (commonly named the "C" axis). In many CFRP layups it is beneficial to perform bi-directional layups to reduce off-part motion which results in higher productivity. A typically bi-directional ply would consist of a series of parallel courses. An AFP head would traverse a course in a direction, then be lifted off the part, spin 180 degrees, touch down on the part, and then traverse in the opposite direction on a parallel adjacent course. To optimize this off-part speed and flexibility two strategies are used. The first strategy is to maximize the performance (both acceleration and speed) of the steering axis. The second strategy is to incorporate slip rings for the electrical and pneumatic connections through the steering axis to enable a "continuous" axis with no travel limitations. This continuous steering axis will literally have no hard stops or software limitations in its entire range. Since the creel is contained on the AFP head, there are no steering axis limitations due to fiber routing and twisting. This enables maximum production flexibility since the AFP head can be steered in any direction.

Industrial robot arms do not inherently have either a high performance last axis or a continuous last axis. 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. Axis 4 and 6 on the KR1000L750 are mechanically continuous, but when electrical cabling and pneumatic lines are routed along the arm and connected to an end effector it forces limitations of these axes.

Electroimpact developed a solution to these limitations of the industrial robot. The improvement involves removing the axis 6 gearbox 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 motor, gear reducer, belt drive, and crossed roller bearing (see Figure 4). The custom drive package also includes slip rings for electrical signal, electrical power, and compressed air. The result is a high acceleration, high speed, continuous steering axis for an industrial robot AFP application.

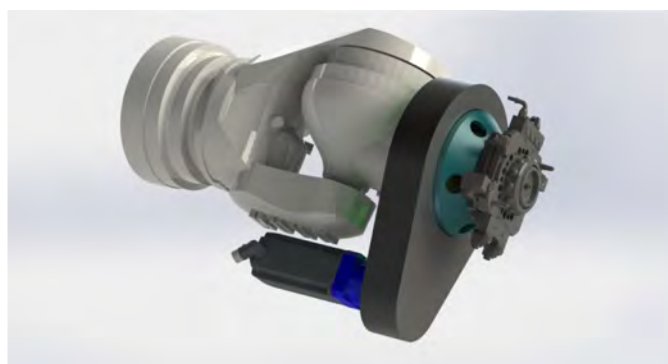

Figure 4. Robot axis 6 drive upgrade including signal, power, and pneumatic slip rings.

Robotic AFP Cell Configurations

Electroimpact delivered a robotic AFP cell that includes a large vacuum table (16 meters × 2.5 meters) and an ultrasonic cutting gantry (see Figures 5, 6, 7, 8). This system is used to produce AFP flat charges. The AFP robot is able to layup charges that have fiber steering and are near net shape. This allows optimization of fiber direction and reduces carbon waste. The ultrasonic cutting gantry (with 30 KHz ultrasonic horn) performs final trim of the AFP charges without having to transfer the charges to another machine since both the robot and gantry operate on the same vacuum table. The cell has 2 transfer stands and 2 AFP heads (one ¼” tow and one ½” tow). The transfer stands provide power and compressed air to the heads. This allows full head functionality for threading and cleaning while the head is offline.

Figure 5. Accurate robot with a modular AFP head.

Figure 6. Accurate robot AFP system integrated with a large vacuum table, CNC controlled ultrasonic ply cutting gantry, and AFP head transfer stands.

Electroimpact is currently manufacturing a robotic AFP cell that will be used for manufacturing payload fairings and payload support structures for space launches (see Figure 9). The cell includes a rotator capable producing of 6 meter diameter × 20 meter long part. The cell also includes 2 transfer stands and 6 AFP heads. The AFP heads are configured for 1/8″ tow, ¼” tow, and ½” tow. The cell also includes integration of a projection laser system capable of projecting layup boundaries, course centerlines, and programmed gaps/laps in areas of tow convergence.

Figure 7. AFP head interfacing with a head transfer stand.

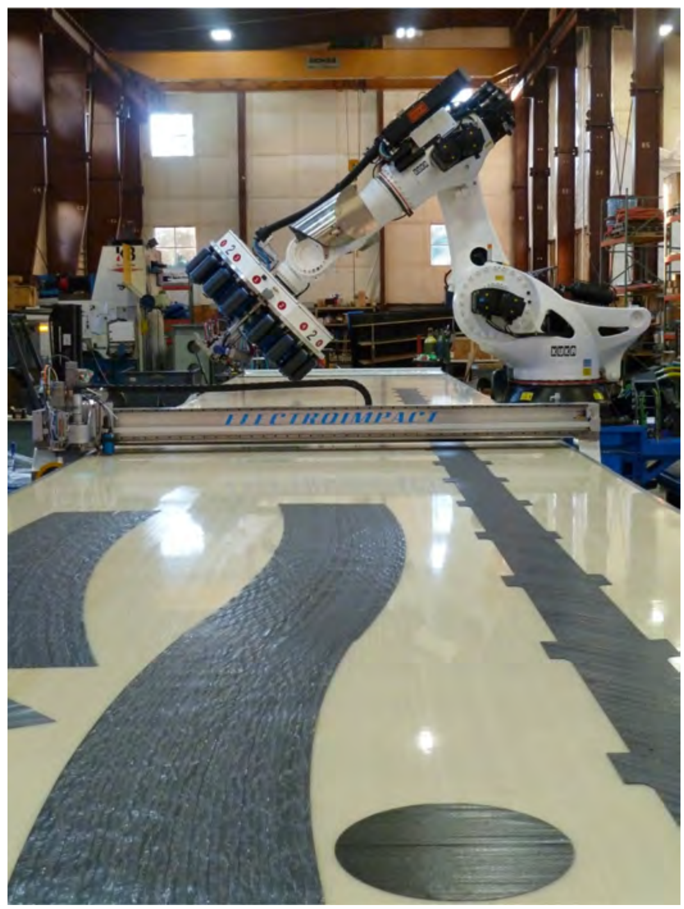

Figure 8. Samples of ply layups performed with accurate robot AFP.

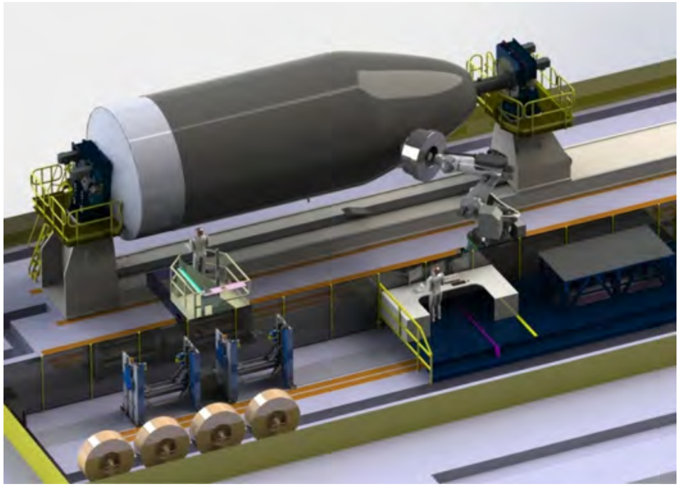

Figure 9. Accurate robot AFP cell for space launch structures and aerospace research and development.

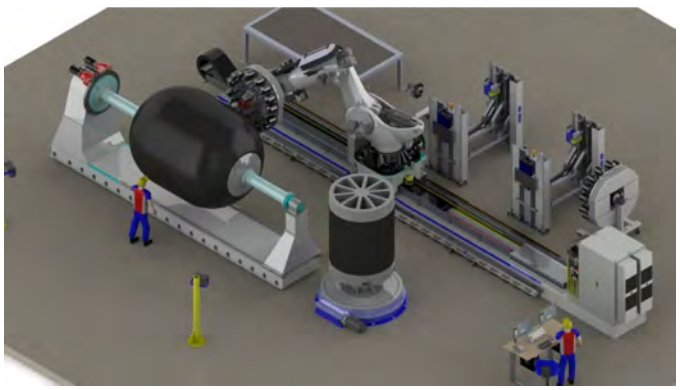

Figure 10. Accurate robot AFP cell concept. Cell includes vertical axis rotator, horizontal axis rotator, horizontal layup table, and head transfer stands.

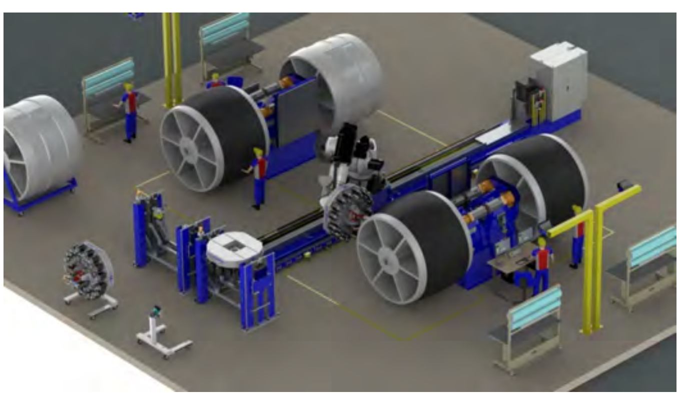

Figure 11. Accurate robot AFP cell concept. Concept shows the potential of man-machine interaction with a single robot capable of servicing multiple work zones.

Many other cell configurations are possible. Figures 10 and 11 show some concepts for application of accurate robotic AFP. Figure 10 shows an accurate robotic AFP system that includes integration with a vertical axis rotator, horizontal axis rotator, and horizontal layup table. Figure 11 shows a cell concept that allows the robot to access multiple parts/work zones. This can be useful for hybrid CFRP structures that include structural core, fiberglass, and/or Kevlar plies.

Offline Programming and Simulation

Electroimpact has worked as a non-exclusive partner with CGTech in their development of offline programming and simulation tools for composite applications. Offline programming for the accurate robot AFP systems is performed with the CGTech VERICUT Composite Programming (VCP) software. VCP reads in CAD surfaces and ply boundary information and generates path geometries with linking moves and then outputs an NC program. VERICUT Composite Simulation (VCS) software can then be used for simulation of the NC program. This simulation is able to detect collisions and verify material application. With a robot installed on a track axis there are multiple possible robot poses that will reach a desired toolpoint position and orientation. VCP allows configuration of the robot pose and VCS proves useful for verifying that the robot pose is optimal. Figure 12 shows a screen shot of an accurate robot AFP simulation generated using VCS.

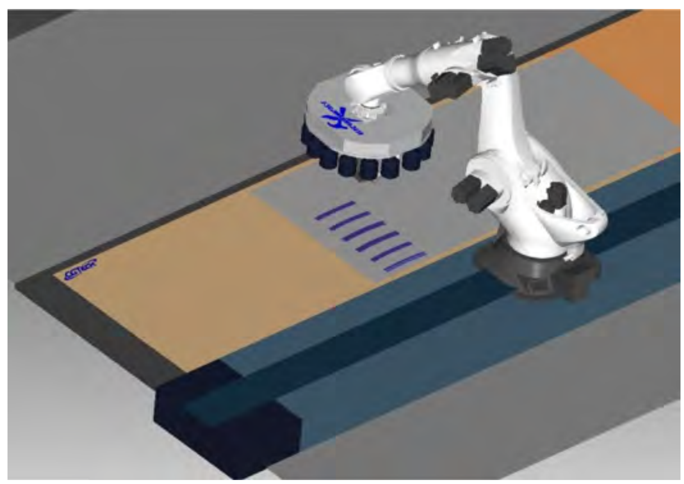

Figure 12. Robot AFP simulation generated with CGTech VERICUT Composite Simulation (VCS) software.

SUMMARY/CONCLUSIONS

The combination of accurate robot technologies and modular AFP heads has provided a flexible platform that is capable of producing a wide variety of CFRP parts with speed, quality, and reliability that rivals larger, more expensive AFP machine configurations. The low cost of industrial robots makes this level of AFP automation achievable for many applications where AFP would not have been affordable in the past.

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DEFINITIONS/ABBREVIATIONS

3-Sigma - measure of accuracy, +/− (average + 3 * standard deviation)

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