ADDITION OF HIGH-PERFORMANCE CONTINUOUS STEERING AXIS FURTHER ENHANCES ACCURATE AFP ROBOT

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ABSTRACT

Robotic AFP technology continues to mature. Previous improvements such as the modular AFP process head attached to a robotic tool changer provides the ability to quickly change process heads and perform necessary work, such as material loading, off-line where it does not interfere with production. Coupling high-order kinematic models with secondary encoders attached to each of the articulated robot-joints increased the accuracy of tow-path and placement as well as increasing the speed at which this accuracy can be achieved. Now the engineers at Electroimpact have added a new high-performance continuous steering axis to the robotic AFP process. The steering axis on a standard off-the-shelf robot does not have the speed and acceleration required for the high lay-down rates expected in the AFP industry. Therefore, this axis was replaced with a newly developed axis which provides significantly higher rotational speed and acceleration. Furthermore, until now the steering axis was unable to make continuous rotations due to the conduit carrying the utilities along the robot arm and out to the process head. This new design utilizes pneumatic, power and signal slip rings which allow for continuous rotation of the steering axis and greatly improves cable management. This new high-speed continuous axis provides reduced off-part motion and increased flexibility in the steering axis utilization.

1. INTRODUCTION

The use of off-the-shelf robots as a motion platform for automated fiber placement (AFP) continues to increase. The high-volume mass production of robots means the capital expenditure for an AFP machine using a robot is much less than a large gantry or post-mill style machine. Advancements in carbon fiber resins have been phasing out the need for a chilled creel house and the introduction of the modular AFP head has simplified the tow path. Both of which hindered the use of robotic manipulators in AFP. Also, the modular head combined with a robotic tool changer allows process heads to be quickly changed so material loading or routine maintenance can be performed off-line without impacting production. Having the tool-changer also allows the robot to use different heads, such as probe heads or ultrasonic cutting heads or to switch to a head with a different material form. Finally, the addition of secondary feedback on each of the robotic joints coupled with high-order kinematic models substantially increased the accuracy with which the carbon fiber can be placed over complex tool geometries at high lay-down rates.

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AFP robots are typically used on smaller highly contoured parts with often hard to reach areas, such as concave parts, where tool/machine clearance can be an issue. These types of parts are generally made up of mostly short courses which lead to lots of off-part motion as the robot repositions the process head for the ensuing course. The final axis (axis 6) of an off-the-shelf robot, which is the steering axis for the process head, is neither continuous nor high-performance. The power transmission from the servo motor to the steering axis is accomplished via a long series of torque tubes, bevel gears and a final gearbox. Improving the performance of the final axis is the focus of this paper. The higher performance reduces the amount of time it takes the robot to reorient the process head and ultimately reduces the overall manufacturing time for the part being produced.

2. ENHANCING ROBOTIC POSITIONAL ACCURACY

Industrial robot arms are primarily used for automotive assembly automation. In these applications the robot is performing automatic welding, pick-and-place material handling, and rudimentary assembly tasks. These tasks require only moderate accuracy and repeatability from the motion platform. The industrial robot is well suited for these tasks. For aerospace automation tasks a higher level of accuracy and repeatability is desired. This is driven by the tighter positional tolerances in aerospace production and the desire to be able to program and simulate an automated system offline with a high degree of confidence. A typical industrial robot is not well suited to these requirements for high positional accuracy and repeatability without enhancements.

It is first necessary to understand the sources of error in industrial robot positioning. Each robot axis consists of a closed-loop control system with a servo motor positioning the robot axis. The servo motor has an encoder measurement system that gives position feedback. However this servo motor and associated encoder are sometimes quite far from the physical rotational axis. This is especially true on axes 4 through 6. In the absence of a secondary measuring system close to the output of each axis, the servo system is unable to correct for windup or backlash in the drivetrain downstream of the motor. There are also physical deflections in each physical link of the robot due to bending and torsion that are unaccounted for in the control system. These deflections are the result of the weight of the robot links, weight of the payload, and process force inputs into the robot arm during automated tasks.

To enhance the positioning accuracy, these sources of inaccuracy are addressed. The robot arm is retrofitted with optical scales at the output of each axis for secondary position feedback. (See Fig. 1) A high-order kinematic model is developed by measuring the deflections of the robot in a variety of poses throughout the robot's range. A Siemens 840Dsl industrial CNC is used to control the robot arm. This CNC control is chosen due to its capability to utilize secondary feedback and execute the calculations for kinematic control and compensation at a high frequency. This approach has been successfully applied to many production industrial robotic systems in aerospace production. After the robot enhancements accuracy has been demonstrated at +/-0.13mm to +/-0.18mm in a 3m x 3m x 2m volume with no restriction on end effector orientations.

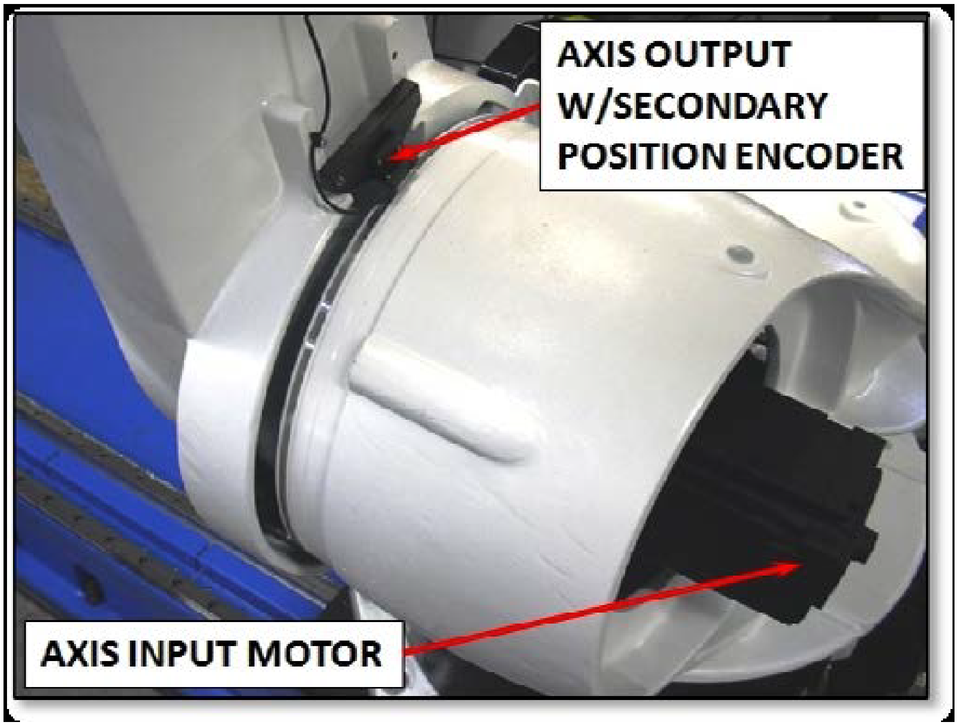

Figure 1. Industrial robot axis with secondary feedback installed.

3. MODULAR AUTOMATED FIBER PLACEMENT HEADS

Electroimpact began development of AFP heads in 2004 for use in production of carbon aerostructures. Several unique developments were made that improved the performance and reliability of automated fiber placement. Some of the key characteristics of the AFP heads include:

• Robotic tool changer on the AFP head. (See Fig. 2) 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 or machine to maintain continuous 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. Since the tool changer provides a generic mounting interface that supplies power, signal, and pneumatics additional processes can also be introduced into the cell including ultrasonic cutting, automated tape laying (ATL), wide fabric handling, etc.

• Onboard creel with short, simple tow path. (See Fig. 3) Every portion of the tow handling hardware and process is on the quick-change AFP head. The short, simple 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 without the use of load cells.

• 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.

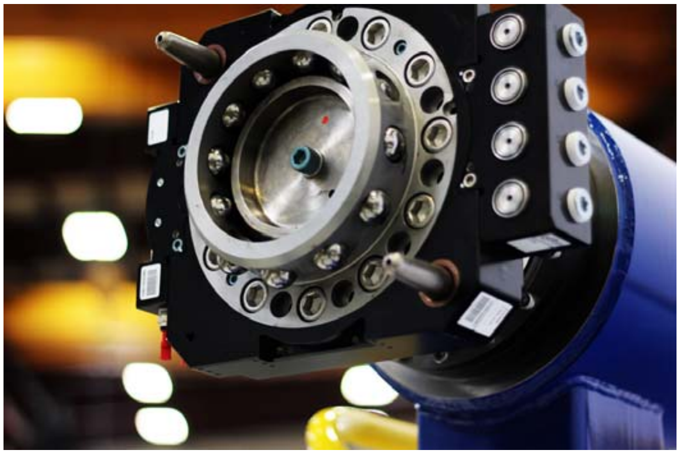

Figure 2. Robotic tool changer utilized for quick-change AFP heads

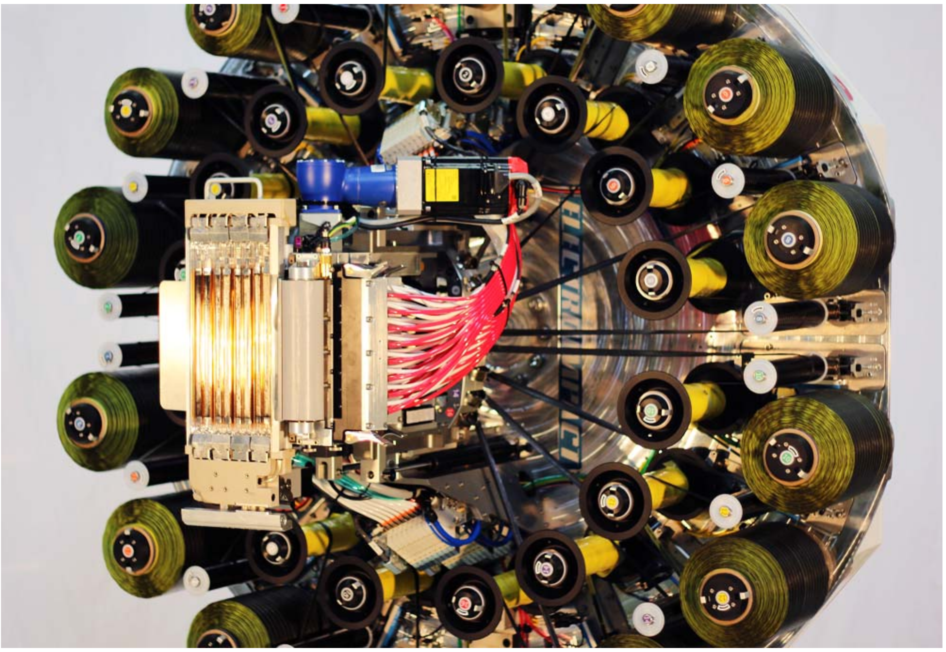

Figure 3. Modular Automated Fiber Placement (AFP) head

4. HIGH PERFORMANCE UPGRADE TO THE ROBOT STEERING AXIS

The robot chosen for this automated fiber placement machine was an off-the-shelf 6-axis KUKA Titan KR1000L750 controlled by a Siemens 840Dsl CNC. The Electroimpact process head weighs approximately 450kg and this robot is designed to carry a 750 kg payload at 3602 mm. All of Electroimpact's non-robotic AFP machines have high-performance continuous steering axes capable of reorienting the process head 180 degrees in one second. This is 3 times faster than using the standard robot axis-6 to perform the same move. (See Fig. 4) Therefore, the purpose of this project was to replace the standard robot axis-6 with a continuous axis having the same performance as our other AFP machines while minimizing any increase in the length of the tool point or mass of the axis. Adding length to the end of the robot pushes the mass of the process head further out which reduces the rated payload. Any additional mass at the end of the robotic arm simply becomes part of the payload the robot must manipulate. Therefore, the new axis needs to be as small and lightweight as possible which makes this project as much of a packaging problem as a performance one.

Figure 4. Standard Kuka Titan Axis-6

In order to have a continuous axis we must employ the use of electrical slip-rings for passing the power and signals from the CNC out to the AFP head. We also must pass all the pneumatic requirements through rotary unions and out to the head. To do this requires the steering axis to have a through-hole large enough for all of these utilities. The availability of through-hole gearboxes is somewhat limited. Off-the-shelf gearboxes with a large enough through-hole were far too large and heavy to meet the goals of this project. Furthermore, all of the available through-hole gearboxes with enough torque to meet the rotational acceleration requirements had the same problems of size and weight.

A gear train was unattractive due their need for continuous lubrication and the requirement that all lubricants must be contained and never allowed to come in contact with the carbon fiber parts. Furthermore, gear trains are very sensitive to manufacturing and assembly tolerances.

Ultimately it was decided to use a synchronous belt drive.

1. It meets the required acceleration/deceleration torque performance.

2. It is relatively small and light weight.

3. It allows for a very large through-hole which is necessary to fit the slip-rings within the axis' space constraints.

Electroimpact's modular AFP head is a very mature design and the speed and acceleration requirements are well defined. The synchronous belt is driven by a Siemens 1FT7086 attached to a small lightweight Wittenstein TP050 gearbox. This arrangement allowed the servo and gearbox to be mounted in a convenient location which does not interfere with the center-mounted nested slip-rings nor does it push the process head further out from the nominal robot mounting flange. By carefully choosing these components a favorable load to motor inertia ratio was achieved.

One of the problems with synchronous belts is backlash. Excess backlash can have detrimental effects on the quality of the layup. Testing was performed on and identical system using standard synchronous drive components applying the same torque the final production system would produce. Under these conditions the measured backlash produced a steering axis error of 0.013 Radians. This was well outside the allowable specification for directional tow steering deviation. One method of mitigating the backlash inherent in the synchronous belt system is to have the belt driving a high gear-ratio gearbox which is then directly connected to the process head. The backlash in the belt is then divided into the gearbox gear-ratio and with a high enough ratio the error becomes negligible. In this case secondary feedback is not needed, but still desirable. However, the constraints of this design did not allow for this method.

In this new axis design the belt is directly connected to the steering axis. With this configuration there are two methods for minimizing synchronous belt backlash. 1. Use a standard belt with custom sprockets. 2. Use a custom belt with standard sprockets. Unfortunately custom belts are prohibitively expensive, need to be ordered in large quantities and have long lead times. Therefore, a standard belt was used with specially designed sprockets to virtually eliminate backlash. The down-side of this method is it increases belt wear. However, standard off-the-shelf belts are readily available, inexpensive and, in this case, quick and easy to replace. Furthermore, this axis utilizes an absolute scale mounted directly to the final steering axis output to further ensure steering accuracy.

The use of the synchronous belt also allowed for the entire axis to be more of a pancake design with the main motor and gearbox mounted off to the side as shown in figures 5 and 6. The large driven sprocket creates a large through-hole allowing all of the other components to be nested inside. The electrical slip-rings are standard MOOG units with slight modifications unique to Electroimpact. The signal slip-ring nests neatly within the power unit. (See Fig. 7) The pneumatic rotary union was specifically designed and built for this project with a special bore used to nest the power and signal slip-rings. The weight and overall dimensions were kept to a minimum while still maintaining the minimum air flow requirements of the AFP process head.

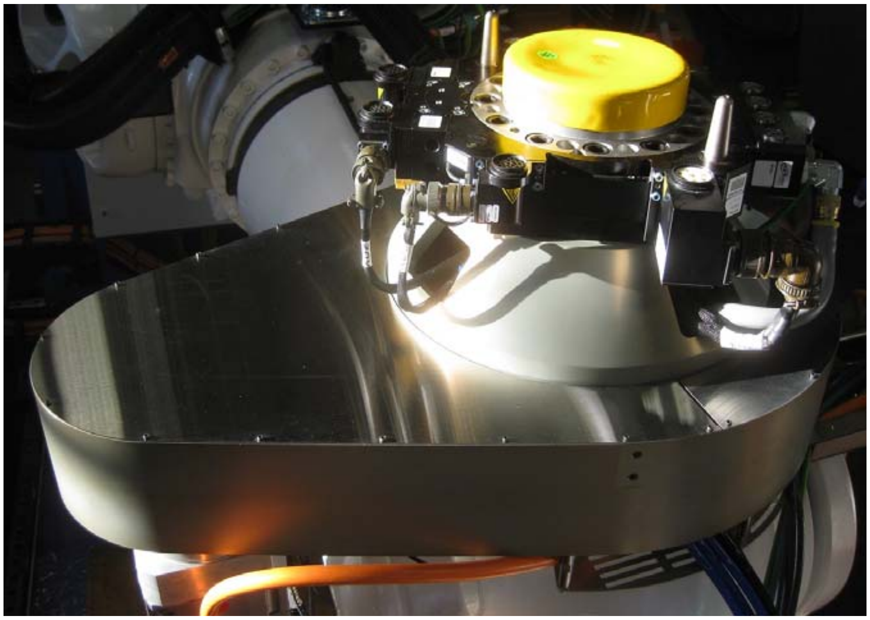

Figure 5. Complete Electroimpact designed axis 6 assembly.

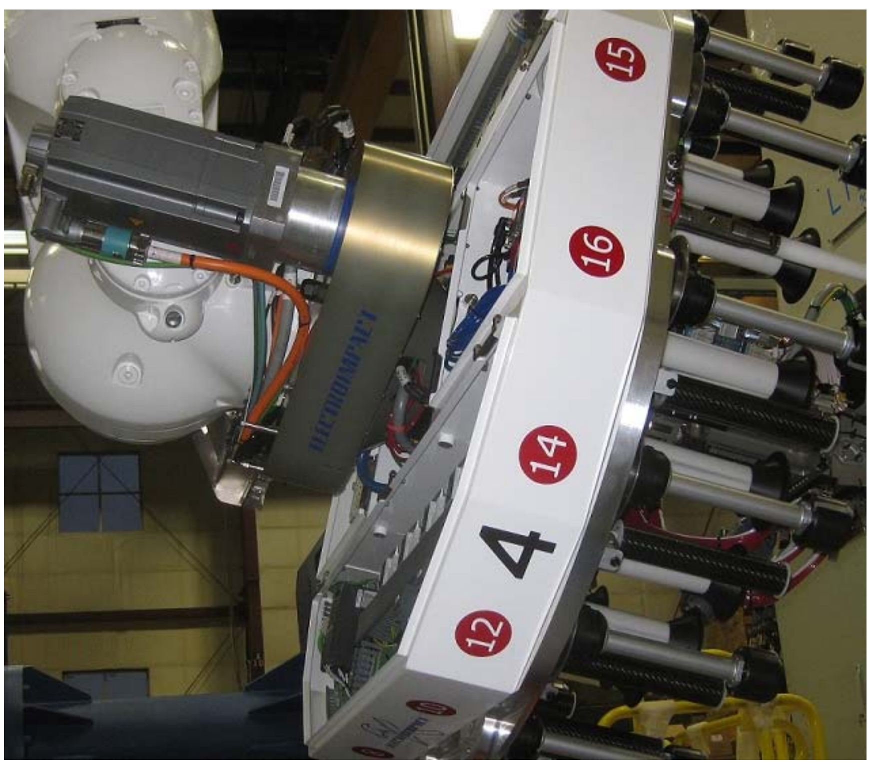

Figure 6. Axis 6 with modular Electroimpact AFP process head.

Figure 7. Pneumatic rotary union with power and signal slip-rings.

Compare this with the steering axis of an Electroimpact non-robotic AFP machine. (See Fig. 8) This machine did not have the same space constraints. Here you can see the off-the-shelf components connected end-to-end as they were never designed to be nested within each other. The overall length of this axis is 705mm whereas the new design measures only 322mm.

Figure 8. Non-robotic axis 6 assembly

The continuous axis has some distinct advantages over a non-continuous axis. With a non-continuous axis the cable bundle must wind around the robot arm as axis-6 is rotated. (See Fig. 9) Further complicating this is axis-5, which is normal to axis-6 and has a range of +/- 90 degrees. Since axis-6 must drag the cable bundle with it, axis-6 is then limited to +/- 180 degrees.

Figure 9. Robot with non-continuous axis 6. Stainless steel shroud keeps the conduit from entangling with the robot.

Furthermore, with a non-continuous steering axis the CNC must look at where the steering axis is relative to where it needs to go next. If the limits of the axis are between these two positions then rotation must be opposite the direction of the limit. Oftentimes this rotation is a longer one than if the axis had no limits. If this event were to occur during a particular course the steering-axis would need to be reoriented prior to starting this course. With a continuous steering-axis none of these events occur which simplifies programming as well as reducing the time off-part by always having the ability to choose the shortest angular rotation.

5. CELL CONFIGURATIONS AND APPLICATIONS

5.1 Robotic AFP Cell with High-Performance Continuous Steering Axis, Large Part Rotators, and Dual Linear Axes

Figure 10 shows a recently completed robotic AFP system that includes the high-performance steering axis retrofit detailed in this paper. The cell also includes part rotators capable of handling 6 meter diameter tools weighing up to 27,000 kg with a top rotational speed of 6 rpm. The same cell utilized a typical linear track but also had a second linear cross-axis (perpendicular to the main track axis) under the robot to increase the overall work volume of the cell. This cell also included a 2 meter x 3.5 meter work table for layups. This work table and head transfer stands are positioned on the opposite side of the track from the part rotators. The robot system provides this unique capability of working on both sides of the linear track with the first rotary axis. This capability is not present in other AFP machine configurations.

Figure 10. Fiber placement robot with axis 6 retrofit, rotators, and dual linear axes under the robot base.

5.2 Robotic AFP Cell with Vacuum Table and Ultrasonic Cutting

Figures 11 and 12 show a robotic AFP system paired with an 18 meter x 2.5 meter vacuum table. The system is designed to produce flat AFP charges. A small gantry on the vacuum table carries an ultrasonic cutter and an ink jet print head. The gantry is used to trim and part mark the AFP charges. In similar cells the robot can be used to carry an ultrasonic cutting head rather than using a dedicated gantry. This style of system is in demand due to the fact that AFP can produce flat charges at a higher rate than Automated Tape Laying (ATL) and produce near net shape layups which significantly reduces carbon waste. This results in a fast return on investment when replacing an ATL flat charge system. A robotic AFP system is also capable of producing flat charges with tight steering radii as shown in Figure 12.

Figure 11. Robotic AFP cell with vacuum table, ultrasonic cutting gantry, 2 AFP heads (1/4" and ½"), and head changing stands.

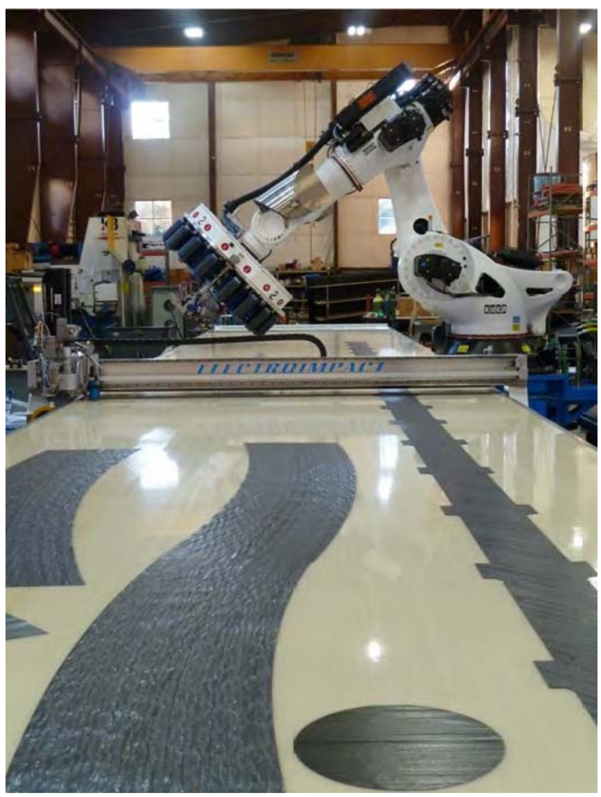

Figure 12. Typical flat charges on the vacuum table.

5.3 Robotic AFP Cell with Multiple Work Stations

Figures 13 and 14 show the potential of a robotic AFP cell to address multiple work zones. Figure 13 show an AFP robot with access to multiple rotators. Figure 14 shows an AFP robot with two vacuum tables and an ultrasonic cutting head for building stringer charges. These are additional examples displaying the flexibility of an AFP robot addressing multiple work zones with encompassing variety of part families on either side of its linear track.

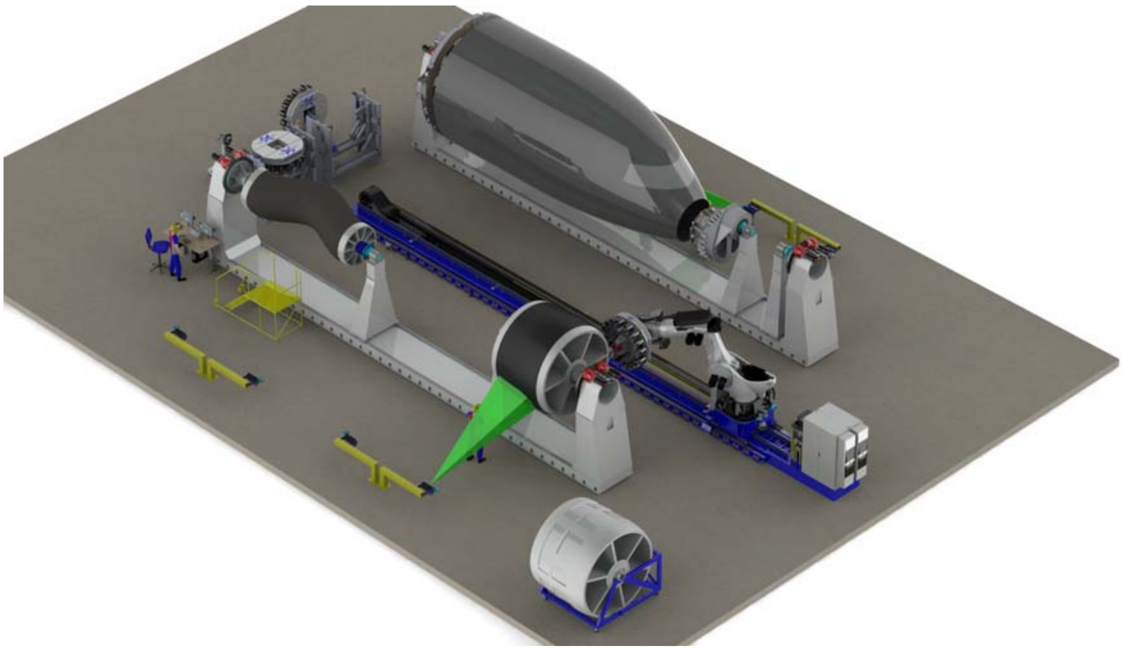

Figure 13. Robotic AFP cell with multiple rotators, head change stands, and laser projection.

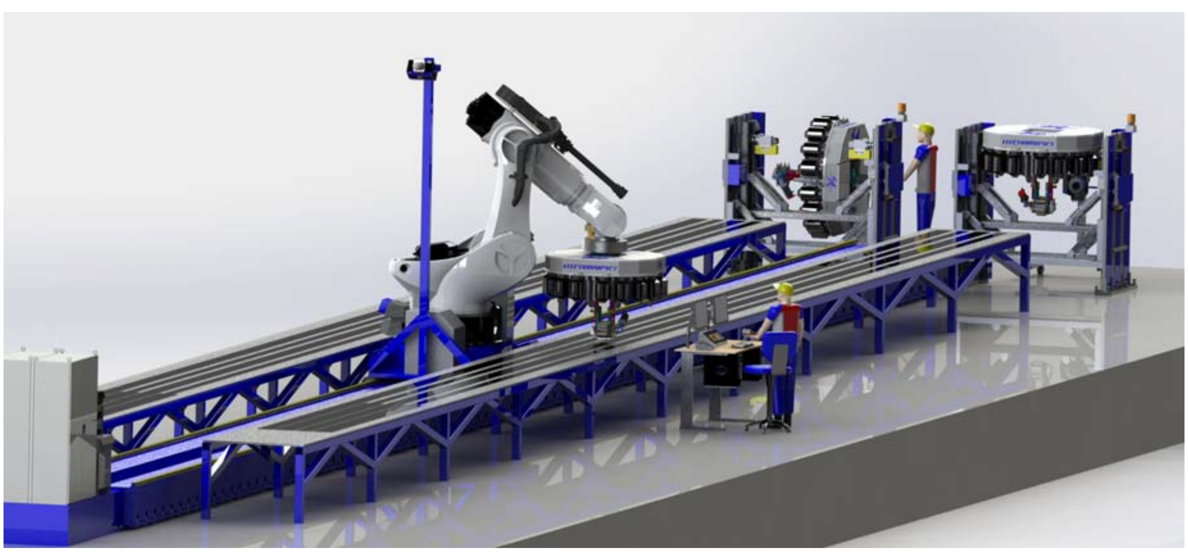

Figure 14. Robotic AFP stringer charge cell with two vacuum tables, ultrasonic cutting head, head change stands, and laser projection.

6. CONCLUSIONS

Off-the-shelf robots are not designed specifically for use in the AFP industry. However, they are very well suited for use as low-cost motion platforms which can then be utilized effectively in the AFP process with the appropriate enhancements and modifications. Using higher-order kinematic models and adding secondary feedback to the robotic joints allow robots to more accurately follow complex part paths and place the carbon fiber tow within the AFP industry requirements. The use of robotic tool changers and modular process heads further increases the flexibility of the robotic AFP cell. Finally, the addition of a newly designed high-performance continuous steering axis decreases the off-part motion as well as allowing for quicker course corrections during high-speed layups over complex parts. This reduces the time to manufacture parts and increases the overall cell utilization.

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