Automated Fiber Placement Machine Developments: Modular Heads, Tool Point Programming and Volumetric Compensation Bring New Flexibility in a Scalable AFP Cell.

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Abstract

Modular, detachable AFP heads allow quickly exchanging heads, tow widths and materials on AFP machines. Two minute head exchange enables offline tow-path maintenance and tow reloading. Modular heads support technology development without impacting production.

Modular AFP heads combined with a flexible control architecture permit the use of a single part program for any machine in a multiple machine cell making that part, even if that machine is on the opposite side of the part. The operator can run multiple machines simultaneously using a single part program and remove or add machines at any time between courses without a CNC programmer.

Technologies for this architecture include use of a common coordinate frame for all machines, tool point driven AFP CNC programming, and volumetric compensation of each machine for that frame. Use of a volumetric compensation program enabled rapid and accurate compensation of the machines in the cell in a common frame.

Introduction

Production of large composite aircraft structures such as wings, spars and fuselages brings new challenges to Automated Fiber Placement (AFP) machines. Larger structures require high axis speeds, longer working axes, and higher lay down rates, yet retain the stringent quality requirements of aircraft systems, necessitating high accuracy and good tow compaction. A non-intuitive requirement of higher lay down rates is excellent short-course performance. Customer part analysis and production has demonstrated that the average tow path length is surprisingly short, even for the largest aerospace structures. This translates to a requirement for high machine axis accelerations.

The mechanical design of AFP machines is critical to performance. For example, the management of carbon fiber tow, and the ease of maintenance are vital for maximizing production throughput and maintaining uptime. However, intelligent setup and control of AFP cells are also essential for maximizing system effectiveness. Improvements in these areas lead to better performance and higher floor to floor rates for the production of large aerospace parts.

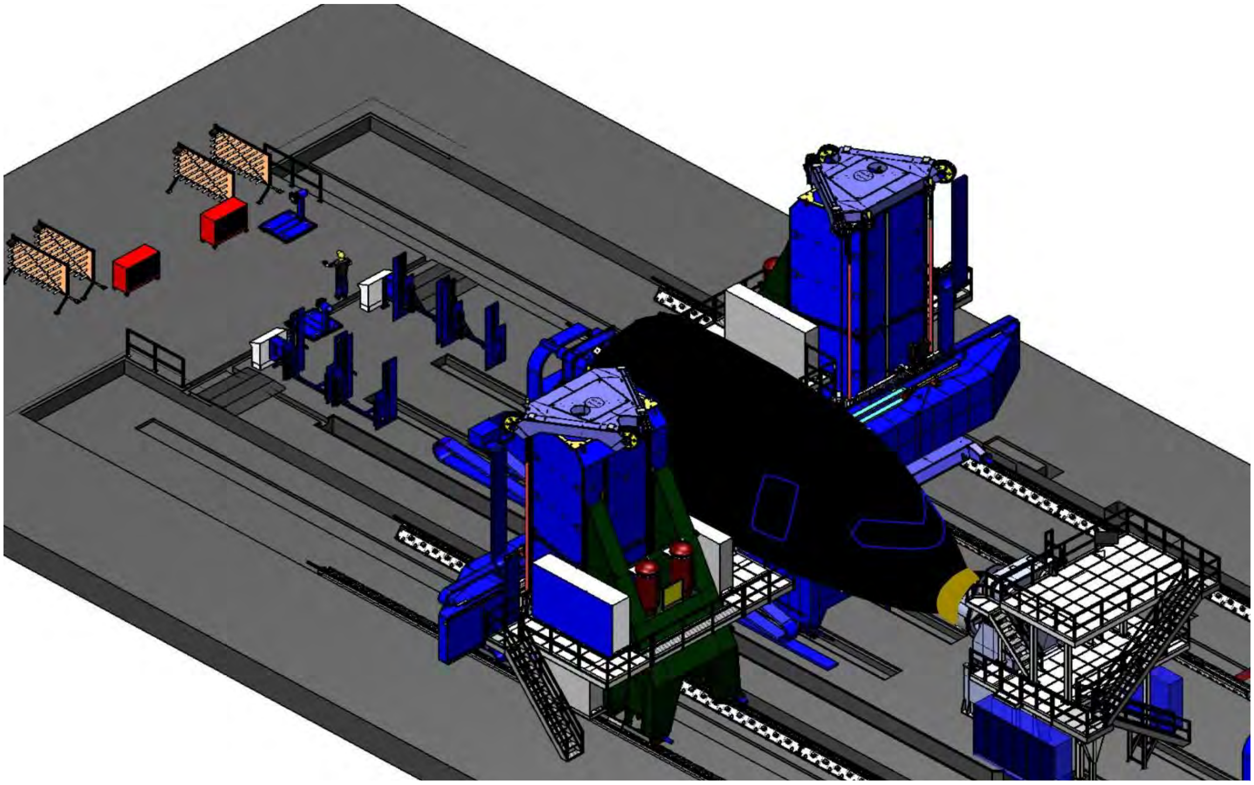
Electroimpact built a multiple machine production AFP cell that demonstrates a number of measures taken to improve the performance of AFP for large aerospace parts. A principle quality requirement is that each individual tow be laid within a tight tolerance according to the part specification. At the same time, production goals include minimizing the total production time of each part via the combination of maximized machine performance and minimized maintenance and machine downtime.

Traditional AFP technology

Traditional AFP machines for large structures feature a large multi-axis machine with an end effector and a long, spool guided, tow path back to a refrigerated "creel house", generally attached to a major structural element mounted on a linear axis, where tow spools are stored. This design offers good protection for tow awaiting placement in case of machine downtime and provides for high onboard tow capacity. On the downside, the very long tow path – perhaps as long as 30' – is time consuming to thread, the refrigerated creel house may result in condensation on the machine or tow, and no offline maintenance is possible for guide spools, cutters, compaction rollers or other AFP path elements. Typically these machines are designed to use exactly one tow width.

New AFP systems descriptions

A new AFP machine cell was designed for fiber placement on a full diameter aircraft fuselage nose section[1]. This system consists of two six axis (Linear X,Y & Z, and Rotational A, B & C), post-style machines, a fuselage mold rotator, a maintenance area and a control station. The AFP machines have a compensated working envelope of 64' of X axis, 21' of Y and 14' of Z axis and provide enough A, B and C axis motion to operate over 135 degrees of the part in "painting" mode. The post machines travel on either side of the servo controlled rotator which positions the fuselage mold as required for the different tow courses. Each post machine is able to connect to



any compatable Electroimpact modular head, including a variety of Fiber placement heads, and a probe head.

Machines were designed to maximize stiffness and minimize backlash, and operate with a maximum linear axis travel rate and layup speed of 2000 inch/minute with linear accelerations of 0.18g.

Multiple Machine Cells

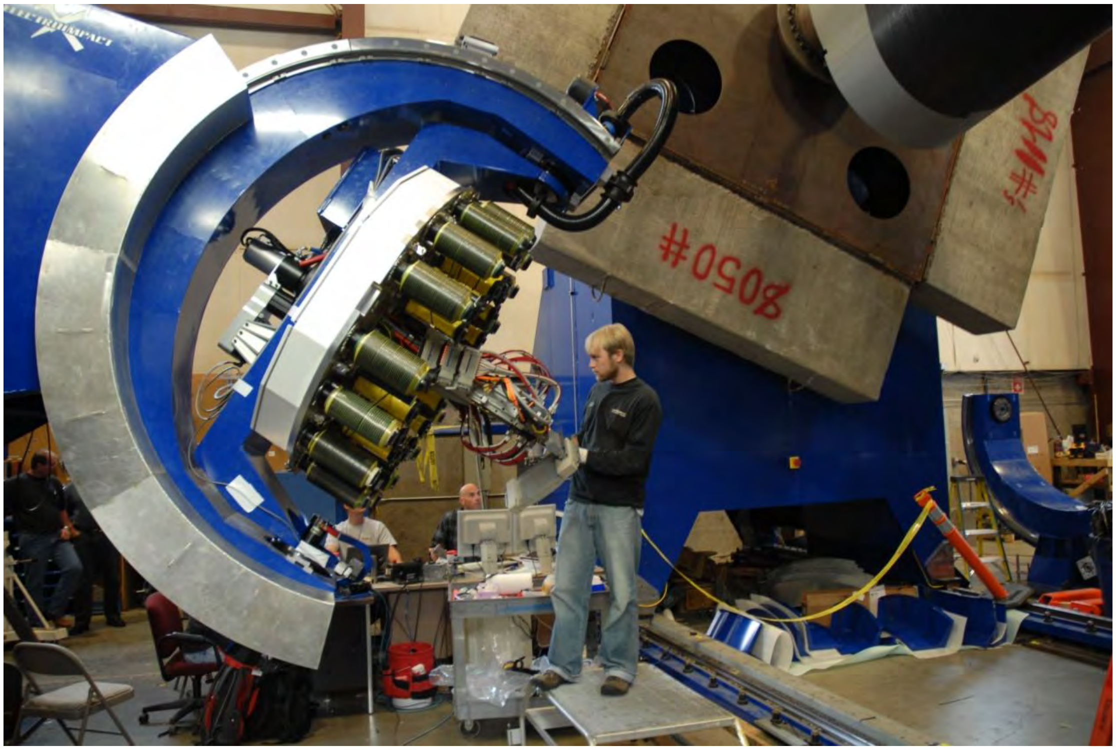
There are a number of benefits to multiple machine AFP cells with a common control architecture.

Fully coordinated AFP machines can decrease production time per part without having to increase individual machine performance. This enables the creation of higher production rate cells without needing to develop higher performing individual machines and components. For larger parts, this may be needed due to the limited out-time or working time of the slit tow tape, and may be even more needed with “out of autoclave” materials. Additionally, multiple machines in one cell can more effectively take advantage of expensive tooling and limited clean room floor space.

While well designed machines and cells can minimize downtime, if one AFP machine or head in a multiple machine cell does need maintenance, part production can continue with the remaining machines while one machine is offline.

Modular heads

The desire to use multiple tow widths, to enable bidirectional layup and to be able to do offline maintenance on fiber placement elements led directly to the development of the discrete, removable, modular fiber placement head.



Head and A, B, C axis during initial testing

Fiber placement head

The resulting head has several outstanding characteristics, making it:

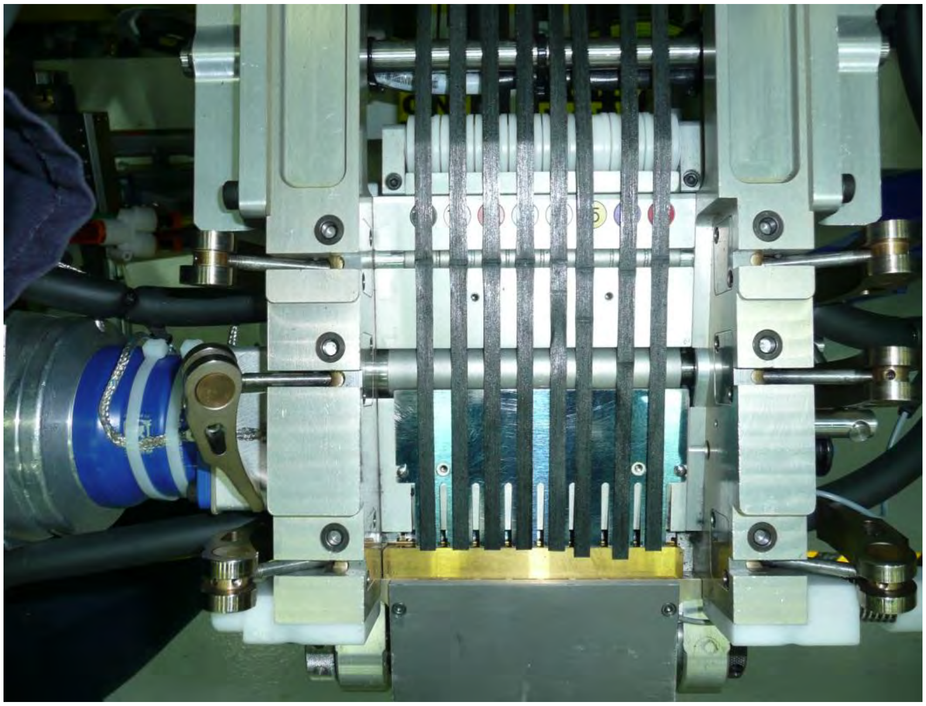
Discrete: The head contains all fiber placement related elements such as tow spools, guide paths, cutters, heaters, and a compaction roller.

Modular: The modular head is a complete functional unit, allowing it to be positioned as a unit without respect to tow path and without concern for the possibility of twisting tows. This modularity also permits bidirectional layup regardless of head orientation or path direction.

Removable: Using robotic tool changing hardware the head can be removed and replaced in two minutes. The hardware permits electrical and pneumatic connections to pass through the connection while being mounted on a rotary axis.

Interchangeable: Standardized connections, tight tolerances and a robust head calibration methodology allow the swapping of heads. This in turn permits off-line maintenance on the heads and permits the use of multiple tow widths on a single machine (1/8", ¼" and ½" width tow heads are currently in production). Tow calibration parameters are stored on the AFP head.

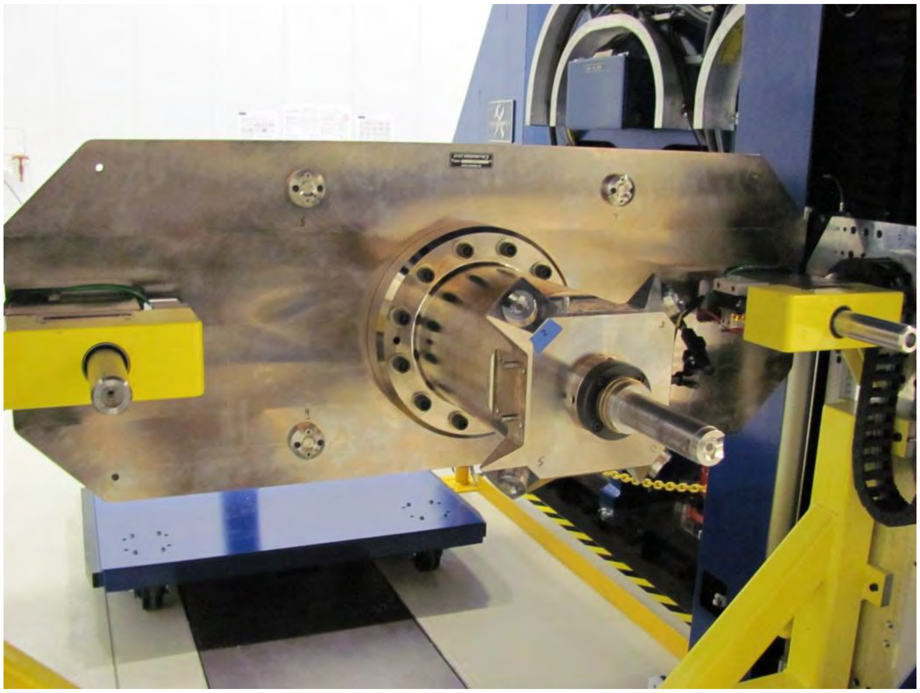
Serviceable: The entire tow path is designed to be exposed for cleaning, without the aid of tools and in only a few minutes. Tow path length is about 36", so the entire tow path can be serviced without the maintenance person moving his feet.



Tow path exposed for inspection

Probe head

The interchangeable head concept also allows for the implementation of a probe head. The probe head was designed to enable the use of a wireless Renishaw probe for measuring the location of 1.5" Spherically Mounted Retroreflectors (SMR) in nests located around the fuselage mold tooling. The probe head can be quickly loaded and unloaded like any other head. It also is designed to be easily and accurately measured for the purposes of valuation and compensation. Finally, the probe head can carry an Active Target or conventional SMR for use in the compensation process. The Active Target is placed in an HSK chuck at the toolpoint. The



Probe head

SMRs can be placed at the toolpoint with the chuck or at multiple positions around the probe head.

Controls architecture

The controls architecture for this AFP cell has a number of features in addition to those found in conventional CNC machine cells. While some are related to AFP process requirements (such as tools related to tow and courses), most are generically applicable to CNC machine cells with more than one machine working in concert.

A series of developments related to machine compensation and CNC programming significantly contributed to successful implementation of the system. These developments are not limited to AFP machines but may be applied to most large CNC machines.

Independent CNCs but a common coordinate frame for (all machines in) the cell

The usual practice for coordinated machines in a large machine cell is to have a single CNC controller for the cell. Instead, multiple CNCs were used but a common coordinate frame was established for all of the machines (the two APF machines and the rotator) in the cell.

Streamlining and improving large machine compensation

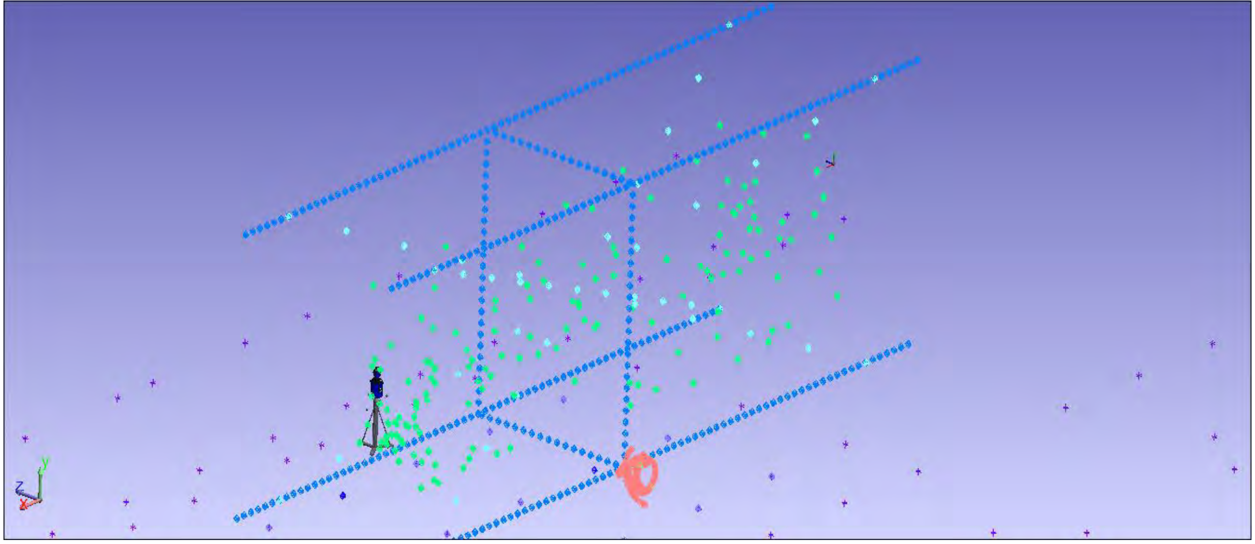
Machine compensation is one of the necessary elements of a successful large AFP system implementation that is able to perform at the required levels of accuracy. Volumetric compensation is a newer methodology that offers some advantages over the more traditional methods commonly used today.

Traditional compensation methods

Traditional methods for compensating a machine include custom shim grinding for each axis to mechanically compensate the machine to within tolerance. This is an iterative, time consuming and expensive process regardless of machine size, but it becomes particularly impractical as the machine size increases and as tolerances tighten. It is sometimes combined with the more common method of single axis compensation via software in the CNC control, whereby each axis is compensated for in isolation, often with a line laser for the linear axes. For greater accuracy, a secondary compensation is sometimes done, whereby one axis is also compensated for by slight effects caused by another axis. Thus, moving a machine along X will cause slight shifts in the Y position of the toolpoint, and a table may be generating compensating “Y for X” or “Z for X”. Many CNC machines do have fairly comprehensive volumetric compensation and part transforms, but these compensations are applied in the post processor. This means a program destined to run on a given machine is custom to that machine and part setup.

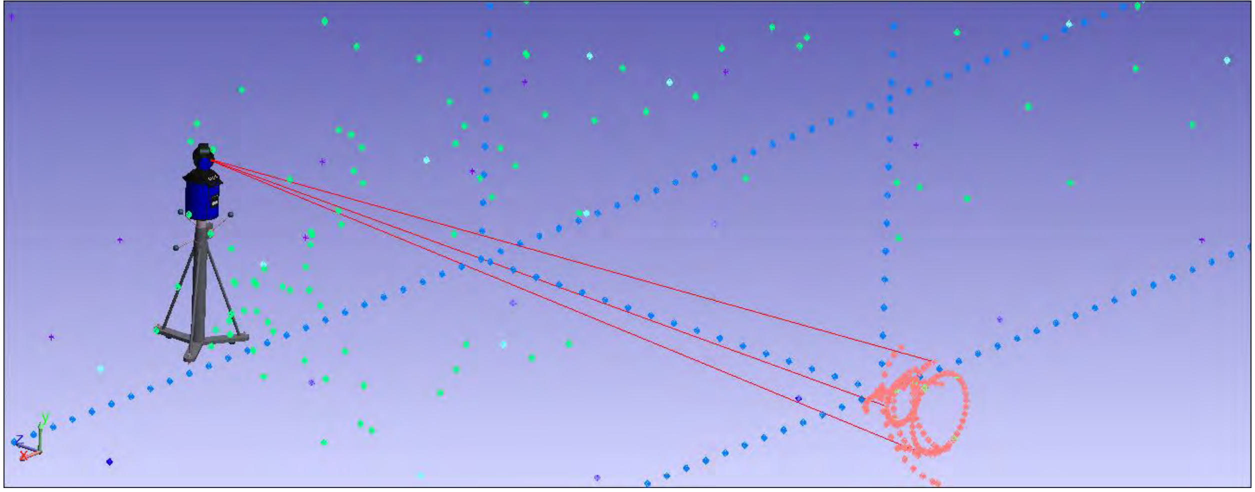
Volumetric compensation

An alternative to traditional compensation methods is to use volumetric compensation. Here, the practice of single dimension, single axis measurements is abandoned in favor of measuring the three dimensional tool point position throughout the range of motion of the machine. The machine is still moved along individual axis, however the X, Y and Z position of the toolpoint is measured for processing. All axis motions can be valued from a single laser tracker station.



Single tracker station with points along the linear axes (light blue) and the rotary axis (orange) and random points (green). The grid of purple points is part of the Machine Reference System of points embedded in the floorAFP machine cell for front fuselage section

For rotary axes, three SMRs are placed in known reference positions on the probe head. The positions of all three SMRs are measured at each machine position, fully constraining the 6 DOF position of the probing head. The Y axis is kept low to facilitate access to the SMR point throughout this process.

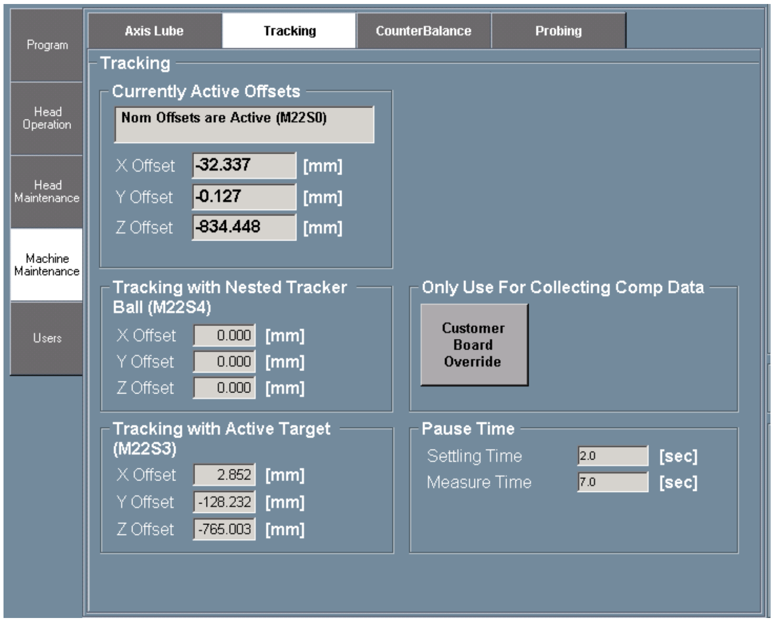


Shooting the A, B, C axes points

After points along or about each axis are measured, over 100 random points, scattered to approximate the full working envelope of the machine, are valued, to later be used to validate the compensation results. In all about 900 points are used.

To facilitate the rapid measurement of these points an “Active Target” was used in place of a conventional SMR. The Active Target automatically rotates in two axes to remain pointed back at the laser tracker regardless of the machine position, a key feature in compensating a machine with 21’ of vertical travel.

Once all the points are valued, a proprietary Electroimpact solver is used to optimize parameters for the kinematic equations previously developed for the machine. The solver optimizes these parameters throughout the entire motion of the machine, and the machine accuracy is then predicted based on the optimization error. This calculated error has empirically been shown to a good predictor of actual machine error. It also provides a ready tool for indicating tracker blunders or otherwise unusable tracker data as either will generate unacceptably large error ranges.



Tracking

Currently Active Offsets

Nom Offsets are Active (M22S0)

X Offset -32.337 [mm]
Y Offset -0.127 [mm]
Z Offset -834.448 [mm]

Tracking with Nested Tracker Ball (M22S4)

X Offset 0.000 [mm]
Y Offset 0.000 [mm]
Z Offset 0.000 [mm]

Only Use For Collecting Comp Data

Tracking with Active Target (M22S3)

X Offset 2.852 [mm]
Y Offset -128.232 [mm]
Z Offset -765.003 [mm]

Pause Time

Settling Time 2.0 [sec]
Measure Time 7.0 [sec]

Cell control maintenance tools reduce the burden of compensation data collection

Electroimpact's custom volumetric compensation is applied real time in the CNC, including all necessary part transforms, so that the part program need not be changed due to specific part orientation or due to the customized volumetric compensation. Furthermore, the display on the CNC will exactly match that of the programmed point in the part program which will exactly match that of the display on the NC programmer's screen.

The volumetric compensation method has yielded excellent results, with under 0.008” (0.2mm) radial error throughout the compensated 64' by 21' by 14' envelope of the example cell, and similar values in over 20 other production machines of similar sizes. The results are determined by sending the machines to another 120 random position throughout the machining envelope and recording the tracker measured value at the tool point. Then the standard deviation is calculated and the accuracy of the machine is determined by the equation ACCURACY = average_error + 3 * std_dev. The method also greatly reduces machine compensation time. The last full compensation of the example cell took two single shift days to complete.

Machine Reference System (MRS)

A metrology control network is invaluable in the commissioning of a large, accurate CNC machine. The network of 100 precision monuments set in the foundation of the cell is here called the "machine reference system" or MRS. The MRS was installed prior to any machine components, with each point set into the concrete with epoxy, placed on an approximately 10' grid pattern. The exact locations are arbitrary but they must be absolutely repeatable. The MRS was valued carefully with a laser tracker with measurements taken from 14 stations. Spatial Analyzer's Unified Spatial Metrology Network was used to evaluate the validity of each individual station and measurement.

Once the MRS was valued, it was used as an aid to install the X axis machine rails and rotator rails, install other machine elements, validate the accuracy of the machine probing, establish position of such elements as the coupon stand and finally, to establish the common reference frame for the two fiber placement machines and for the rotator. Although the MRS grid covers the entire cell, in practice only a small number of points (about a dozen) are used on a regular basis.

The MRS provides the ability to reference the same common coordinate system for different cell components measured from different locations.

Conventional programming for AFP layup

A number of existing AFP machines are programmed by axis position. Each and every machine needs each program customized for it in light of its geometry and any traditional compensations techniques that have been applied. Additionally, each and every program needs to be changed if there is any change in machine geometry and kinematics. This also means that any software simulation of the program needs an exact model of the machine.

Tool point driven programming for AFP cells

The combination of volumetric compensation and a common coordinate frame built from a MRS enables all AFP CNC programming to be done via tool point. The volumetric compensation enables construction of a fully kinematic model of the machine being compensated. Each individual axis is compensated in all 6 degrees of freedom, and this kinematic model is used to generate commanded machine position on the fly as the part program supplies toolpoint positions. Moreover, each modular head contains its own kinematic parameters, meaning that once a head and a machine are individually compensated, the combination is also compensated for, and able to run tool point driven part programs without any reposting of the program.

Combining either of the two volume compensated machines with each of 5 modular heads with their kinematic parameters determined in a development cell resulted in all combinations passing end customer machine and layup qualification without any additional compensation or CNC program alteration needed.

Common part program for all machines in cell

With a common coordinate frame established it was possible to develop a common tool point driven part program for use by both machines in the cell. This common program is used regardless of initial mold tooling position, and is unchanged whether used for either machine, or any hypothetical n^{th} machine added to the cell.

This structure allows very flexible course assignment through a user-friendly cell controller interface, permitting the operator to add or remove a machine from the layup process without making any part program changes or referring to a NC programmer. The operator also has full control of feed rate, with the ability to modify the feed rate on-the fly. Finally, machines can be added or removed from the process without interrupting another machine currently running part programs. Each machine runs completely independent of the other and is slaved to the moving rotator and mold with a single Mcode.

More generally, toolpoint driven part programming means the same part can be made by the same program in different cells, or using modified AFP equipment. This means that a part program can be developed and tested in a development machine and, after a quick simulation (using the VERICUT Composite Programming and Simulation Suite) to detect possible collisions between machine and tool, be moved over to a production cell without any reposting of the program.

Taken all together, this lets the machine operator run **any program on any machine, using any head** (with the right width of tow), and running any programs with matching rotator behavior at once, with both using a rotator behavior based on the cell operating in a Static or Dynamic Operation mode.

Static Operational mode

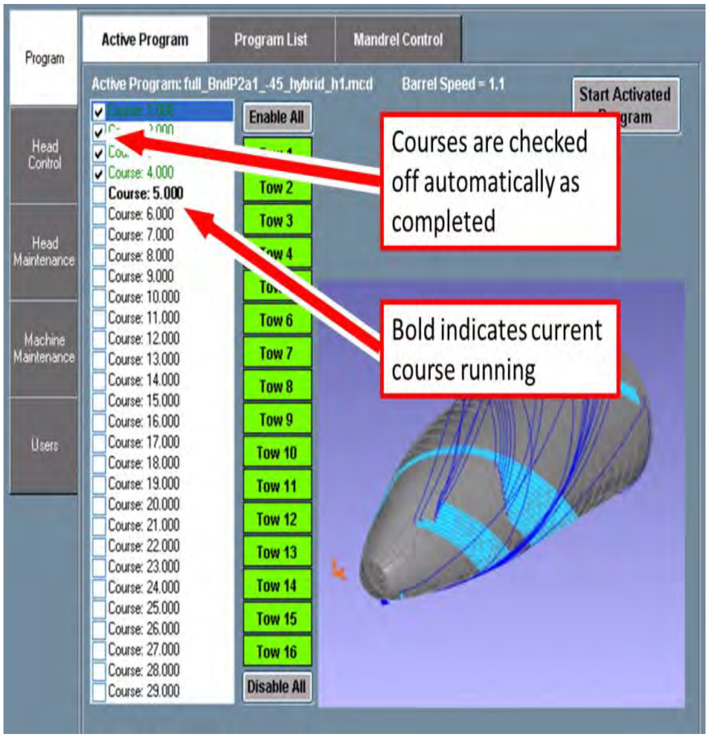
In static operation mode, the rotator holds the fuselage mold in an arbitrary fixed position. The operating AFP machines then adaptively operate in a coordinate system defined by the tool, so long as the range of motion (135 degrees of range over the arc of the barrel) is sufficient to execute the current layup. The individual AFP machines enter and exit the cell without regard to each other, and except for a collision detection program, have no influence on each other.

Dynamic Operational mode

In dynamic operation mode, the rotator rotates the fuselage mold while any operating AFP machines are independently slaved to the rotator by a single Mcode. The AFP machines enter and exit the cell without regard to each other, and except for a collision detection program, have no influence on each other.

Electroimpact AFP cell control and build scheduler

Electroimpact cell control and build scheduling software lets machine operators take full advantage of the common part programs for static or dynamic operation modes in order to monitor and trigger individual programs in real time.



Active Program: full_BndP2a1_-45_hybrid_h1.mcd Barrel Speed = 1.1

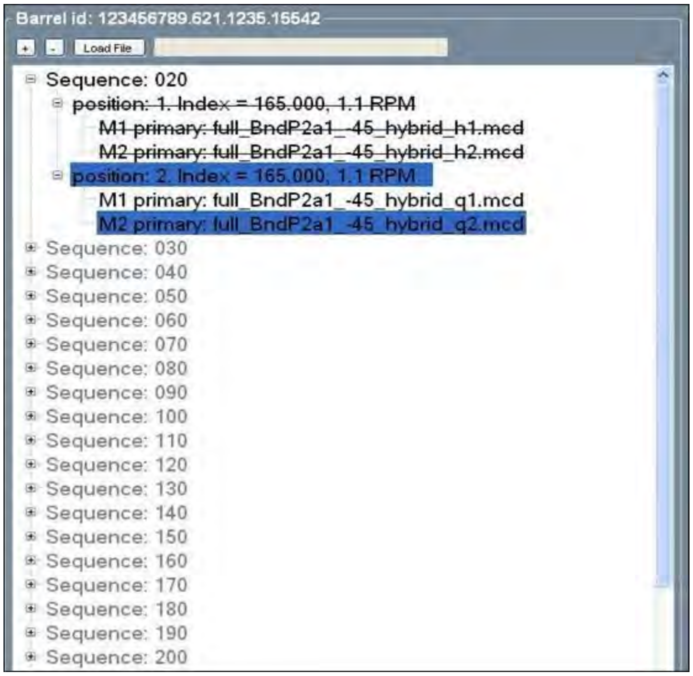
☑ Course: 4.000
☐ **Course: 5.000**
☐ Course: 6.000
☐ Course: 7.000
☐ Course: 8.000
☐ Course: 9.000
☐ Course: 10.000
☐ Course: 11.000
☐ Course: 12.000
☐ Course: 13.000
☐ Course: 14.000
☐ Course: 15.000
☐ Course: 16.000
☐ Course: 17.000
☐ Course: 18.000
☐ Course: 19.000
☐ Course: 20.000
☐ Course: 21.000
☐ Course: 22.000
☐ Course: 23.000
☐ Course: 24.000
☐ Course: 25.000
☐ Course: 26.000
☐ Course: 27.000
☐ Course: 28.000
☐ Course: 29.000

Courses are checked off automatically as completed

Bold indicates current course running

The cell controller software enables the operator to easily understand and control the workflow

Programs can be switched back and forth between machines based on estimates of remaining tow before a head change or spool replacement is needed, or even divided between machines to more quickly finish a single program, splitting courses between the two machines. Individual tows can be enabled or disabled for each course, enabling total operator control of what is done in each layup.



Barrel id: 123456789.621.1235.15542

- Sequence: 020
  - ~~position: 1. Index = 165.000, 1.1 RPM~~
    - ~~M1 primary: full_BndP2a1_-45_hybrid_h1.mcd~~
    - ~~M2 primary: full_BndP2a1_-45_hybrid_h2.mcd~~
  - position: 2. Index = 165.000, 1.1 RPM
    - M1 primary: full_BndP2a1_-45_hybrid_q1.mcd
    - M2 primary: full_BndP2a1_-45_hybrid_q2.mcd
- Sequence: 030
- Sequence: 040
- Sequence: 050
- Sequence: 060
- Sequence: 070
- Sequence: 080
- Sequence: 090
- Sequence: 100
- Sequence: 110
- Sequence: 120
- Sequence: 130
- Sequence: 140
- Sequence: 150
- Sequence: 160
- Sequence: 170
- Sequence: 180
- Sequence: 190
- Sequence: 200

The Build Schedule software enables the operator to assign individual sequences to each machine in the cell as desired.

Conclusion

The new machine developments discussed in this paper – modular heads, toolpoint programming, etc., are now proven, refined and utilized in the production environment. The technologies have been implemented on both post style machines and gantry style machines. They have been successfully applied to a diverse selection of large structural types, such as fuselage "barrels", individual fuselage quarter sections, and even spars. The more generic technologies of toolpoint programming and volumetric compensation are now being used on custom drilling machines, wing panel fastening machines, and wing assembly drilling machines. Looking forward, these tools are of great value to maximizing the performance of a wide range of CNC machines.

CONTACT
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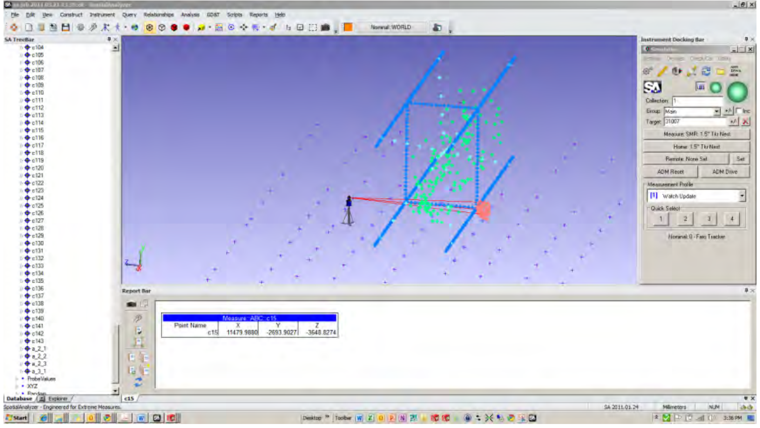
References:

1. Production Implementation of Multiple Machine,
High Speed Fiber Placement for Large Structures. Rob Flynn, Justin Nielson, Todd Rudberg, 2010 SAE International, Paper No. 2010-01-1877.

Commercial References:

Spatial Analyzer is a metrology product of New River Kinematics, Inc.



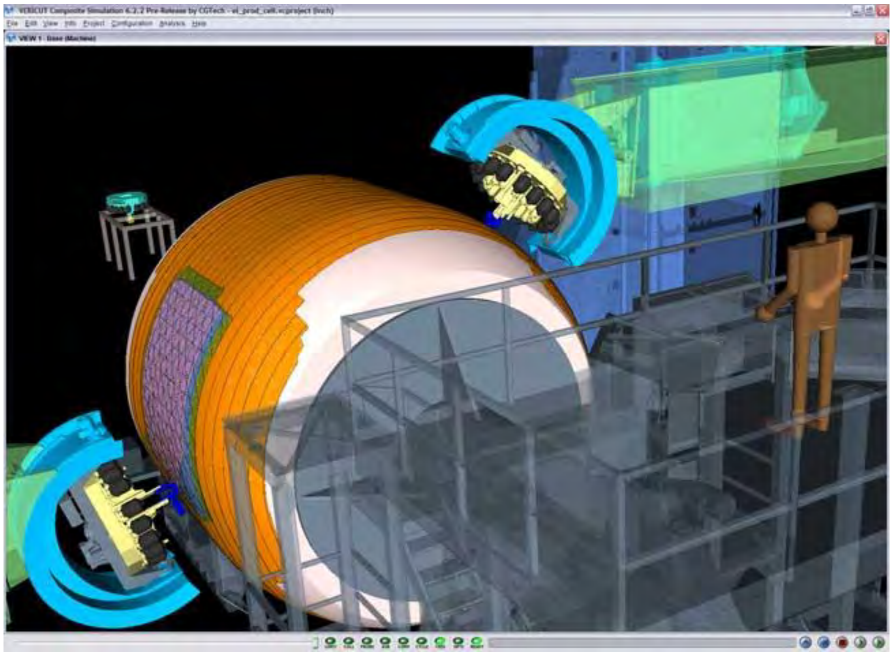
Measure::ABC::c15			
Point Name	X	Y	Z
c15	11479.9880	-2693.9027	-3648.8274

New River Kinimatics' Spatial Analyzer showing sample points from volumetric compensation

The Active Target is a product of Automated Precision, Inc.

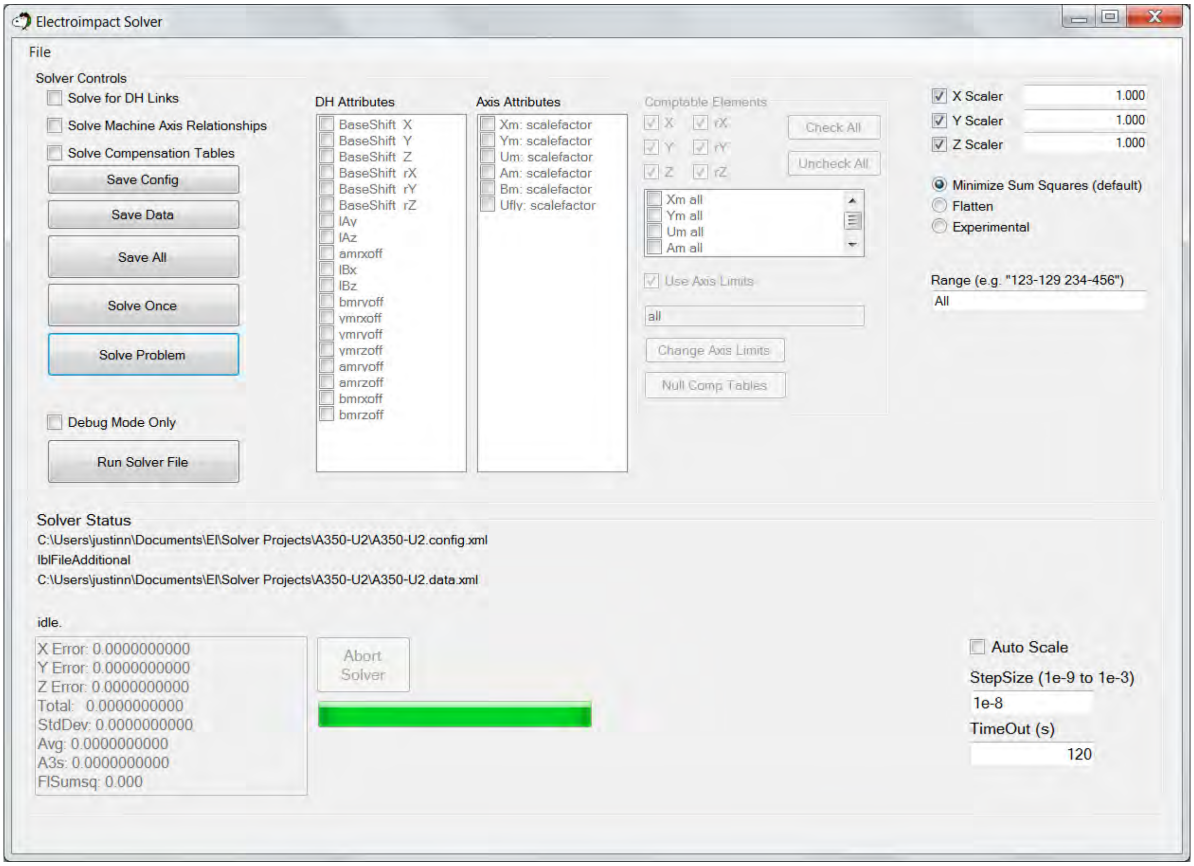
Automated Precision's Active Target

VERICUT Composite Programming and Simulation Suite is a product of CGTech



CGTech simulation of 2 Machine AFP Cell

Electroimpact Solver is a tool built by Electroimpact, Inc.



Solver Controls

☐ Solve for DH Links
☐ Solve Machine Axis Relationships
☐ Solve Compensation Tables
☐ Debug Mode Only

DH Attributes

☐ BaseShift X
☐ BaseShift Y
☐ BaseShift Z
☐ BaseShift rX
☐ BaseShift rY
☐ BaseShift rZ
☐ lAy
☐ lAz
☐ amrxoff
☐ lBx
☐ lBz
☐ bmryoff
☐ ymrxoff
☐ ymryoff
☐ ymrzoff
☐ amryoff
☐ amrzoff
☐ bmrxoff
☐ bmrzoff

Axis Attributes

☐ Xm: scalefactor
☐ Ym: scalefactor
☐ Um: scalefactor
☐ Am: scalefactor
☐ Bm: scalefactor
☐ Ufly: scalefactor

Comptable Elements

☑ X ☑ rX
☑ Y ☑ rY
☑ Z ☑ rZ

☐ Xm all
☐ Ym all
☐ Um all
☐ Am all

☑ Use Axis Limits

all

☑ X Scaler 1.000
☑ Y Scaler 1.000
☑ Z Scaler 1.000

● Minimize Sum Squares (default)
○ Flatten
○ Experimental

Range (e.g. "123-129 234-456")
All

Solver Status

C:\Users\justinn\Documents\EI\Solver Projects\A350-U2\A350-U2.config.xml
lblFileAdditional
C:\Users\justinn\Documents\EI\Solver Projects\A350-U2\A350-U2.data.xml

idle.

X Error: 0.0000000000
Y Error: 0.0000000000
Z Error: 0.0000000000
Total: 0.0000000000
StdDev: 0.0000000000
Avg: 0.0000000000
A3s: 0.0000000000
FlSumsq: 0.000

☐ Auto Scale
StepSize (1e-9 to 1e-3)
1e-8
TimeOut (s)
120

Electroimpact Solver