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Automated In-Process Inspection System for AFP Machines

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ABSTRACT

In many existing AFP cells manual inspection of composite plies accounts for a large percentage of production time. Next generation AFP cells can require an even greater inspection burden. The industry is rapidly developing technologies to reduce inspection time and to replace manual inspection with automated solutions. Electroimpact is delivering a solution that integrates multiple technologies to combat inspection challenges. The approach integrates laser projectors, cameras, and laser profilometers in a comprehensive user interface that greatly reduces the burden on inspectors and decreases overall run time.

This paper discusses the implementation of each technology and the user interface that ties the data together and presents it to the inspector.

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INTRODUCTION

Inspection of composite plies is an important step in AFP manufacturing. To ensure quality the current industry standard is to have dedicated personnel visually inspect each ply before the next ply is deposited. Each part has specific inspection requirements, which typically include accuracy of tow end placement (ply boundary), control limits on overlaps and gaps between tow lanes, foreign object detection (FOD), and detection of defects such as puckering and bridging. Presently tow end accuracy is verified by visually comparing location to a laser line projected onto the surface by laser projectors. The other requirements are inspected by using human eyes to scan the surface. This type of manual inspection is time consuming and vulnerable to human error. Studies have shown that manual inspection can consume more than 20% of total production time [1].

To reduce manufacturing time and improve quality the new generation of AFP equipment will automate inspection. The Electroimpact inspection system integrates cameras, laser projectors, laser profilometers, and a user interface.

For decades laser projectors have projected ply boundaries for inspection. Recent advances have added the ability to project individual courses, tows, and 3-D points [2]. The upcoming generation of functionality provides integration with automated defect detection software, in which the laser projectors will project the location of identified defects onto the part surface.

In parallel with material deposition, camera systems capture a complete image of each composite ply. Individual photos are used together to create a macro-image of each ply. Feature recognition software measures end placement and verifies they are within tolerance. Out of tolerance features are reported on the user interface, which will provide the inspector with both a photo of the defect and a real time camera view of the defect location.

Laser profilometers scan the surface of each ply in parallel with material deposition. A profilometer is made of a laser line emitter and a detector array. The laser line spans the seam between tow lanes. The detector measures the height of more than 1000 discrete positions along the laser line. The profilometer thus provides a 2-D profile of the surface. By moving the profilometer along the surface we create a 3-D profile. Profilometers are used to measure the width of overlaps and gaps between each lane. This data is supplied to the user interface, which lists defects for the inspector to review.

The inspection user interface ties together data from cameras, profilometers, part programs, and operator input. Using the part program the UI creates a ply-by-ply 3-D model of the part. Camera images, tow ends, and profilometer measurements are referenced to the model, where they are available for display. The UI identifies defects and locates them on the model. Defects are also listed in tabular format in a separate UI display. Defects can be sent to the laser projectors, which project defect locations onto the part surface.

INSPECTION COMPONENTS

Laser Projectors

Laser projector systems installed by Electroimpact benefit from tight integration with the entire system. In addition to standard inspection capabilities (ply boundaries, ply direction, tooling points, etc.) operators have the ability to highlight any feature on a course (individual courses, individual tows, etc.) through the use of an intuitive 3D interface. Tow errors are automatically logged and prepared for projection at any time [2].

Laser projector integration allows for fast, automated part locating. In many installations the accuracy of locating a part by laser projector negates the need for potentially dangerous manual jogging of the machine for touch probing. Where laser projector accuracy is insufficient for final layup locating the part transform created by laser projector allows for the automatic operation of touch probing thus bypassing the need for manual jogging.

Camera System

Electroimpact photographs composite plies using specially modified laser projectors. LASERVISION projectors from Assembly Guidance feature two sets of steerable mirrors (these are known as galvanometers in the industry). One set steers a traditional green laser beam. The other set steers a high resolution camera with a 300mm lens. Figure 1 illustrates the LASERVISION hardware.

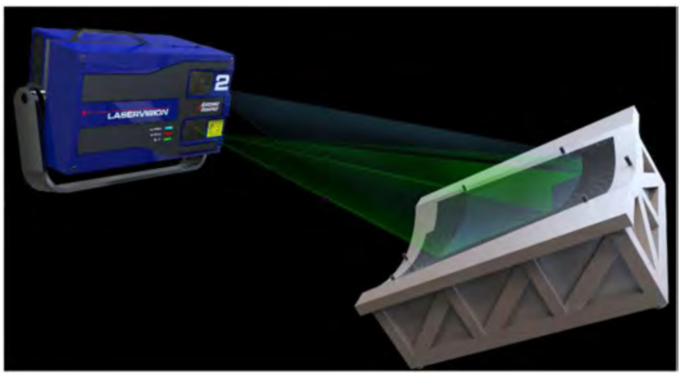

Figure 1. LASERVISION

As the part is laid up, the LASERVISION system will capture images of the part. The 3-D location of each pixel is identified using the same software that enables laser beam steering. A set of small images are conjoined to create a complete image of the ply.

Image resolution is high enough that the location of ply boundaries can be automatically measured from the image. Feature recognition software is used to measure the location of features. The algorithm requires a vast amount of image data to train the software how to identify a feature. Tow ends are the feature most relevant for inspection. To locate a feature the algorithm first detects a tow end and determines its position locally on a small image. Using its knowledge of 3-D location for each image pixel the software then locates the tow end in part coordinates. For display and inspection, tow end measurements are sent to the inspection user interface.

Laser Profilometers

Concept

A laser profilometer is a device that projects a laser line onto a surface and measures the distance to points along that laser line. The array of distances creates a profile of the surface, which can be evaluated to identify and measure surface features. Figure 2 illustrates the concept of a profilometer. The X axis is defined as the direction along the laser line length. The Z axis is defined as the direction in which the laser line is projected.

The laser profilometer provides an array of raw data the represents a surface profile. Figure 3 illustrates that the data provided by the profilometer matches a profile view of the contour of the surface. The gap in the surface from Figure 2 is mimicked in the data plotted in Figure 3, where the horizontal axis is data point in the X direction defined by Figure 2 and the vertical axis represents the Z distance from the profilometer to each data point.

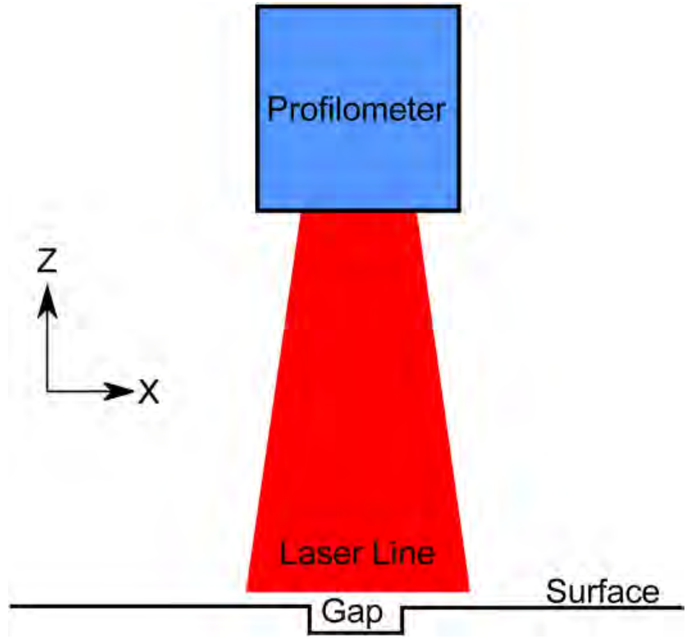

Figure 2. Profilometer Diagram

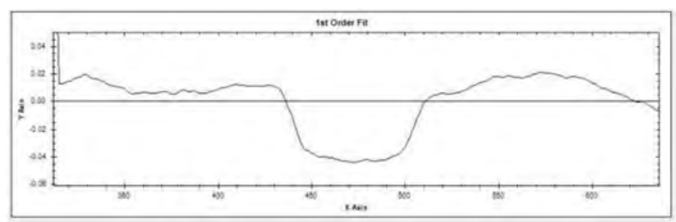

Figure 3. Profilometer Data Plot

Figure 4. Overlap and Gap

Surface features that are important to AFP inspection include gaps, overlaps, FOD, bridging, puckering, delamination, and tow twists. Laser profilometers can detect all of these types of features (given sufficient size) and measure the width of gaps and overlaps. Examples are shown in Figures 4, 5, 6.

Figure 5. FOD

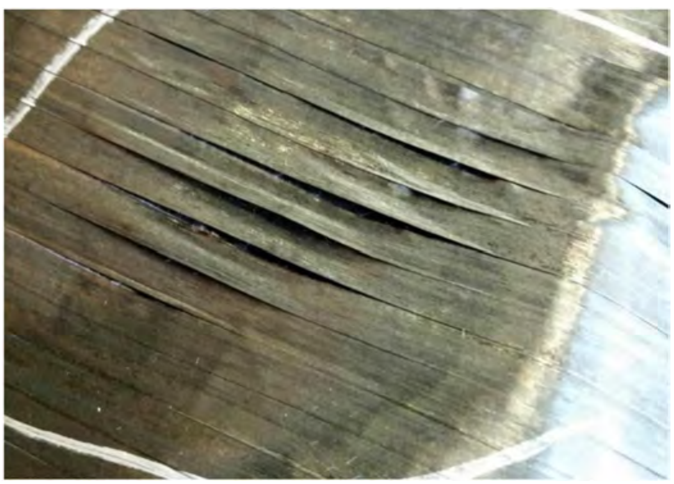

Figure 6. Bridging

Data

Raw profilometer data is passed through a software algorithm which identifies the feature type and measures width for overlaps and gaps. The algorithm begins by using the difference between adjacent data points to identify a steep change in profile. Steep changes in surface profile indicate the presence of a feature. Feature data passes through a second algorithm to classify the feature. Data identified as an overlap or gap passes through a 3rd algorithm to estimate width.

Overlap and gap width are measured every 0.5″ along the length of a course. A plot of consecutive measurements shows how the feature width varies along the course. An example of consecutive gap width measurements for a single tow lane is shown in Figure 7, which illustrates a gap that widens as the course progresses. Each point in the X direction is a measurement derived from a single profile.

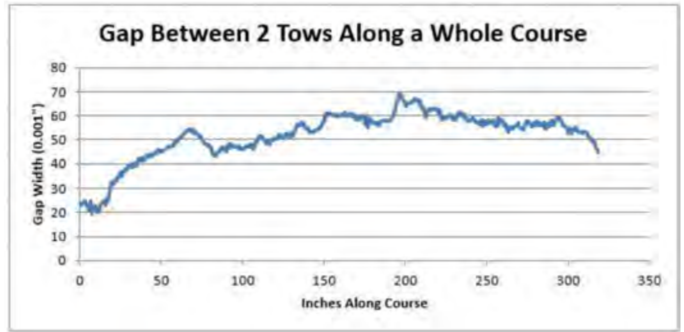

Figure 7. Gap width measured every 0.5″ along course direction.

The system can reliably measure overlap and gap widths between 0.004″ and 0.200″. Widths outside this range can also be obtained, but reliability might be reduced.

Parallel Inspection

To achieve the goal of inspection in parallel with material deposition profilometers must provide data that spans course width. AFP process heads with wide course formats can require 12 or more profilometers working in parallel to scan the entire course width. Figure 8 diagrams the hardware layout used to support multiple profilometers.

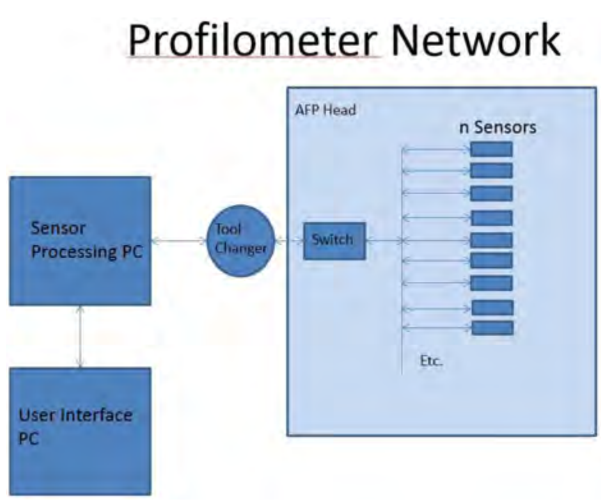

Figure 8. Profilometer Network.

One challenge of the profilometer system is data management and processing speed.

Profilometer manufactures provide pre-packaged software to measure gap width. Because these algorithms execute on board the manufacturer hardware they have no trouble keeping up with sample rates in the kHz range. However, the complexity of the range of feature detection and accuracy required for AFP inspection is not satisfied by these on-board algorithms. Electroimpact's solution is to gather raw profile data and process it with custom software algorithms.

In order to measure small features on a large part an enormous amount of profile data is required. Table 1 shows specifications and operating conditions for the profilometers. To provide a measurement approximately every 0.5″ at a machine feedrate of 3500 inches per minute a profilometer measures profiles at 140 Hz. A single profile contains 1280 data points. Wide course formats with 12 profilometers will generate 12x the data of a single profilometer.

To keep pace with new profile data incoming at 140 Hz each profile must be processed in under 7 ms on average. This requirement can limit the algorithm complexity used to identify and measure features. Electroimpact mitigates the throughput bottleneck by using a dedicated high performance PC to process data. The sensor processing PC shown in Figure 8 contains 8 processor cores that can each execute 2 threads simultaneously. This approach allows parallel processing of data from 16 profilometers in a total time of 1 to 2 ms on average.

Table 1. Profilometer Performance Specifications.

Sample Rate	140 Hz
Data points per profile	1280
Target Surface Speed	3500 Inch/minute
Maximum Distance per Sample	0.416 Inch
Minimum Detection Width	Less than 0.004 Inch
Maximum Detection Width	0.250 Inch
X resolution (see Figure 2)	0.0015 Inch
Z resolution (see Figure 2)	0.00015 Inch
Nominal Laser Width	2 Inches

Data Display

Profilometer measurements are logged into a database with position and time information. The user interface queries this profilometer data to identify defects and out of tolerance conditions. These are then displayed in an intuitive format for a user interface operator to observe and decide how to address the issues. The user interface operator reviews all inspection data on a PC and does not need to walk along the part inspecting surface quality visually.

Inspection User Interface

Inspected Part Model

The Electroimpact inspection user interface uses an interactive 3D model with the in-process part images overlaid in real time. Image resolution is dynamic such that resolution increases with the degree of zoom. The interface allows an inspector to view images as they are obtained and review previous images in an intuitive manner. The interface can display a whole ply, or be zoomed in to show an arbitrarily small window of the ply. Figure 9 shows a zoomed out view of the 3D model. Figure 10 shows a closer view, as well as the features for highlighting individual courses and tows.

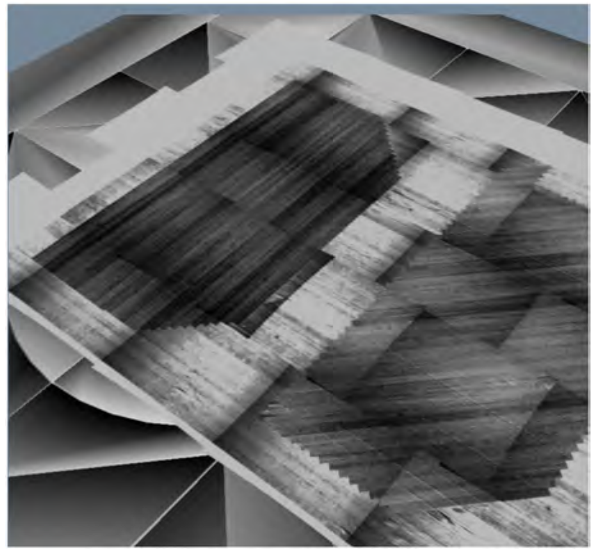

Figure 9. Conjoined Ply Image.

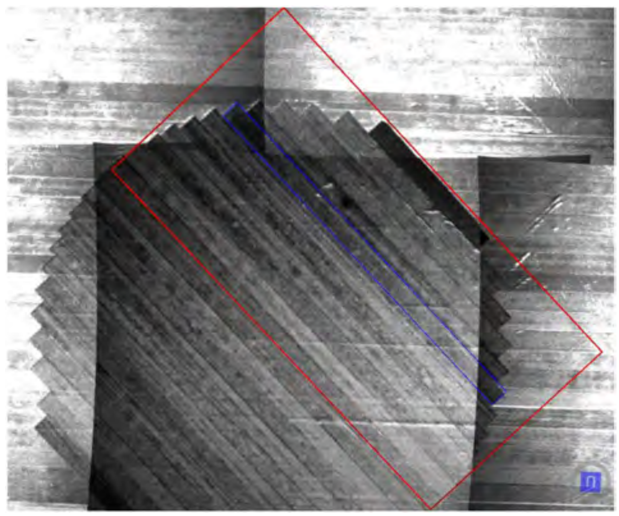

Figure 10. Ply Image with Highlighted Course and Tow.

For a unified inspection experience the interface also shows:

- Lap/gap measurements and errors
- Ply boundaries
- Tow end tolerance bands
- Tow errors indicators
- Part coordinates
- Course and tow numbers

The interactive inspection screen is shown in Figure 11. It shows inspection data for one ply at a time. The displayed ply is selectable. The inspection UI contains an image of the ply constructed from multiple camera images. Upon that image can be overlaid lap/gap inspection data and ply boundary inspection data. The control interface for each is located on the left hand side of Figure 11 as grey boxes. These display a list of automatically detected defects and out of tolerance conditions. The end user inspects defects using a combination of the list view and the overlay on the ply image.

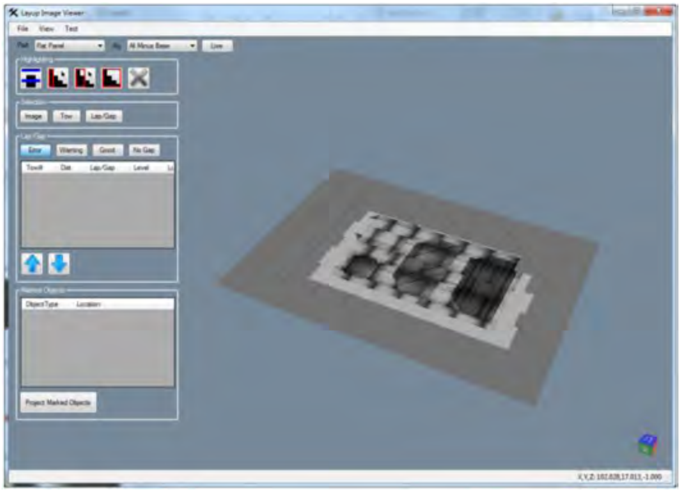

Figure 11. Inspection User Interface.

Should inspection or rework at the part need to occur, the inspector/operator has the ability to control the laser projection system directly from the interface to facilitate identification of features or defects on the part.

Lap/Gap Interface

Electroimpact's automated lap/gap detection measures the lap/gap between every tow in parallel with process layup. The 3D position of each measurement is recorded, and this ties each measurement to its location on the part.

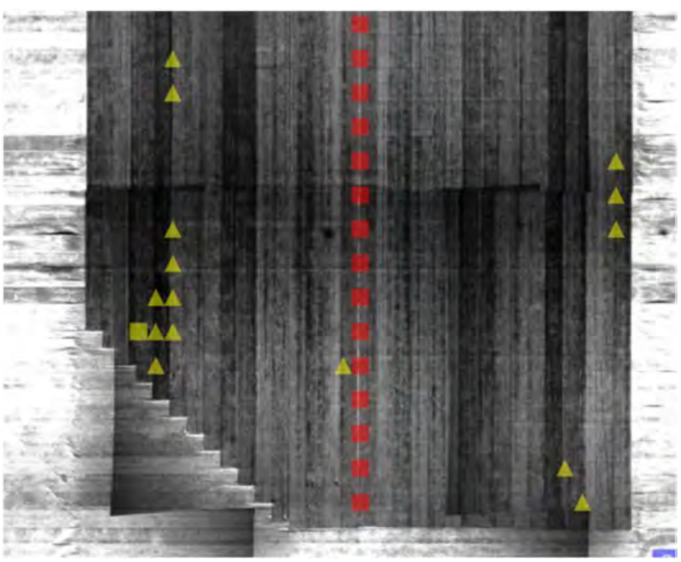

Figure 12. Lap Gap Errors Overlaid on 3D Model of Ply.

Measurements that are out of tolerance are overlaid on the display of the ply in the interactive 3D model user interface. The end user is presented with information detailing the out of tolerance condition.

Measurements that violate the acceptable limits will be displayed in red on an image of the course in the proper location. Measurements that approach the limits of acceptance will be displayed in yellow. An example is shown in Figure 12. Out of tolerance conditions are configured per customer inspection goals.

The user is able to zoom in on an image of the defect location to get a close up view of the actual layup. An example is shown in Figure 13, which is zoomed in on a single out of tolerance gap measurement.

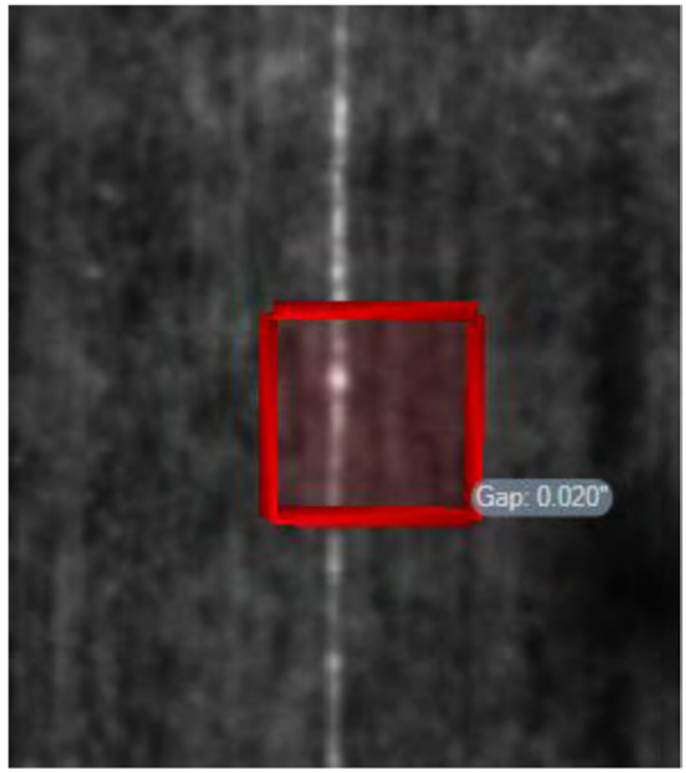

Figure 13. A Single Gap Error.

Each measurement is logged into a database that includes the following information:

3D position in part coordinates

- Path distance from start of course
- Part number
- Program Name
- Ply/Sequence number
- Course number
- Gap identifier (tow number)
- Time and date

All lap/gap data is stored in a database, and it can be queried by position, program, ply, course, and tow. This allows the inspection software the flexibility to be tailored to custom inspection requirements. Examples include cumulative measurements across a ply and lap/gap density over multiple plies.

In addition to overlap and gap measurements, this system can detect surface anomalies, such as FOD and twisted tow conditions, as long as the anomaly occurs over a length exceeding 0.5″ and a surface height of 0.050″. The system will flag an anomaly as a gross error on the UI to prompt the user to further examine the region surrounding the anomaly.

Ply Boundary Inspection

Semi-Automatic

The 3D model is capable of displaying all elements required for ply boundary inspection. Available elements include expected boundaries, tolerance bands, the expected path of any individual tow and course boundaries. The semi-automatic feature provides a UI operator images that can be used to inspect tow end placement and ply boundaries. An example is shown in Figure 14. If the tow ends are visible between the blue and green lines the operator indicates they pass inspection. Otherwise a defect is flagged for rework.

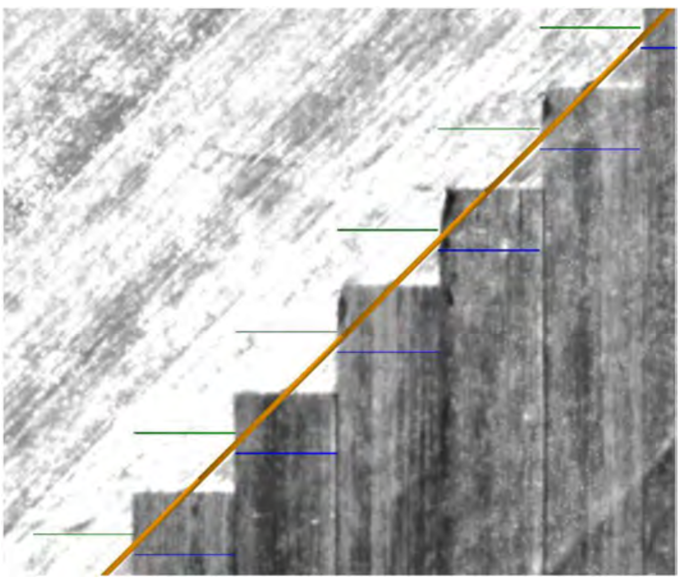

Figure 14. Boundary and tow tolerance highlighting.

Fully-Automatic

Using feature recognition software, the location of ply boundaries and tow ends can be automatically measured from ply images. Error is computed by comparing ply boundary targets (from the part program) to the locations measured in the images.

Initial results detect and locate 90% of all tow ends. Production detection rate is projected to be 99%. To achieve 99% detection a large set of data is necessary to train the feature recognition algorithm for improved performance. This data will be gathered during the initial few months of production. Even at 90% detection, automated measurement is still very valuable, as it reduces the semi-automatic ply boundary inspection workload to 10% of total.

An example of current progress with automated edge detection is shown in Figure 15. Yellow lines indicate automatically detected tow ends, which are overlaid on the ply image.

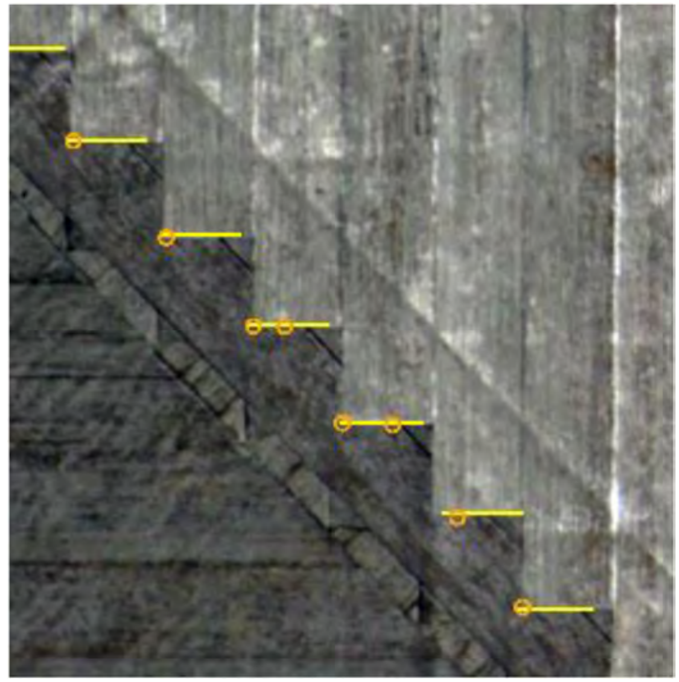

Figure 15. Example of Automated Edge Detection.

Pointing to Defects

The user interface is fully integrated with our laser projection system. An inspector can mark any defects or concerns from within the UI and have the laser projector project the location on the part surface for quick identification.

SUMMARY/CONCLUSIONS

Rapid advancements in automated inspection technology are leading to a new generation of AFP equipment that reduces inspection time. Manual inspection procedures are becoming automated with the use of laser projectors, cameras, feature recognition, and laser profilometers. Integrating all of these technologies in parallel with composite layup can lead to a production time savings of more than 20% [1].

Automated data collection provides higher reliability and more thorough inspection. Laser profilometers accurately and reliably measure every overlap and gap on every ply. Cameras and feature recognition software detect and measure ply boundary locations better than 90% of the time. The 10% that remain undetected can be rapidly inspected by a single operator presented with a sequence of high resolution photographs. Furthermore, the ply boundary inspection algorithm will continue to improve as production data is generated and is expected to achieve 99% detection or better.

Automated inspection records terabytes of inspection data for each production part. Rigorous study of this data can lead engineers to a more comprehensive understanding of composite design and manufacturing, and it opens a conversation about implementing statistical process control on particular composite ply features.

Machines featuring automated inspection are scheduled to begin production in the middle of 2016. As production increases we will begin to see how powerful automated inspection can be.

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DEFINITIONS/ABBREVIATIONS

AFP - Automated fiber placement

Tow - A single strip of carbon fiber

Lane - The path for a tow

Layup - Deposited carbon fiber

Ply - A layer of layup

Feed-rate - Speed of layup

Inspection - Observe the as-made part surface and determine if rework is necessary

Rework - Manually or automatically correcting defects in the layup

Gap - A space between parallel adjacent tows

Lap - An overlap between parallel adjacent tows

Ply Boundary - Tow ends and edges of a ply

FOD - Foreign object detection

Defect - A misplaced tow or tow end, missing tow, FOD

Ply Boundary - Tow ends and edges of ply

Laser Projector - Hardware that projects laser lines onto the part

LASERVISION - A laser projector that can also capture camera images

Profilometer - A laser sensor that measures surface profile