3D PROCESS ANALYTICS FOR CARBON COMPOSITE MANUFACTURING

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ABSTRACT

The fabrication of carbon fiber reinforced plastic (CFRP) structures is generating more and more digital data. This data includes NDI data, dimensional data, thermocouple data, material properties data, and many other forms of process data. Currently, integrating all of this data into a global view of the process is very difficult. Typically each data set is analyzed in its own software package, limiting the ability to integrate the multiple data types.

This paper discusses work being supported by the US Air Force, US Navy, industrial partners such as Spirit AeroSystems, and early adopters such as GKN Aerospace to develop a software package to collect, organize, archive, and analyze this data. The data is organized by automatically aligning the data to 3D models of the parts being manufactured. The software can then visualize and layer the process data on various 3D models, such as mold models showing mold seams and thermocouple locations, ply models showing ply drops, preform models showing individual preforms, etc. This enables performing detailed analysis to detect trends at specific locations on the model. These trends can be indications of process problems.

This technology has been successfully applied to improve first pass yield, reduce scrap, and lower risk associated with the CFRP structure fabrication process. Further, this aggregation of data on a 3D model has been used to improve Material Review Board (MRB) processes, increasing production rate while managing risk. Finally, this technology can be used to drive the digital thread, a linkage of the manufacturing and in-service maintenance data aggregated over the life of a component.

INTRODUCTION

Etegent Technologies has a long history of working for government authorities to develop technology for automatically aligning surveillance data to 3D models of the earth (Geolocation).

Seven years ago, Etegent was contracted by the US Air Force to apply this data mapping technology to the Air Force's ever growing set of digital inspection data generated by their maintenance processes. Etegent leveraged their success in the maintenance application to develop support for carbon composite manufacturing applications. At this time Etegent created the NLign Analytics Division focused on developing NLign, a data aggregation, archival, and analysis software package targeted specifically at carbon composite manufacturing. This paper discusses how NLign has demonstrated its ability to improve first pass yield, reduce scrap, and improve MRB processes.

1.1 System Overview

Figure 1 shows the four main components to the system: collection, organization, archiving, and analysis. The key principle to organizing the inspection and process data is aligning the data to CAD models of the inspected structure. By doing so, each of the pixels in the image has not only a value but also a location. Once the images have been aligned, NLign can also align all markings, indications, and other associated spatial data to the CAD model. By archiving the data in this structured way it is easy to mine the data. Once the data is aligned to a common reference frame, data from various inspections across the fleet or across a manufacturing run can be superimposed. This facilitates the discovery of trends across time and parts as well as the determination of areas of missed inspection coverage.

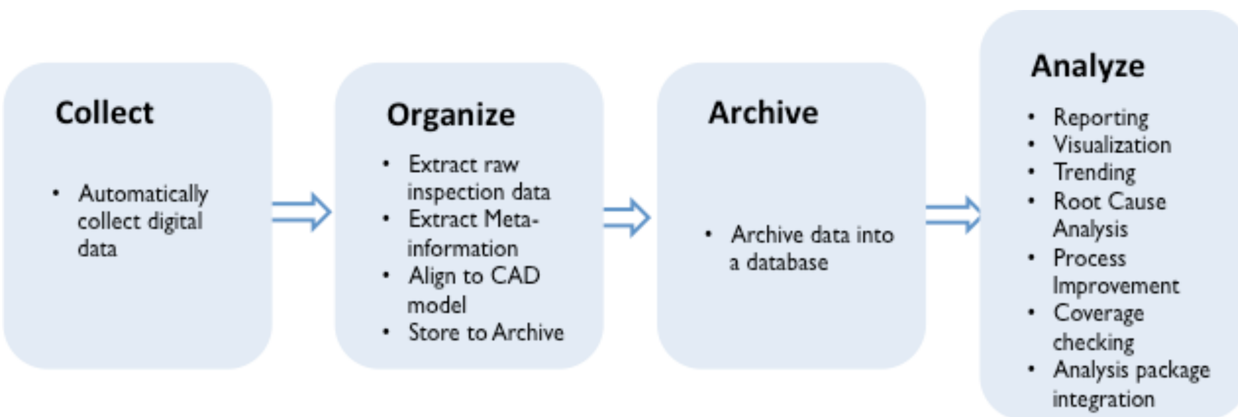

Figure 1. Overview of data analysis process.

Figure 2 depicts an example of the operation of NLign. In this example a C-Scan image from an ultrasonic inspection of a composite fuselage is automatically mapped to a 3D CAD model, stored in an archive database, and then visualized on the 3D model. Both the raw inspection data and any meta-information (e.g., inspector annotations) contained in the data are mapped onto the 3D model.

C-scan with Annotations

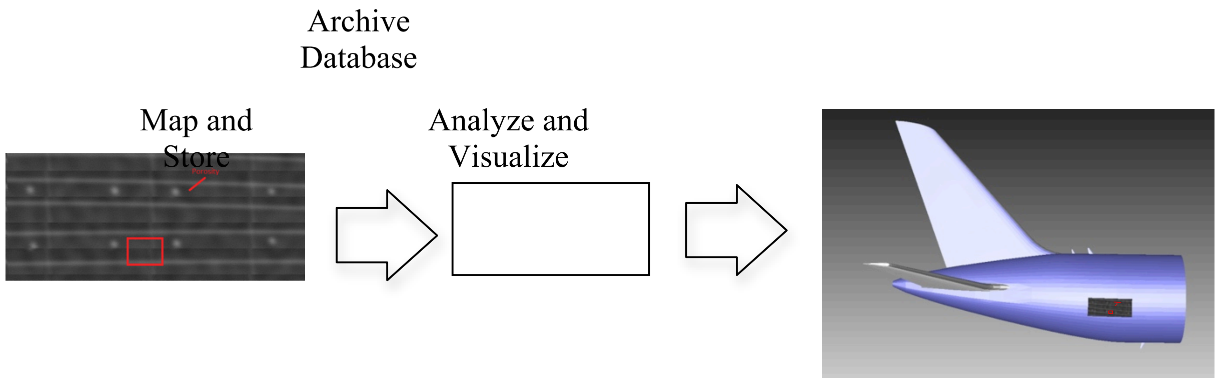

Figure 2: Example of mapping and visualization.

1.2 Data Organization

1.2.1 Extract of Metadata

Automated alignment of inspection data requires several steps, as shown in Figure 3. Metadata associated with the inspection is processed using user configurable rules. This helps remove any abbreviations, variations in terminology, or shorthand. Depending upon the type of inspection, the specific scan, and the information in the tags, the best alignment method is chosen. Once the alignment method is determined the NDE data is automatically aligned to the model. Any inspector-made annotations are aligned to the model as well, and the combination of the alignments and the standardized annotations are stored. This database containing the alignments and the inspector annotations serves as the data source for any mining or visualization of the data.

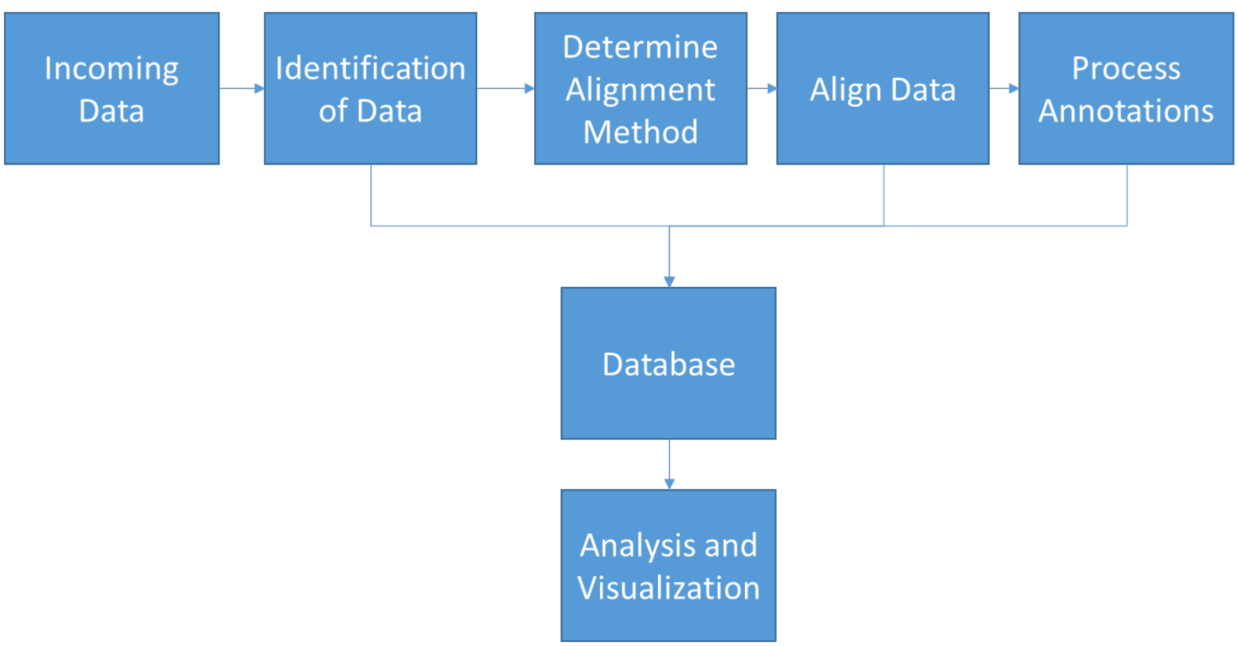

Figure 3: High Level Automatic Inspection Data Alignment Flowchart

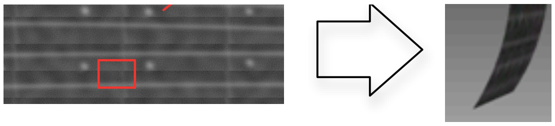

Figure 4: 2D Scan Data to 3D Mesh

1.2.2 Alignment of Data to CAD Model

During this step the inspection data and other process data is mapped onto a 3D CAD model of the part being manufactured. The technique used to map the data depends on how the data was generated. Several techniques NLign uses have been described in previous papers [1][2], but a brief summary of the different types of data and methods of alignment currently being used will be given here.

1.2.2.1 UT Data Mapping Using Robot Trajectory

For scan data taken by a robotic system, 3D robot positioning information may be available in the metadata associated with the scan data. This positional information can be used to generate a 3D triangle mesh surface, associated with the specific scan, as seen in Figure 4.

The 3D mesh can then be registered to the 3D CAD model via matching features found on the CAD model to their representations in the UT data. Once this is done, a rigid body transformation is calculated via least squares fit to align the data to the model, as shown in Figure 5 and Figure 6.

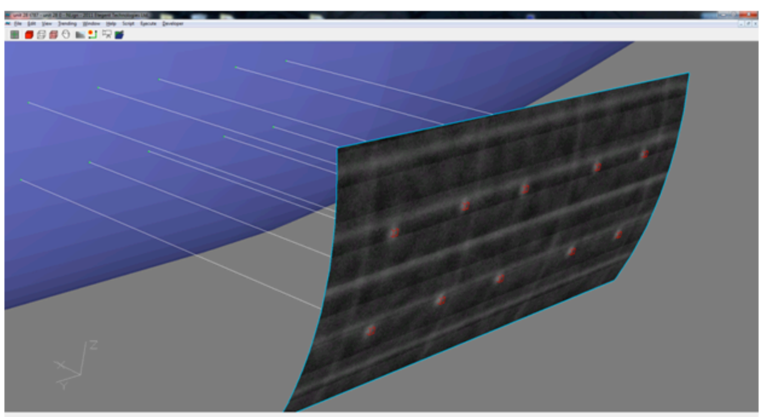

Figure 5: Scan Feature to Model Feature Correspondences

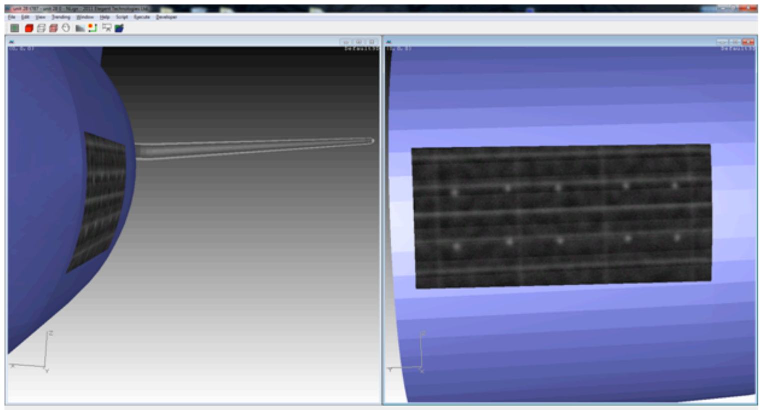

Figure 6: Aligned Data

Once this process has been performed, it is a simple matter to extract the inspector's annotations on the data, interpolate their position on the 3D mesh, and save the data in the database.

1.2.2.2 Turntable UT Inspections

Turntable ultrasonic systems generally provide 3D positional data. However, when used in through transmission mode, the ultrasonic transducer does not need to be positioned relatively normal to the surface of the inspected part, unlike pulse-echo ultrasound. Scan system trajectories for TTU, therefore, are often a poor approximation to the surface geometry of the inspected part, as there is no need for the transducer to track part geometry.

Instead, an algorithmic model of the turntable inspection system is developed. The current simplified model assumes the inspection is performed using a strictly cylindrical coordinate system, in which the direction the UT probe is pointing is always orthogonal to the axis of the turntable. Using this model, the 3D CAD model can be algorithmically "unwrapped" to a 2D image in the same manner that the UT data was collected. Features on the 2D UT data and the unwrapped version of the CAD model are identified, matched, and used to register the two together. The UT data can then be wrapped back to 3D, the inspector annotations extracted and mapped onto the CAD model, and the data stored in the database.

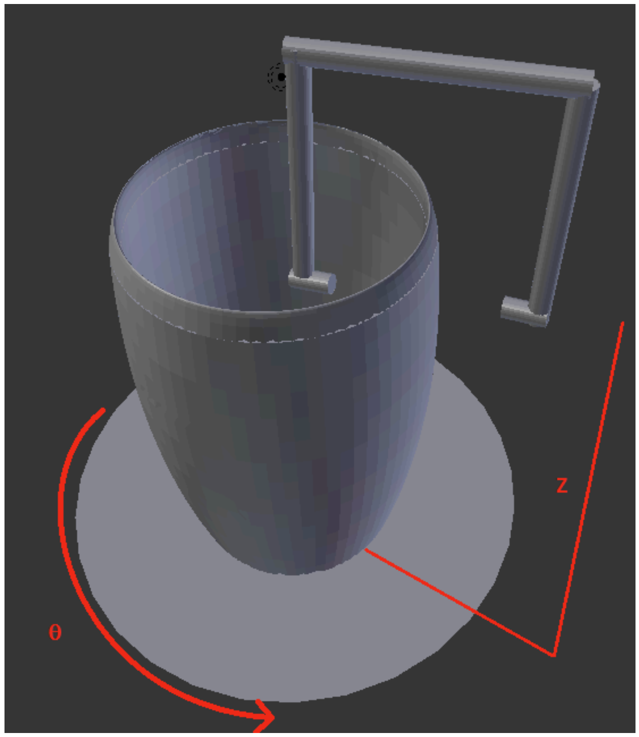

Figure 7. Schematic of turntable inspection setup.

1.2.2.3 UT Crawler Data

Other robotic inspection systems may not have knowledge of their head positions or trajectories in 3D, or may simply not output this information. With knowledge of the part geometry and higher level knowledge on how the inspection is performed and the image is acquired, 2D to 3D mapping can still be performed.

Performing this mapping requires knowledge of where the robot starts scanning on a part, in what directions it scans, and the correspondence between the scanning directions and the horizontal and vertical dimensions of the resultant image. This generates a coordinate system comprised of the normal to the part, the "right" direction, and the "up" direction. This is used to unwrap the 3D model into 2D. Features in the 2D representation and the data are registered, and the data wrapped back to fit the 3D surface geometry.

1.2.2.4 Dimensional Data

Dimensional measurements are made at various locations on a structure as part of the inspection process. Existing software tools do a good job of comparing the "as-manufactured" dimensional measurements to the "as-designed" model for the purpose of accepting/rejecting a part. Our software has been used to collect dimensional data from multiple parts and visualize the variations in 3D to help identify root causes of the problem.

Aligning this data is not a problem because dimensional data typically is tagged with the "as-designed" location (either in the form of an (x, y, z) location or a name of a point with a known (x, y, z) location). The challenge is how to visualize the data accentuated patterns in the positional errors so that the patterns are apparent. This is complicated because the magnitudes of the position error can be multiple orders of magnitude smaller than the dimension of the part being inspected.

1.2.2.5 Other Inspection Data

At times, an inspection procedure does not lend itself to automated registration of data. The outcome of an inspection may simply be paper reports, or may be documented by the maintainer in part by physically marking the location of damage. Existing non-conformance databases may be used to record issues found during manufacturing, and the records in these databases may just be text. To handle such situations, more manual and semi-automated methods are available to input data into the system.

At one extreme, the user can manually add individual records to the system. For small numbers of records, this can be a suitable approach for adding data to the system.

Additionally, spreadsheets of data can be generated and imported into the system. This can be a mechanism for larger quantities of data. This can often work when data is exported from an existing tracking system to a file. The data can then be massaged into a format ready for import.

Findings can also be captured from photographs showing inspector markings on a part. In a fixed bay, this might be an automated method of collection, but for general situations this may be best served as a user in the loop process. Mapping photographic data consists of four steps:

1. User identification of features in the photographs and corresponding features on the 3D CAD model
2. Algorithmic determination of a model of the camera used to take the photograph
3. User identification of damage markings
4. Ray-tracing of damage markings onto the 3D CAD model.

This camera based damage mapping process was developed with support of the US Navy and is currently utilized by the Navy in a composite maintenance and repair process.

Text based data can also be organized within the system. References to particular locations (such as a hole number on a part) can be translated to an actual position on the structural model. Less specific information can be associated with a region of a part or a particular part number within a larger assembly.

1.2.2.6 Other Process Data

Other process data can be stored and correlated with inspection findings for a serialized part. For example, toolset information and cure data can be stored and queried upon. This allows users to determine if a tool is wearing out as well as correlate particular process parameters to the formation of particular defects. This can greatly assist root cause corrective action as well as other process improvement efforts.

1.3 Analysis Tools

After the data has been registered to the 3D model and archived, the user can leverage a suite of tools to analyze the data.

1.3.1 Visualization

NLign provides a powerful and easy to use 3D visualization environment so that the user can easily see how defects, damages, and other discrepancies correlate with part, tooling, and other manufacturing features. The user can overlay a variety of tooling data over the findings, including manufacturing mold features (e.g. seams between parts of the mold), thermocouple locations, and vacuum and resin ports. Further, anomalies during fabrication can be overlaid on defects found during inspection, such as detected loss of vacuum, errors during automated fiber placement (AFP), and temperature thresholds being (or not being) hit.

1.3.2 Querying and Trending

NLign provides tools for the user to trend and query on the data stored in its database. Different finding types can be created, such as CMM findings, NDI findings, Tool Repairs, and so forth, each of which can have appropriate query-able and trend-able fields. Figure 8 shows all the fields that have configured for NDI indications in one application of the software, along with a basic query that would return all porosity indications in the database.

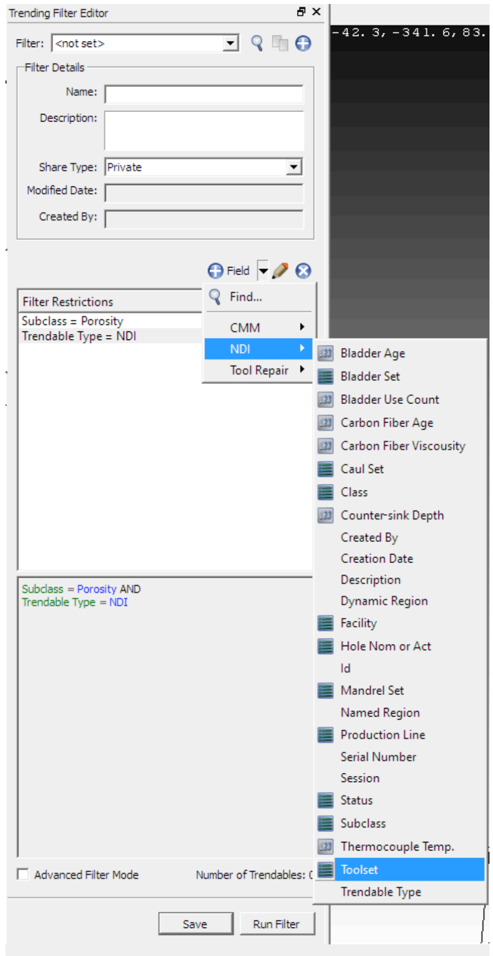

Figure 8: Trending Filter Editor

1.3.3 Charting

A set of basic charting capabilities are available to the user. Bar charts, scatter plots, and histograms are among the different types of charts that can be generated in NLign. All of the fields that can stored with a trendable can be made part of a chart as well. Figure 9 shows a chart configuration that will be later used in Figure 12 to show tool wear resulting in increasing amounts of porosity with each subsequent use.

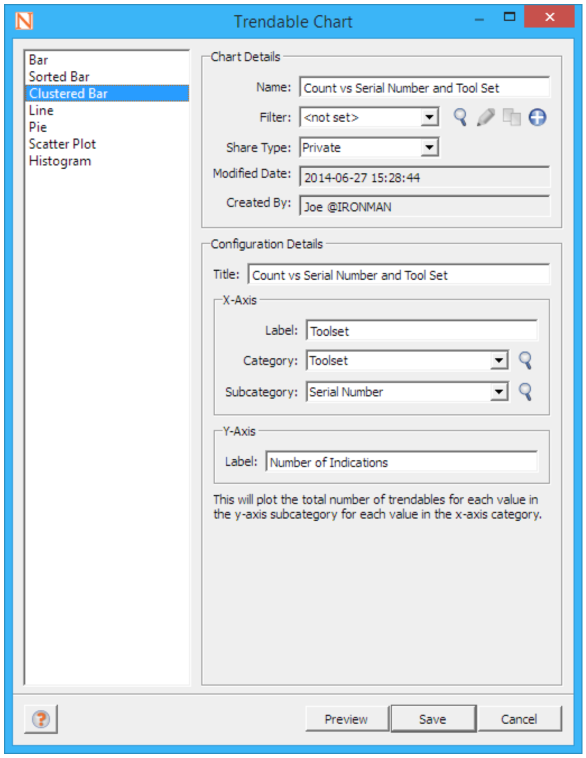

Figure 9: Chart Configuration

1.3.4 External Package Integration

When analysis is required beyond the capabilities of the software, it is important that the user be able to easily continue their analysis in external packages. These external packages can include FEA packages as well as statistical analysis packages, such as Minitab. NLign provides this capability through data export/import tools.

RESULTS

Several conceptual examples and customer case studies of using NLign for improving manufacturing processes are shown here.

1.4 Detection of Tool Wear

Over repeated usages, tools will begin to wear and cause defects in the fabricated product. Molds or other curing tools may begin to leak, leading to porosity, while cutting tools may dull and start causing delaminations. By including the tool information used for each part produced, queries can be performed and charts generated showing potential wearing of a tool. This allows users to catch and replace or repair a worn tool before a major problem occurs.

Figure 10 shows the locations of porosity indications from a number of manufactured parts. Diving into this data further, it can be shown that there seems to be a generally increasing trend of issues, as seen in Figure 11. If the tools used to fabricate a part are also tracked, the chart in Figure 12 can be generated which shows an increasing amount of porosity each time a specific tool is used.

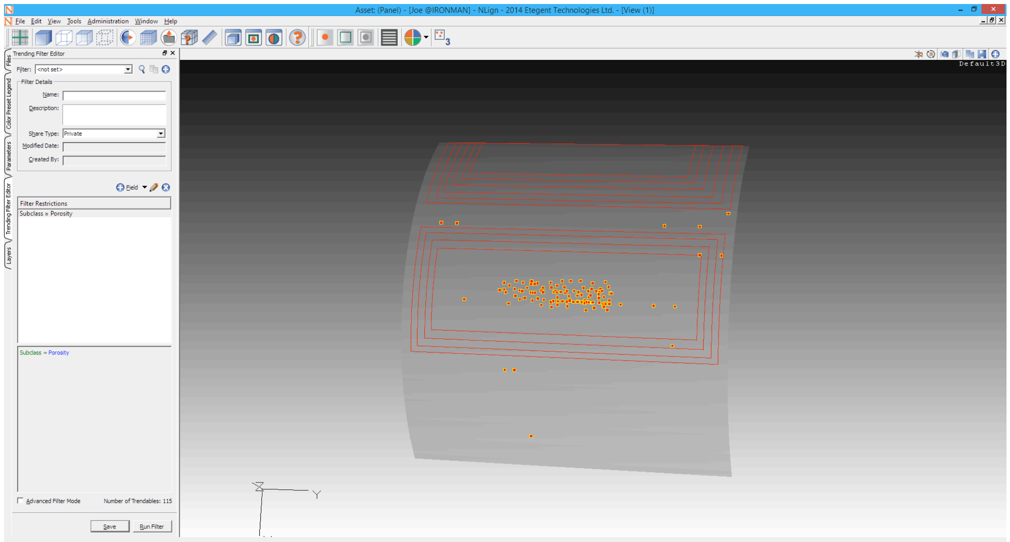

Figure 10: Porosity Indications on Part

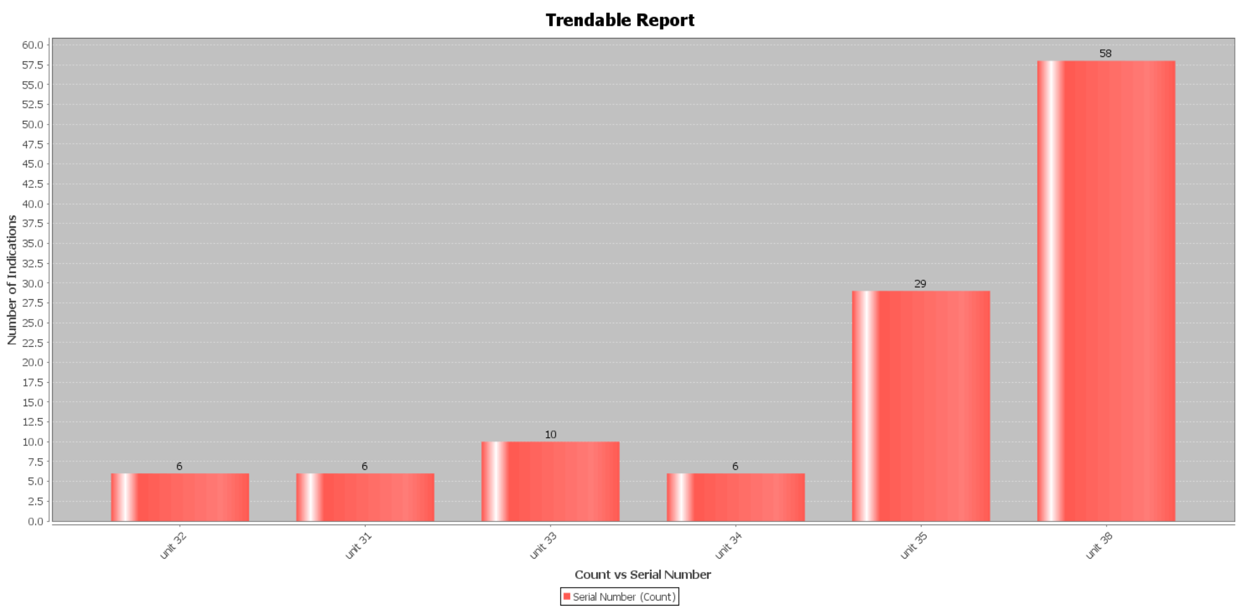

Figure 11: Increasing number of porosity indications

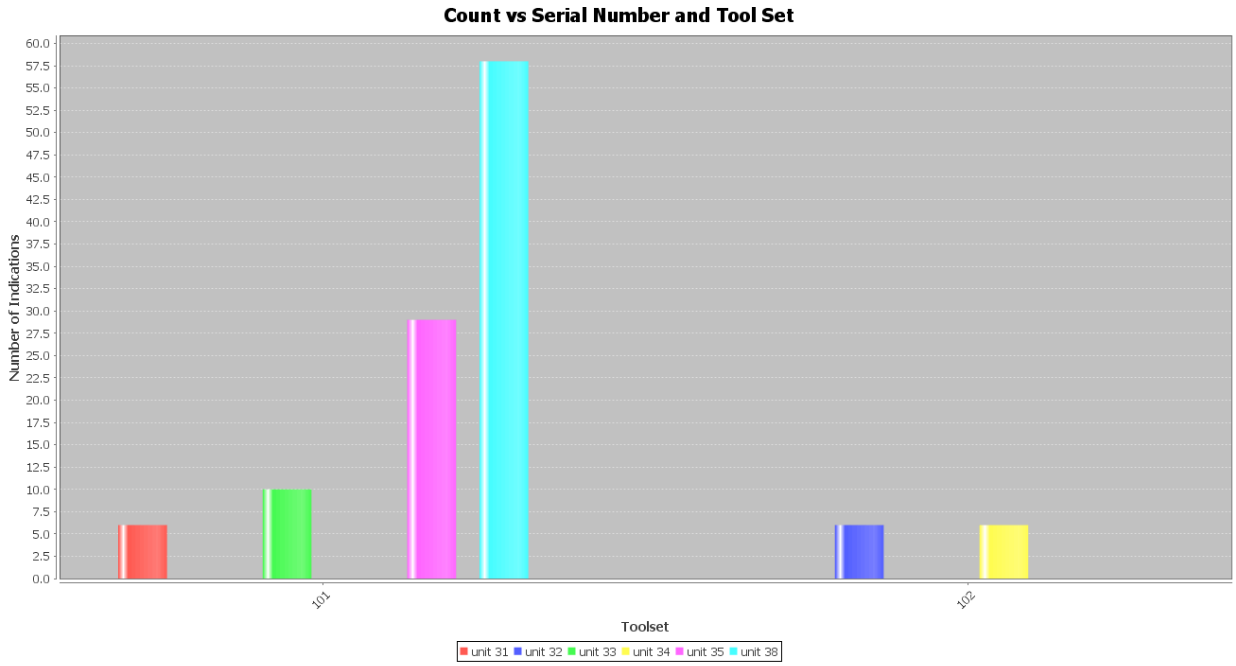

Figure 12: Tool wear resulting in increasing porosity

1.5 Root Cause Corrective Action (RCCA)

Continuing the previous example, it can be seen that there were a large cluster of porosity indications. It may not be enough to know that a tool is wearing; the root cause of the issue may still need to be determined. By storing, querying, and overlaying additional types of information, the system can be used to assist in root cause corrective action.

By overlaying defects found during inspection with tooling information, root causes of issues can be uncovered. Figure 13 shows the model of a manufactured part over which has been overlaid the location of a tool seam. The cluster of porosity indications around the tool seam could indicate that a degrading seal at the seam of the tool is the root cause of the growing number of porosity indications.

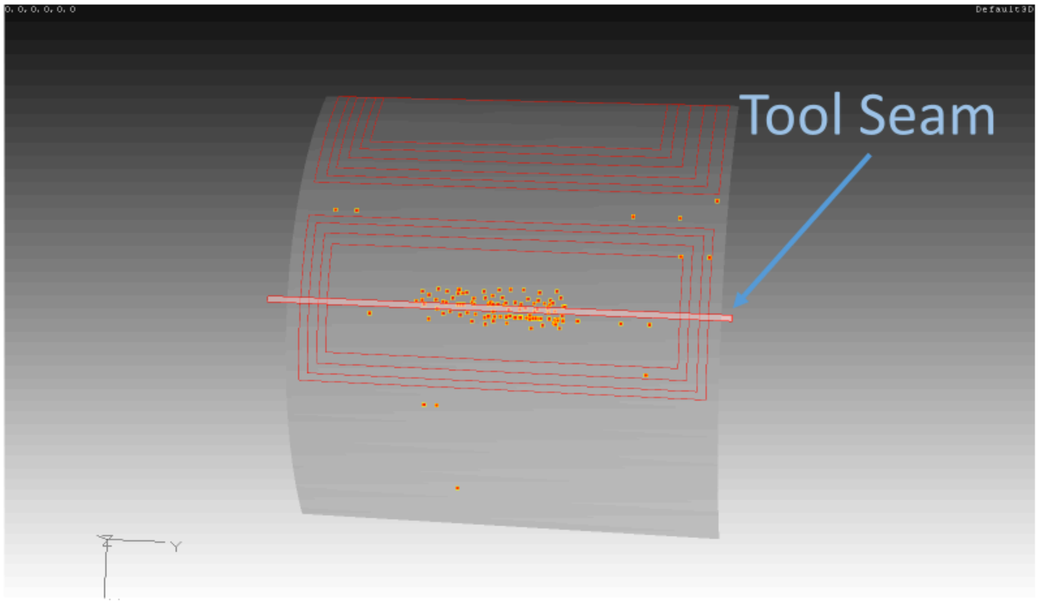

Figure 13: Overlay of Porosity Indications with Tool Seam

1.6 Detection of CMM Trends

CMM results can also be stored in the system and analyzed for trends and biases across multiple parts. Figure 14 shows 7 parts worth of CMM data for the location of a drilled hole overlaid on the model. The nominal location for the drilled hole is shown in orange. The deviation of the actual hole locations is exaggerated for visualization purposes, and is indicated by the blue and green dots. The true deviation is stored in the system and is made available for querying, trending, and charting. The colors of the dots correspond to the direction of the shift of the actual hole location. As can be seen from this image, there is a significant bias in the error of the actual drilled holes' locations.

Figure 14: Locations of Drilled Holes on Part

1.7 Detection of Coverage Issues

For large composite structures, a number of inspections must be performed to cover the entire part. However, it can be difficult to ensure that 100 % of the structure has been inspected. By overlaying the inspection data onto the 3D model, it can be readily apparent if coverage has not been achieved. Figure 15 shows NDI data overlaid on the 3D model, which has been colored red. It can be seen that the edges of the part have not been completely inspected. Without looking at the data and model in the same 3D reference frame, it would be difficult if not impossible to determine that full coverage has not been achieved.

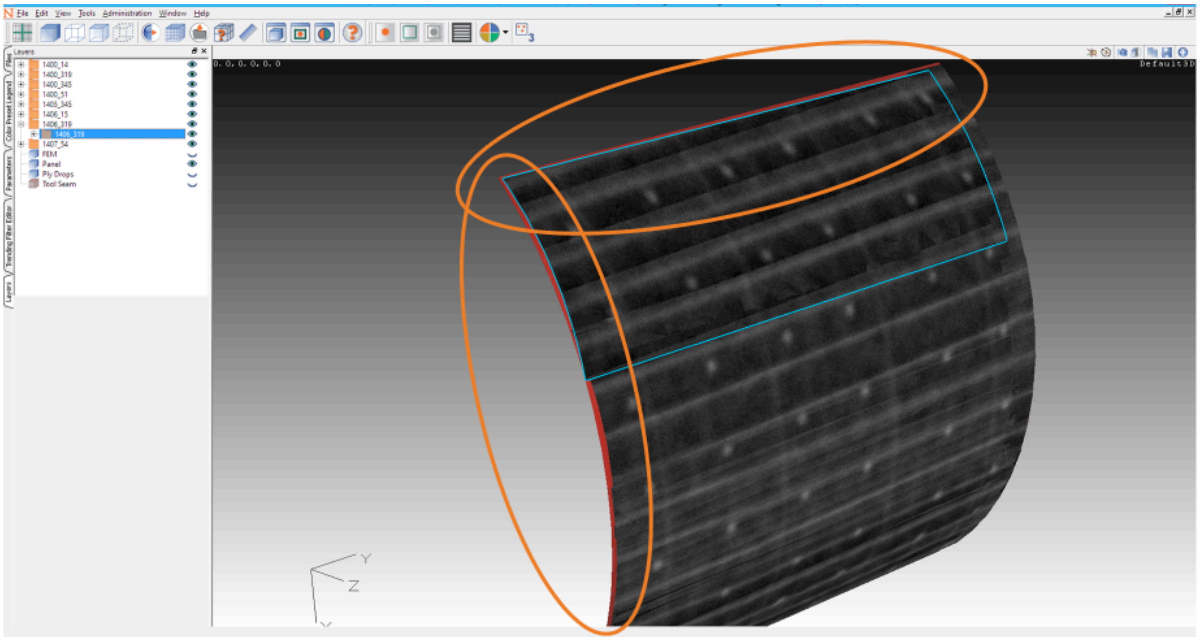

Figure 15: Missing Coverage

1.8 Digital Thread

Efforts to develop the digital thread aim to generate a thread of digital information for a part from cradle to grave. Use of NLign in both manufacturing as well as Maintenance Repair and Overhaul (MRO) provides a powerful tool to further digital thread efforts. Repairs made during manufacturing can be easily retrieved during maintenance. Assessing the health of individual aircraft is also made easier, as previous repairs and other associated data (e.g., flight history) for that specific aircraft can be easily queried.

1.9 Customer Case Studies

1.9.1 Spirit AeroSystems – RCCA, Scrap Prevention, Coverage Verification, Process Improvement

The root cause for the occurrence of localized sporadic acceptable porosity indications on a fabricated fuselage section was unknown to Spirit. By visualizing the porosity indications which were of an acceptable level on the 3D model of the fuselage, the bladder causing the issues could be identified. This allowed for early detection of a pattern that if otherwise undetected would have led to expensive rework and potential scrappage.

Spirit currently utilizes the combination of mapped NDI data and process information organized within NLign on a regular basis to promote improvements to their manufacturing processes in a major composites program. Additionally, Spirit has utilized NLign for coverage verification in support of an NDI machine qualification activity.

1.9.2 GKN - MRB Process Improvement

GKN produces a part where MRB authority rests with the OEM. The MRB process can take up to four weeks, during which time parts are pulled out of the production pipeline, limiting production rate and increasing work in progress.

By storing historical MRB decisions within NLign, GKN was able to assess the likelihood of an MRB disposition and act accordingly. This enabled GKN to reduce work in progress by three weeks, highlighted areas for process improvements, and increased inventory turns.

CONCLUSIONS

This paper discussed Etegent's NLign software package's ability to collect, organize, archive, and analyze CFRP manufacturing process data. These analysis tools have been successfully used by commercial customers to improve first pass yield, reduce scrap, and lower risk associated with their CFRP fabrication process.

REFERENCES

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2. Sharp, Thomas D., Kesler, Joseph M., Ashton, William T., *Improving CFRP Structure Fabrication: A comprehensive data driven approach*, SAMPE 2013 Conference and Exhibition, 2013.