IMPROVING DAMAGE AND REPAIR EVALUATION USING STRUCTURAL DATA VISUALIZATION AND ARCHIVAL TECHNIQUES

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ABSTRACT

Aircraft structural engineers are continuously searching for new processes and technologies to improve damage evaluation and analysis in order to expedite repair dispositions while ensuring the integrity of the airframe. To that end, technologies have been developed that can automatically map photographic and Non-Destructive Inspection (NDI) data to 2D and 3D structural models. This automated damage mapping technology enables engineers to quickly visualize reported component damages on multiple data sources such as Finite Element Models (FEMs), composite ply boundary drawings, substructure models, zonal weight limits, standard repair areas, and so on. Visualizing the data in this manner improves the overall accuracy and efficiency of damage and repair evaluations conducted by Engineers, thus helping to ensure aircraft structural integrity over the life of the aircraft and reducing the turn-around-time (TAT) of repair developments. Additionally, comprehensive data organization and archival functions are used to allow users access to a database of historical damage and repair data. This historical database can then be queried, in 3-D model format, by engineers for previous component repairs, previous similar analyses, commonly damaged locations, frequency of damage types, etc. Archival of damage data is critical to repair processes as this eliminates redundant repair developments or, colloquially, "re-inventing the wheel". In short, this technology development enhances the capability of the engineering workforce to appropriately, accurately, and quickly evaluate damaged conditions in order to develop a comprehensive understanding of damaged components and, therefore, the most appropriate repair configuration.

1. INTRODUCTION

In aging aircraft platforms, substantial efforts are often undertaken in order to ensure structural integrity of the aircraft in operation. These efforts commonly increase the need for engineering analysis, complex repair procedures, and reliable damage tracking to track damage initiation, propagation, and potential failure. This increased reliance on engineering involvement coupled with a high volume of damage findings can cause high turn-around-time of engineering analyses and dispositions. The following is a case study for the F/A-18 and E/A-18G Hornet, Super Hornet, and Growler platform and how modern technologies were implemented to increase engineering efficiency in an effort to maintain structural integrity of the aging fleet while minimizing excessive engineering workload and improving overall efficiency of the engineering organization. Specifically, this case study will cover how the implementation of modern technologies has been applied to maintenance of the composite airframe components; however, the technologies discussed here can and have been applied to metallic airframe components.

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Topics to be covered will include a brief history on the standard engineering practices prior to implementation of the technology, the functional requirements of the technology to be implemented, a discussion on the development of the relevant technology, and the eventual impact of implementation.

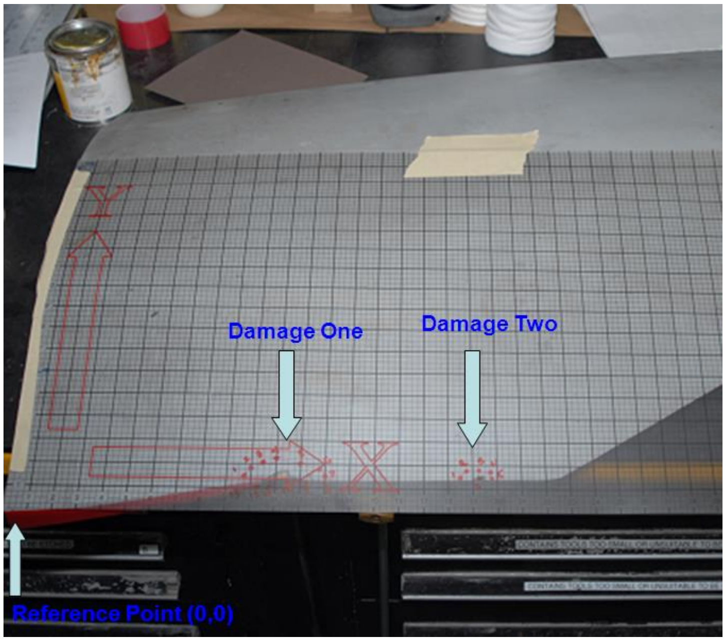
1.1 Engineering Evaluation Requirements

In order to convey the needs of the engineering workforce, a rudimentary understanding of engineering evaluation of damaged components as they pertain to composite structures is necessary. Firstly, composite components often have complex ply definitions including stack-up areas, multiple ply configurations over various aircraft configurations, and multiple composite material types. In order to properly evaluate damaged components, it is necessary for the engineer to know exactly where a damage is located with respect to these ply definitions. Additionally, the engineer must transcribe these damage locations to several other informational databases including, but not limited to, FEMs, Standard Repair Locations, and Repair-Weight-Restricted Zones for Flutter Analysis. In order for engineering to accurately evaluate damage conditions it is incumbent upon the engineer to locate the damages on all relevant reference information discussed herein as these references pertain to the damage to be evaluated and analyzed. This gathering of reference information is often a tedious and time-consuming effort requiring anywhere from minutes to several days depending on the complexity of the damages being reported and the component that has been damaged.

1.2 Historic Practices in Damage Reporting and Engineering Evaluation

The typical process by which damages are found and reported to engineering is a multi-step process involving aircraft technicians, NDI technicians, process evaluators, and engineers. Damages are most commonly found by aircraft technicians during routine inspections. These damages are then inspected, identified, and the technicians generate documentation of the damage size, type and location to be delivered to engineering. However, the nature of many composite components is such that there is little visually definable locational information such as local fastener and substructure locations making it difficult for technicians and artisans to adequately report damage locations on aircraft components. Historic practices have required technicians to generate hand-drafted diagrams, such as the example shown in Figure 1, and mylars of the component including dimensions from edges of the component perpendicular to the edge being referenced. However, for components with complex contoured edges, this form of dimensional locating of damages can be subjective and subsequently inaccurate and so it is necessary to obtain a more efficient and accurate way of locating damages on complex components.

Once engineering is provided with the documentation from the technicians and process evaluators, an engineer is then required to gather all relevant information discussed in Section 1.1. Additionally, and perhaps more importantly, the engineer needs to find out if a similar damage has occurred historically and has already been analyzed and repaired, thus eliminating the need for redundant engineering workload in performing an identical analysis for a damaged component. Historically, these analysis archives had been kept in either a folder-based archive



DAMAGE MAPPING FORM

Prepared By: John Doe
Date: 18-Sep-09
Component: MLG Door
Buno: 999999 Component Flight Hours: #####
P/N: 74A426010-XXXX S/N: 0

- Type of Damage: Puncture and Delamination
- Damage Moldline: x Upper Moldline
  x Lower Moldline
- Description of Reference Point:
  Forward Outboard Corner.
- Measured Distance From Reference Point to (0,0) Coordinate Point on Mylar is: 0 Inches
- Descriptions of +X and +Y Directions:
  +X Running Forward To Aft Along Outboard Edge.
  +Y Running Outboard to Inboard Along Leading Edge.

List of Coordinate Points (X,Y) of the Damage

NO.	X	Y	NO.	X	Y	NO.	X	Y
1	9 3/4	1 1/2	11	10 3/4	1	21		
2	10	1 3/4	12	10 1/4	1	22		
3	10 1/2	2	13	9 3/4	1	23		
4	11	2 1/4	14	9 3/4	1 1/2	24		
5	12	2	15			25		
6	12 3/4	1 3/4	16			26		
7	13	1 1/2	17			27		
8	13	1 1/4	18			28		
9	12 1/4	1 1/4	19			29		
10	11 1/2	1 1/4	20			30		

Figure 1. Historic Damage Reporting Example –
Gridded Mylar (left) and Dimensional Report (right)

of pdf documentation or, at best, a Microsoft Access database of damage and analysis information. The nature of these two forms of archiving is that they provide the engineer with little concrete information on the damage location given that dimensional references are required to be used and most database entries do not provide dimensional referencing to the damage location. In order to find a relevant historic analysis, engineers were required to manually open dozens of electronic documents or to rely on the memories and knowledge of other local engineers to determine if a component had been previously analyzed at the required location. This further highlights the lack of efficiency and menial workload required on the part of the engineer to fully evaluate a damaged component.

2. TECHNOLOGICAL DEVELOPMENTS

In an effort to streamline the engineering process while simultaneously improving the quality and accuracy of the engineering work as it pertained to structural integrity of the aircraft, Naval Air Systems Command (NAVAIR) initiated a Small Business Innovative Research (SBIR) program to address this issue. Subsequently a multi-year project was assigned involving collaborative research and development with Etegent Technologies in 2009. This project was aimed at revolutionizing the damage evaluation process from initial damage reporting through final engineering analysis and repair disposition.

The first step in improving damage reporting and engineering evaluation processes was to define the necessary top-level functional requirements. Firstly, the software package would need to be able to locate damages on a 3D Engineering model from a digital picture taken of a physical component. The next requirement was defined as the ability to maintain and display "layered reference data". This reference data would include any and all dimensionally defined data that must be evaluated by the engineer during damage evaluation such as FEM, composite ply boundaries, standard repair zones, repair-weight-limited zones, etc. The third requirement was that the software must be able to search through and display historic damage data in an intuitive and dynamically definable way.

2.1 Projecting Damages to 3D Engineering Models

During the first stage of development, Etegent Technologies developed a software algorithm that utilizes a user-interface (UI) driven tool to allow the user to create correlations between definable points in the 3D model, such as fastener locations, corners, and substructure locations, and the same points in the picture. An example of this user-defined point correlation interface can be seen in Figure 2. Once these points are correlated, the algorithm then computes the relative position of the camera with respect to the model at the time the picture was taken. This requires some rudimentary information regarding the camera model used and a minimum of four point correlations between the model and the picture. The model points are projected to a 2D view plane perpendicular to the camera vector and compared with the corresponding points in the 2D picture. The algorithm then manipulates the camera vector and the camera aperture distance, or model zoom, in order to yield a best fit between the model and the picture before overlaying the model and the image.

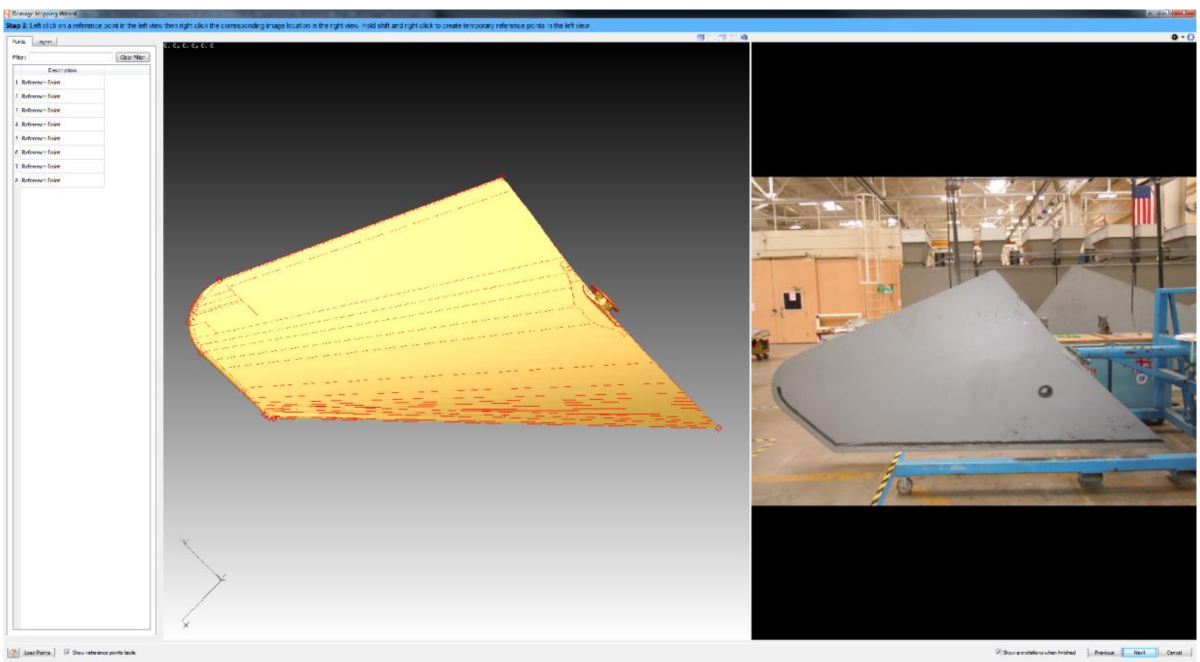


Figure 2. User-Interface for Image-to-Model Point Correlation

Once the camera position is determined, the model can be overlaid on top of the picture and the damage locations can be extracted from the image and projected along the camera vector to the surface of the model as shown in Figure 3. This development was seen to adequately remove the requirement for tedious and comparatively inaccurate hand-drawn diagrams of damage locations. However, this development has several limitations; the primary limitation is that it requires a good quality, un-edited picture of the damaged component with sufficient locational information visible in the picture. This UI-based alignment tool also requires the user to evaluate the alignment for accuracy before extracting damage locations in order to verify the quality of the damage projection functionality. Despite these restrictions, however, the ability to project multiple damages from a single picture to a 3D model laid the foundation for the remainder of the functional requirements and the issue then became how to efficiently utilize the data.

The accuracy of the image alignment and subsequent damage projection can vary substantially based on several factors including the quality of the original picture, the size of the component in the picture, the visibility of damage in the picture, and the accuracy of the user-defined point correlations between the model and the picture. For example, clear pictures of a small component with clearly visible damages will yield a much more accurate projection than a lower resolution picture taken of a large component. However, the algorithmic alignment of the model to the picture is viewable by the user and any gross discrepancies in alignment can be seen, evaluated, and corrected by the user before extracting damage locations in order to ensure accuracy. Early tests of repeatability accuracy in damage projection yielded accuracies ranging from ±0.030” for small components with simple geometry to ±0.250” for larger components with more complex geometry.

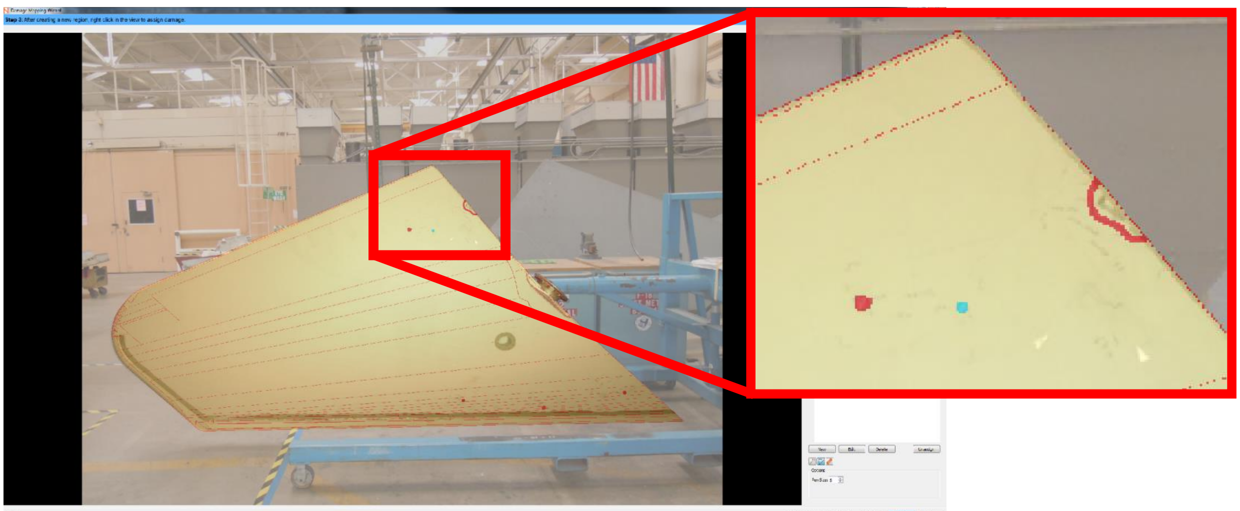


Figure 3. Model-To-Image Alignment and Damage Projection

2.2 Enabling Layered Reference Data

Once the ability to project digital images of damages to a 3D model had been developed, it was still necessary to develop the ability to handle several forms of reference data and to do so in an easy to use and intuitive way. The first thing that was determined was that all of the reference data must be converted into a model-based format in order to display it within the software. While much of the relevant information on the F/A-18 platform was being stored in paper or scanned-document format, the information that was dimensionally defined was quickly converted to a model format for use in the software. The FEM information, by contrast, existed digitally as a third-party structural analysis model that was not easily translated to a readable format for use in the software. To resolve this issue, NAVAIR and Etegent Technologies cooperatively developed a code to import the raw structural analysis model into the software.

After all of the relevant reference information for each component was defined and translated to a readable format, these references were loaded into the same 3D space as the corresponding component model. Once all of the reference data existed in the same 3D space, a display layer system was implemented with individual visibility settings for each reference layer. This system allowed the user to manually turn the visibility of reference data on and off and to also modify such settings as transparency, coloring, and shading. While simple, this system gave the user the ability to quickly display the projected damages on all manner of reference information needed for damage evaluation of composite components. For example, after using the image alignment in Section 2.1 to project damages onto the 3D component model, the user is then able to display then interrogate the damage locations with respect to the FEM, ply boundaries and standard repair areas simply by toggling these reference layers on or off. This system reduced hours of remedial dimensional locating of damages to reference data down to minutes and thereby satisfied the requirement for providing layered reference data pertaining to damage locations. The damage projections illustrated in Figure 3 can be seen overlaid on examples of layered reference information in Figure 4.

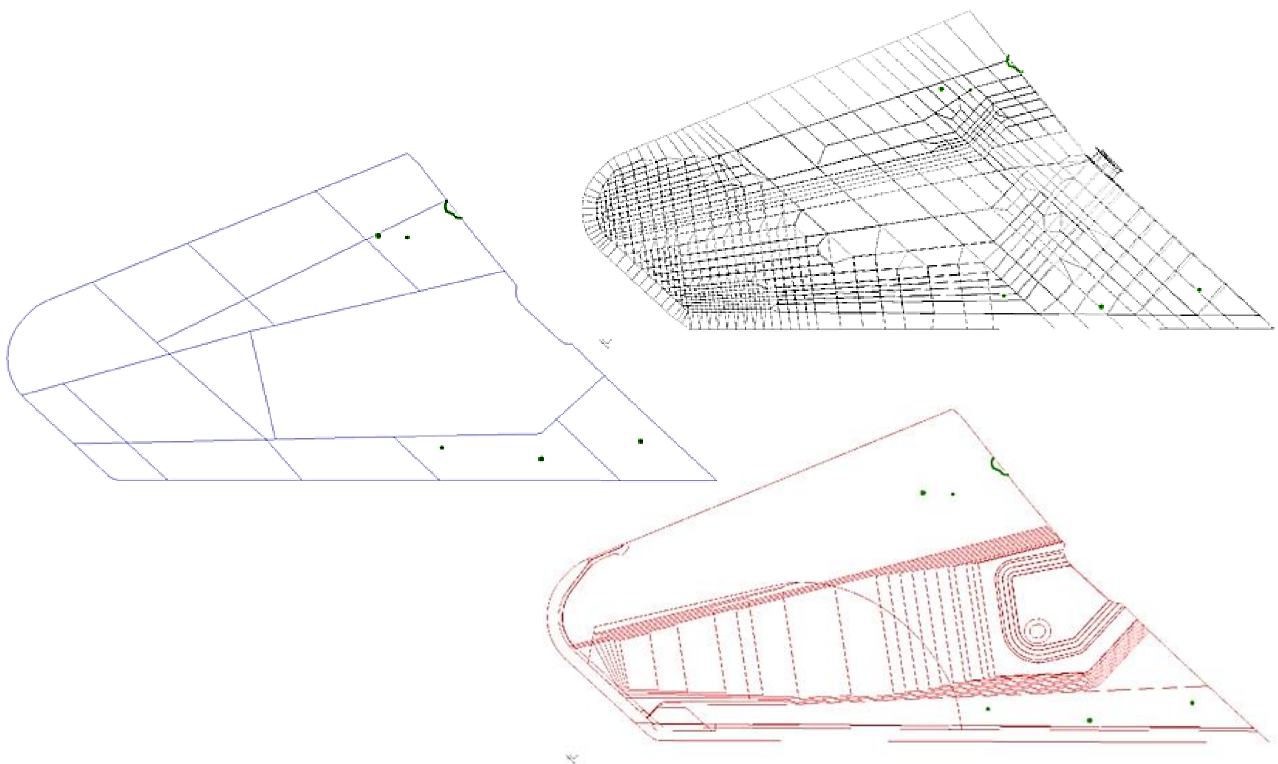


Figure 4: Damages Projected to Layered Reference Data:
FEM (top right), Weight-Limited Zones (left), and Composite Ply Configurations (bottom right)

2.3 Archiving Historic Data

While streamlining Engineering evaluation of damages was the primary purpose of these technological developments, a full engineering analysis is often unnecessary. Many damages to aircraft components, particularly on more matured programs, have already been subject to the necessary analyses during the evaluation of historic damages of similar sizes, types, and locations. In many of these cases, damages can be considered acceptable by previous analysis and subject to the same repair performed historically. For this reason it is necessary to have a robust system of repair and analysis archival that can be efficiently searched for historic analyses that may be relevant to current damages.

The enhanced archive query capability actually involved two separate additions to the software. The first was the ability for the user to populate "reference data" pertaining to the damages at the time of mapping that could be stored along with the 3D damage projections within the archived system. This reference data is different than the reference data used in the damage mapping evaluation as it contains information regarding the damage itself rather than its position on the model. For example, each damage or group of damages could be assigned a governing document number, damage number, damage type, damage size, component serial number, aircraft tail number, etc. The second addition is a robust query tool that allows the user to search the archived damage database both by location on the component as well as by any value or values within the populated reference data. This versatile query tool allows the engineer to easily search for any damage that is within a user-defined distance of the current damage mapping, search for all previous damages on the particular component serial number, search for previous damages of the same type and size, or any other combination of factors that may be relevant. An example of a full archive display of damage locations can be seen in Figure 5.

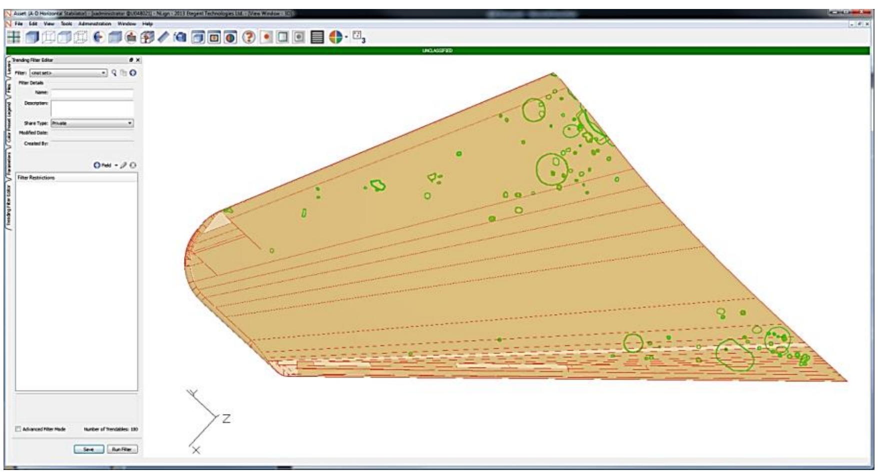


Figure 5. Historic Damage Archive in Model-Based Format

3. RESULTS

3.1 Impact on the Aircraft Maintenance Platform

The technical advances employed in this study primarily impact the accuracy and efficiency of engineering analyses. As a result, these improvements represent a qualitative impact more than a quantitative one. While some aspects can be quantified such as reduced turn-around-time of engineering analyses reduced analysis time, and reduced Aircraft-on-Ground (AOG) time, these are the less direct benefits of the utilization of the technology.

The most prominent impact of the technology is increased accuracy of damage locational mapping. For some components, the variations in locational accuracy inherent in hand-drawn diagram reporting methods are less consequential. However, for more critical or highly loaded components, a locational difference of just half an inch can be the deciding factor between whether an analysis yields positive or negative margins of safety resulting in return to flight or scrapping of a component. The past reporting methods had substantial variation in locational accuracy and, when compared with the use of the newer digital alignment, ranged anywhere from exactly accurate to inaccuracies as high as 3.0” depending on the size and shape of the component and the skill of the artisan or engineer generating the diagram. It should be noted that even with a perfectly drawn diagram, there are areas for human error in such interpretation. For example, someone interpreting a drawing could misread a “2” as a “3” or make typographical errors when entering the locational data into the computer. Certainly there are still areas for human error to be introduced into the digital alignment software but the use of the raw digital picture of the component and the ability to visually see the accuracy of the alignment make the technology less prone to human error and subjective interpretation.

The efficiency improvements of engineering analysis processes are most commonly used to justify the business case of technological development and, while these arguments have merit, they are not the focus of this study. Rather, it is important to show the qualitative impact of having a robust archival system on the structural integrity of the aircraft platform. The primary means by which archival can affect structural integrity is by helping engineers to locate, identify, and address damage “hotspots” on the airframe. The way in which this is done is by evaluating the full archive of damages displayed by location which can be displayed directly on the model of the aircraft platform. Once areas with high volumes of damages are seen in the archival display, an engineering investigation can then be conducted to determine the root cause of the prevalence of damages in the area. Then, after the root cause is found, processes can be put in place to minimize the damage occurrence or standard repairs can be developed in order to address the damaged area and eliminate the need for further engineering analyses in the subject area. By this means, archival can be very useful in identifying critical areas or potential failure locations on the aircraft platform as a whole and thereby increasing the overall capability of engineers to adequately maintain the structural integrity of the aircraft.

3.2 Overcoming Technical Barriers

One of the main hindrances to the implementation of this software for the F/A-18 A-D Legacy platform was the lack of any 3D Engineering Model Data. The original intention at the start of the project was to make use of the existing reverse engineering technology to create laser-scanned models of existing components that could then be used in conjunction with the software. By use of this technology, laser scanned models were created for the most commonly damaged and analyzed components. These models were vast improvements over no model at all but still left much to be desired. It should also be noted that depending on component size, the time required to scan and post-process a component was anywhere between 2 and 8 hours for small and large components respectively using a common industry laser scanning arm.

While these models provided a decent representation of the components that could be used for damage mapping, they were very coarse and often had several areas of missing data. It was then decided that, with a relatively small amount of added effort, the models could be cleaned up using existing CAD software in order to be more useful in conjunction with this damage mapping software.

The lack of 3D model data is a common concern among older platforms as a result of which it is necessary to clarify a few points to address these concerns. The first misconception regarding the necessity of generating 3D model data for use in damage mapping is that the models must be of blueprint quality; this is not the case. All that is required for the model to work is a representative model that closely enough resembles the component geometry to be recognizable and usable for the purposes of determining damage location. It should be made clear however, that the more effort, accuracy, and detail the CAD designer puts into the model, the more beneficial it will be to the user and that any gross tolerance discrepancies in the model will be translated into tolerance discrepancies in damage mapping.

The other item that should be addressed is the use of Loft Data in the creation of the models as a method of reducing the time required to generate representative models. The F/A-18 platform, while not designed in 3D format, had some access to 3D versions of the theoretical loft surfaces that control the outer mold line of the vehicle. These loft surfaces were used in conjunction with the reverse engineering scan data to rapidly generate representative models that were exceedingly sufficient for use with the software package.

3.3 Impacts on Maintenance Costs

While cost savings was a driver in the initiation of this technological development, it was not the primary subject of this case study. Despite this, it is prudent to convey that the vast majority of the cost savings of the implementation of this technology, at least as viewed by the individuals involved in this case study for the F/A-18 platform, were indirect savings. These difficult to quantify savings included such things as less Aircraft-On-Ground time due to long engineering TAT, reduced repetitious work load, the increased availability of engineering man hours associated with a more efficient work flow, and better overall structural integrity of the aircraft as a result of increased visibility of exceptionally damage-prone components. While some direct cost savings were evident, such as reduced engineering man hours required to evaluate damages, these direct savings are suspected to be insignificant when compared to the potential indirect benefits.

4. CONCLUSIONS

In order to revolutionize an antiquated system of damage reporting and engineering analysis, NAVAIR initiated an SBIR contract with Etegent Technologies. This research program involved the development and subsequent implementation of a software package that was capable of digitally mapping damaged components to a 3D model by use of a digital photograph of the respective damaged component. The software was further developed to incorporate required engineering reference data including such things as FEMs, composite ply boundaries, standard repair zones, and weight limited zones. This reference data assisted engineers in more quickly and accurately addressing damages and gathering required analytical information. Additionally, an archive database was added to the software to provide engineers with an intuitive means by which to search for historical repairs that might be relevant to current damages.

This software package has been deployed to the engineering work force at Naval Air Station North Island (NASNI) working on the F/A-18 and E/A-18G Hornet, Super Hornet, and Growler platform and is scheduled to be deployed across all depot repair facilities nationwide. With an aging fleet of aircraft undergoing structural life extension efforts, the need for engineering support and analysis is increasing and it has become necessary to seek avenues for improving engineering efficiency while maintaining an exceptional quality of work.

After encountering several barriers to development and implementation of the software, the barriers were addressed and development continued. Engineers are consistently finding new uses for the technology beyond those discussed here and further feature developments may be implemented in the future. This case study has been an illustration of NAVAIR's approach in identifying technological shortcomings and addressing them accordingly. Additionally, it has served as a successful example of cooperative technological development between NAVAIR and the contracted company, Etegent Technologies.

While this technology has been discussed primarily with respect to its uses on maintenance, analysis, and repair of composite airframe components, the same technology could be readily utilized in composites manufacturing and assembly. During post-manufacturing NDI of composite components, defects can be projected to the governing 3D model and archived with defect information, potential Material Review Board (MRB) tags, and repair information. These archives could then be used to locate common areas exhibiting manufacturing defects and addressed with process or tooling changes to reduce the occurrence of the manufacturing defects. The primary benefit of this technology is that it gives a the user, or company, the ability to archive damages in 3D space which can then be utilized to identify areas for improvement whether in maintenance and improving structural integrity, in manufacturing and improving material processing, or in any application for which 3D data visualization could be applied.