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A-10 IMPLEMENTING PROGNOSTICS WITH THE DIGITAL THREAD

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Abstract: Digital transformation is trending across the United States Air Force (USAF) to optimize modern and legacy aircraft lifecycle management. A desired output of the digital thread is to provide prognostic tools to forecast the future structural health of a defense system. Legacy aircraft, like the A-10, face additional challenges in implementing the digital thread compared to modern counterparts; however, legacy aircraft would benefit further and immediately from digital thread predictive capabilities.

This research will investigate the route the USAF's A-10 aircraft structural integrity program (ASIP) has taken to implement a complete digital thread solution for digital engineering, specifically regarding prognostic tools. It is necessary to have high quality and informative data models to make accurate predictions. This research found that specific data types needed were often fragmented and must be amalgamated before analysis could be performed. The acculturation of maintenance groups to the digital transformation and engineering rigor is another requirement identified for implementation of the digital thread and is often overlooked.

While these requirements presented many challenges, setbacks, and lessons learned, A-10 ASIP has built the foundation needed to begin implementing prognostic maintenance tools. Maintenance data is digitally captured with digital thread software that provides an interactive 3D environment to tie metadata to coordinates. In addition, A-10 has piloted the use of smart tools to take full credit of repair operation in damage tolerance predictions. Analyzed maintenance data is then integrated with additional PLM and SLM data to provide a holistic interpretation of the health of the active fleet.

A major takeaway from this study is that implementation of the digital thread for prognostics is not trivial; to ensure successful operations of these systems and that captured data is complete and verified required multiple additions of full-time personnel to A-10's technical division. However, for A-10, the ability to proactively maintain an aging fleet comes with many benefits, including a significant reduction in sustainment costs, better management of risk, and improved aircraft availability.

Keywords: Digital Thread, Digital Engineering, Digital Twin, Prognostics, and Sustainment

INTRODUCTION

In January of 1973, the United States Airforce (USAF) selected the A-10 aircraft conceived by Fairchild Republic to meet the nation's future close-air support (CAS) needs. While the infancy of the USAF Aircraft Structural Integrity Program (ASIP) was more than a decade before the introduction of the A-10, the A-10 was designed at a time when fatigue life requirements were beginning to be considered with the first publication of MIL-STD-1530 in 1972 [1]. Through research between Fairchild and the USAF, the A-10 was given an expected service life of 6,000 flight hours.

In 1997 A-10 aircraft across the fleet were approaching or surpassing the safe service life of 6,000 hours and a retirement plan was anticipated. However, without a replacement aircraft selected for production coinciding with shrinking budgets, the decision was made to sustain the A-10 beyond its original retirement age since it was speculated to be less costly than funding a replacement [2]. Sustainment efforts began with implementing a service life extension plan (SLEP). As inspections required by the SLEP discovered more and more critical cracks in the A-10 wings, maintenance costs significantly increased, raising budget concerns. Eventually, an enhanced wing replacement program was proposed and selected as a less costly alternative to keep the aircraft flying up to 16,000 hours. Ultimately, the wing replacement program was the catalyst to spark the beginnings of the A-10 digital transformation.

The anticipation of retirement for the A-10 in the early 1990s, compounded with Fairchild Republic's divestiture, resulted in a gap in documentation vital to ASIP. Additional discontinuity was caused by a decision made by the USAF to relocate the engineering authority of the A-10 from Sacramento Air Logistics Center to Ogden Air Logistics Center at Hill Air Force Base (HAFB). In 2002 a USAF investigation declared the A-10 ASIP was "broken." This potential disaster for the A-10 had a silver lining; the path towards recovery for A-10 ASIP resulted in a USAF organic engineering capability that is often only realized by the OEM [3] for a weapon system. The result was a solid engineering base that consisted of USAF and contractor engineering expertise with cost-effective conciseness that could effectively support A-10 ASIP and fulfill obligations required in MIL-STD-1530. This organic engineering ASIP team recognized the benefit of digital engineering solutions and pushed the need for a digital transition. Today, the A-10 is often viewed as leading the USAF into the digital future to sustain legacy aircraft.

The enhanced wing assemblies (EWA) were manufactured using model-based definitions, digital configuration control, and a digitally managed engineering bill of materials (EBOM). In 2007 the USAF awarded Boeing the contract to manufacture the new wings. While developing models of the EWA, Boeing chose to utilize Teamcenter, a Siemens PLM software, for model configuration management, which led the A-10 System Program Office (SPO) to entrust Teamcenter with model configurations. In using Teamcenter, it was possible to have a seamless transfer of models from Boeing to the A-10 SPO. The A-10 SPO, at that point, had decided that Teamcenter would be used for more than managing the new wing’s digital product data, it would also create the primary PLM software for the entire SPO with the goal of having a single digital repository to become the "source of truth." However, it is understood that systems other than Teamcenter are now vital to lifecycle management and will ultimately author organic data into an external database. An example of an external database and the focus of this work is ASIP’s force management database (FMD) configured and housed using NLign Analytics software platform as a digital thread solution.

While the digital thread is being deployed across the entire A-10 organization, forming a complex of intertangled networks, this investigation will focus on the digital engineering solutions deployed to fit the needs of the renewed A-10 ASIP of the structures department, a subset of the SPO's engineering branch. Figure 1 shows where the A-10 structures group resides in the organizational hierarchy of the A-10. Also shown in Figure 1 are the different originations involved in managing the A-10 fleet. There are three central departments: Depot, performing major repairs, intensive inspections, and overhauls; SPO, providing engineering support and managing upgrades; and the field, carrying-out aircraft missions and light maintenance. It is important to note that although the focus is on the digital thread implemented by A-10 ASIP, the field, and depot play a vital role in providing inputs into the digital thread.

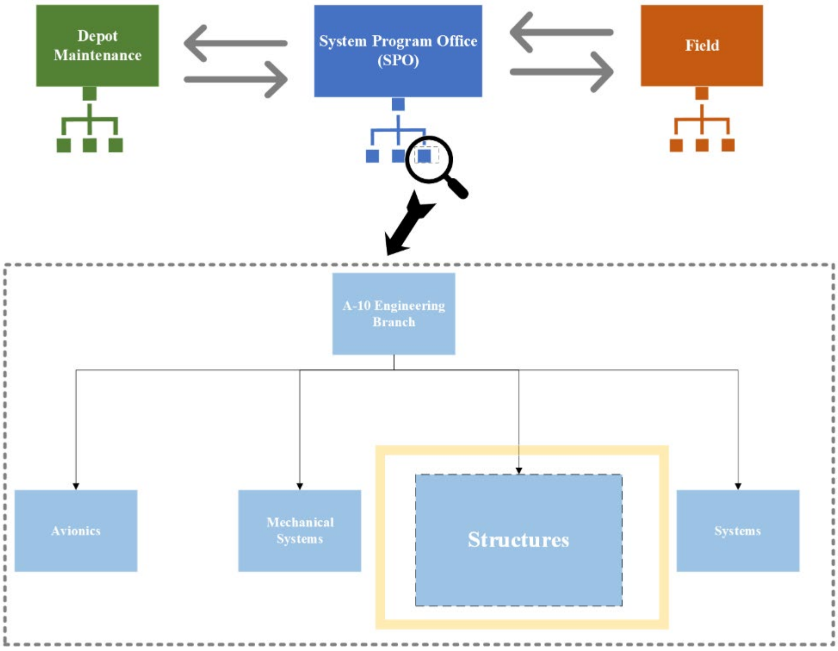


Figure 1: Simplified representation of sustainment organizations, drilling down to the structures group.

The digital thread implemented by ASIP is intended to act as more of a cycle than a process. This cycle is defined by Task V within MIL-STD-1530D [4], and starts with a requirement for ASIP to manage a FMD. The intent of the FMD is to allow for data driven updates for ASIP tasks also defined in the standard, like damage tolerance analyses (DTA) programs, technical orders, and non-destructive inspections (NDI). Continuing the cycle, these updates are carried into the force structural maintenance plan (FSMP), the cornerstone of ASIP. In turn, the FSMP dictates daily maintenance operations where maintenance related data originates, completing the cycle as data is fed into the FMD. In implementing the digital thread ASIP has relied on software developed by NLign Analytics. The NLign software suite is currently used by all three significant departments mentioned above and has become a vital aspect of the digital thread for maintenance operations related to ASIP.

A significant benefit to the digital thread is prognostic tools that allow engineering to proactively flag risk and prioritize inductions and maintenance tasks resulting in reduced sustainment costs and increased aircraft availability. The benefits of a digital thread are significant and numerous, however, implementing a digital thread is an enormous undertaking. While implementing its digital thread, A-10 ASIP experience substantial setbacks, unforeseen cost expenditures, and came away with many lessons learned.

ASIP DATA BEFORE THE DIGITAL TRANSFORMATION

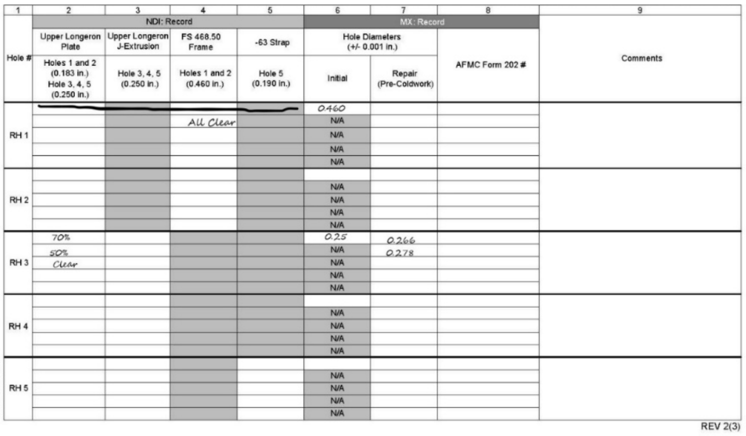
With the A-10 service starting in 1976, it is no surprise that the original manufacturing design and manufacturing data originated in paper-based form. Maintenance-related data was also largely paper-based and remained paper-based until efforts were made toward a digital solution in 2018.

Capturing Fatigue Damage for ASIP

One of the primary data types to be captured in the FMD is fatigue-related. To record fatigue-related data during inspections and maintenance, the renewed organic A-10 ASIP collaborated with depot maintenance groups. The inspections considered pertinent to the A-10 ASIP are named scheduled structural inspection (SSI). Aircraft would be scheduled to be serviced at the depot for these inspections approximately every 2,000 hours of flight operations. There are 149 SSI locations, with the majority of inspections on the wing. Each SSI is unique and often consists of multiple holes to be inspected. The primary NDI technique for these inspections is eddy-current using a bolt-hole attachment or a pencil probe.

Initially, paper-based logbooks were utilized to record structurally relevant data as these inspections were performed. An example of the logbooks used is shown in Figure 1. The format and data types collected in these logbooks were structured on the methods and process in which NDI technicians and maintainers carried out operations. An idealized process consists of the steps below:

1. The aircraft mechanic prepares the aircraft or component for inspection by removing panels and fasteners to allow access.
2. NDI is notified and an inspection is conducted.
3. NDI documents findings in the logbook by recording which holes/areas had crack indications.
4. Aircraft mechanics are notified and perform corrective maintenance, typically oversizing the hole by a nominal size dictated by technical orders (TO) set forth by the USAF.
5. NDI reinspects repaired holes.
6. Steps 4 and 5 are repeated until NDI clears the hole of any crack indications, or the hole has been oversized to the maximum diameter allowed by the TO and required technical assistance.



1	2	3	4	5	6	7	8	9
Hole #	NDI: Record				MX: Record			Comments
	Upper Longeron Plate	Upper Longeron J-Extrusion	FS 468.50 Frame	-63 Strap	Hole Diameters (+/- 0.001 in.)		AFMC Form 202 #	
	Holes 1 and 2 (0.183 in.) Hole 3, 4, 5 (0.250 in.)	Hole 3, 4, 5 (0.250 in.)	Holes 1 and 2 (0.460 in.)	Hole 5 (0.190 in.)	Initial	Repair (Pre-Coldwork)		
RH 1					0.460			
			All Clear		N/A			
					N/A			
					N/A			
					N/A			
RH 2								
					N/A			
					N/A			
					N/A			
					N/A			
RH 3	70%				0.25	0.266		
	50%				N/A	0.278		
	Clear				N/A			
					N/A			
					N/A			
RH 4								
					N/A			
					N/A			
					N/A			
					N/A			
RH 5								
					N/A			
					N/A			
					N/A			
					N/A			

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Figure 2:Example of fuselage inspection #2 with fabricated data

The data requested by the A-10 ASIP was minimal. NDI technicians were requested to record the screen height for each hole/area that a crack indication was detected. Additionally, NDI technicians would record the layer in which the indication was detected. The mechanic would record initial diameters and incremental oversized diameters. Once an inspection was complete, a stamp or signature was recorded on the front of the SSI name. The goal of collecting this type of data is to indicate where fatigue damage was occurring and to provide an estimate of the crack lengths from the difference in initial and final diameters of the oversized hole. Even though the data requested was minimal, the form seen in Figure 2 is complicated, making it challenging to request any additional data types be recorded.

Issues began to surface as the data began to be delivered to ASIP. Many problems were due to the nature of collecting data with paper logbooks, like an engineering technician was required to input data into a database manually. Inevitably, many handwritten entries were illegible. However, the most significant issue affecting data quality originated from the ample time between data being recorded and delivered. Typically, logbooks would be delivered to A-10 ASIP seven to nine months after an aircraft had been inducted and data was first recorded. This extensive period meant that it was not possible for engineering to address any issue found in the data at the same time the asset was open and accessible; often, the asset had already departed the depot. Perhaps even more detrimental, this enormous time gap led to a sense amongst maintenance groups that the data served no purpose and was unimportant, even to ASIP. This large amount of time also meant that it was not possible for engineering to provide any feedback, support, or request corrections while data was being recorded.

History of Serialized Tracking

The A-10 was designed to be modular, making the aircraft more damage-tolerant as components can be swapped when damage occurs. The aircraft comprises nine structurally significant components, also called the "major nine," as shown in Figure 3. Because of this interchangeability, each one of these nine major components had to be individually tracked for structural monitoring.

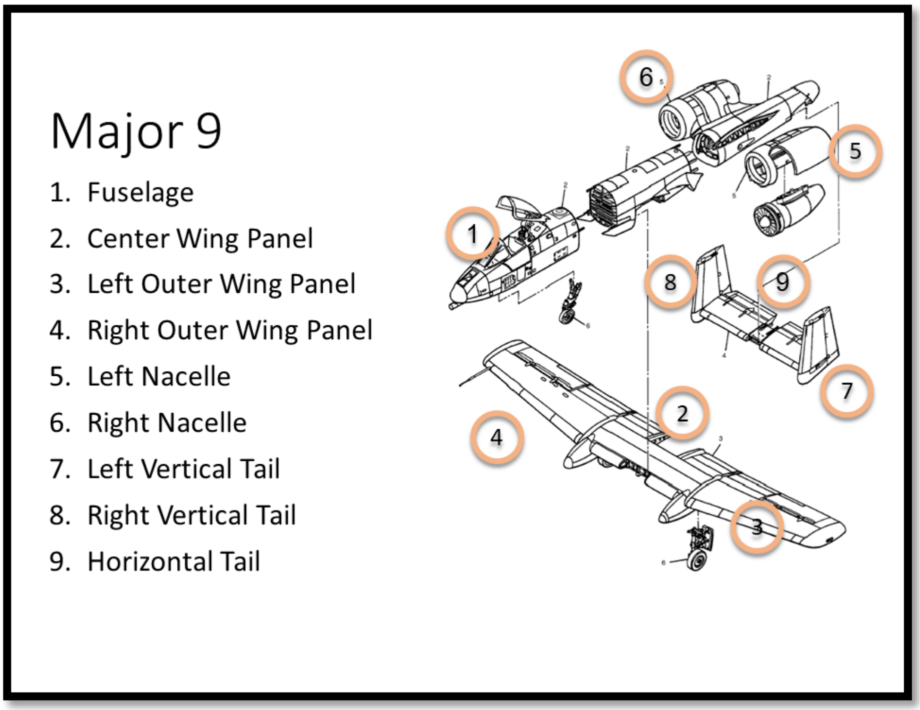


Figure 3: Diagram indicating the major nine serialized structural components.

Fairchild Republic documented the original configuration of the different components for each aircraft manufactured. However, the serialized configuration changes as components were swapped or replaced with new components over many years of operation. Documentation of these serialized configurations was historically inconsistent. Documenting serial numbers, aircraft configurations, and component replacement/swapping was recorded on paper forms, custom databases, shared drives, and communication documents (email, letters, and presentations). Because of the inconsistency, it often required a significant amount of probing for ASIP engineers when serialized information was needed. Additionally, the inconsistency and gaps in ASIP due to service life extension resulted in holes in many serialized tracking records.

STEPS TAKEN TO IMPLEMENT A DIGITAL THREAD

Enhanced Wing Assembly Pushing the Digital Transformation

The actual digital transition began for the A-10 ASIP when engineers began the groundwork to design a new enhanced wing assembly (EWA) for the aircraft in 2004. R. Heller et al. [5] provide a comprehensive set of all the requirements of the EWA. The digital transition began to meet the needs of multiple parties as simultaneous production of various parts and hardware for the EWA began. The digital thread would allow for these parties to access and manage product definitions, EBOM, and configuration control all at the same time.

An effort was initiated by the SPO to fully define the legacy thick skin wing with computer-aided designed (CAD) 3D models using the original 2D hand drawings created by Fairchild Republic. These 3D models of the legacy wing would then be given to the contracting manufacturer to incorporate design changes with the idea that model-based definitions of the EWA and all associated parts would facilitate accelerated wing production. 3D solid models of the legacy wing were developed one section at a time.

As planned, Boeing utilized the 3D models of the thick legacy wing as a base and ultimately developed a new set of 3D models that comprise the design of the EWA. As part of the contract, the models developed by Boeing were included as a deliverable with the new wings, giving ownership of the "tech stack" [6] to the A-10 SPO.

The benefits of having complete model definitions for the wings were apparent and made a big difference for the A-10 ASIP, driving the need to develop models for the entire A-10. This led the A-10 SPO to work with Northrup-Grumman to develop these models for the entire aircraft. Northrup-Grumman eventually delivered 25,000 modeled A-10 parts. Like the legacy wing, these parts were developed using 2D hand drawings. As part of this effort and to make the 2D engineering drawings available to multiple parties, over 70,000 drawings were scanned and converted to PDFs.

Digital Environments for Product Life Management

As mentioned above Teamcenter was initially chosen as A-10’s primary PLM software, making Teamcenter the "Source of truth." However, there are many challenges when implementing PLM software intended to house all required data for the digital sustainment needs, especially for legacy aircraft. Most obstacles the A-10 Teamcenter PLM team faced and continue to see today are related to implementing customized data-structures to capture data in usable format. Adding to this challenge, the data structure is required to correctly capture inputs from legacy systems, outside contract support systems, and live internal data simultaneously. These custom data structures require a tremendous amount of resources and time and will require continues maintenance since it is impossible for Siemens to maintain data structures that are not out of the box solutions. Ultimately, this has led to a timeline far exceeding the initial expectations for fully implementing the PLM software. Despite these setbacks, the A-10 SPO continues gaining traction with Teamcenter and has become vital to sustainment operations for all of the A-10.

While Teamcenter is intended to be the single "source of truth," it was always known and anticipated that other PLM-related data systems would author data to be consumed by Teamcenter later. As mentioned before, the data architecture and the involved process of these digital environments are relatively complex and involve many organizations. For this paper, only the NLign Analytics Platform will be discussed further.

NLign Analytics Platform is a software suite developed to analyze aircraft manufacturing and maintenance data in a 3D environment. NLign originates with a small business innovative research (SIBR) funding project led by Air Force Research Laboratory in 2007 [7]. The original intent of NLign software was to house non-destructive inspection (NDI) data. Through additional USAF programs, specifically SIBRs and rapid innovation funding (RIF), NLign received sprints of software enhancements to grow the software's capabilities. Today, NLign's product suite consists of three different products, all aimed at capturing, analyzing, and communicating as-maintained aircraft data in real-time to allow for rapid response from decision-makers. While NLign can be utilized by many other programs, much of its development was catered to fit the needs of ASIP applications.

The A-10's first use of NLign began with an individual, Hazen Sedgwick, in 2014 [8]. Mr. Sedgwick used NLign to house structural and damage tolerance analysis data initially. Shortly after this, in 2015, an effort was made to comb through the many locations where serialized data was stored and then combined and imported into NLign to be used as a centralized serial tracking database. In 2018, the software was expanded to replace the previously discussed logbooks by capturing SSI data at the depot located in Hill AFB. The use of NLign's product suite has continued to expand with more than 20 data types collected and managed and is used at many maintenance touch points at the depot and field.

IMPLEMENTING A DATA MODEL FOR PROGNOSTICS

Before 2010, A-10 had implemented a fixed-interval-based depot induction method. Once a certain number of hours of flight was reached, A-10 aircraft would be inducted to have a complete SSI package performed on the aircraft and the nine primary components to meet the requirements of MIL-STD-1530. In 2010 the A-10 ASIP transitioned the induction methodology to be risk-based, resulting in an average increase in flight hours of ~35% between inductions for the fleet. The move to a risk-based induction method resulted in a depot workflow that was no longer overburdened and cost avoidance adding up to millions of dollars annually. The benefits of the transition have generated a strong motivation for the A-10 ASIP to further the holistic prognostic capabilities through a digital thread.

Risk Based Inductions and Holistic Prognostics

Risked-based induction for the A-10 consists of probability to failure (PRoF) calculations and holistic prognostic data models to prioritize depot induction predictively. PRoF calculations utilize deterministic and probabilistic data models to assign risk levels to individual aircraft. The PRoF data models incorporate the factors listed below.

- Individual aircraft tracking (IAT) and usage severities
- Fatigue characteristics of specific material
- Unique geometries that are considered the most critical
- DTA
- Fatigue test data
- Inspection history

Holistic prognostics augments the PRoF analysis by interpreting maintenance data and adjusting the depot cycle risk accordingly. For the research presented here, prognostic implementation and prognostic data model specifics will be the main focus of discussions. Prognostics for the A-10 are intended to proactively flag risk in real-time, whereas PRoF calculations are only performed twice yearly. ASIP engineers can utilize prognostic tools via NLign application and the digital thread to assess risk for the fleet or even for a specific structural component. In addition to prioritizing depot inductions, prognostic tools enable predictive maintenance and guide engineers when implementing ACI, time-compliant technical orders (TCTO), corrosion prevention actions, field maintenance actions, and many other engineering/maintenance activities.

Data Capture for Prognostics using the Digital Thread

The A-10 ditched the paper logbooks and began capturing maintenance data in 2018 using the NLign application. NLign allows maintenance data critical to ASIP to be accessed by engineers immediately through its connection to the digital thread. NThread, provided as part of NLign’s Analytics platform, includes the framework to easily implement NLign Analytics’ software into A-10s digital thread which is hosted by Hill Enterprise Data Center (HEDC) at Hill AFB.

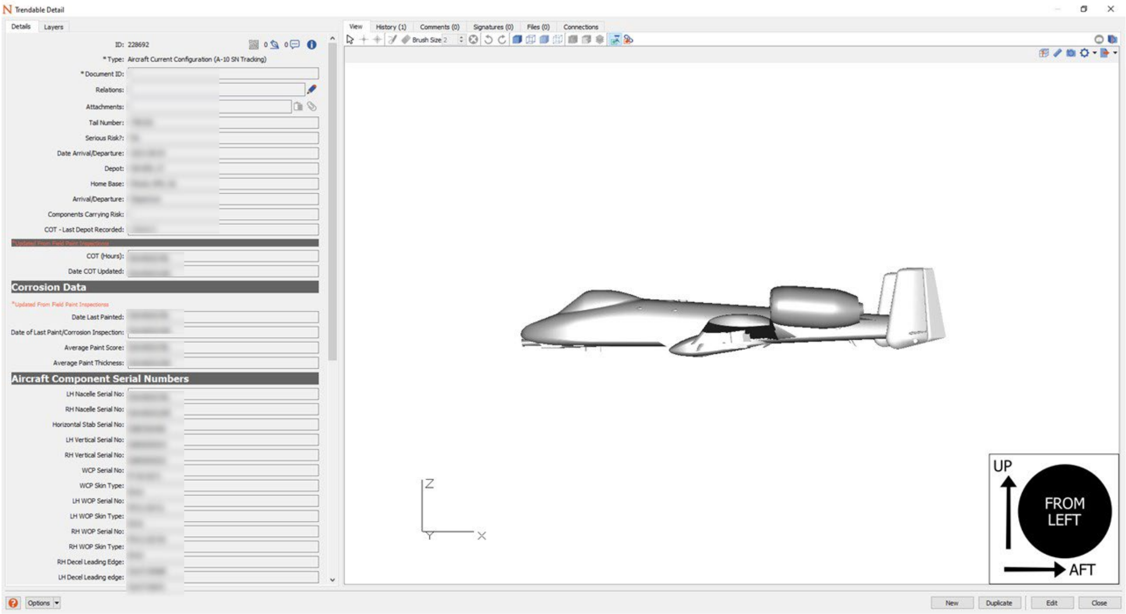
In 2020 NLign Analytics offered an additional product called NCheck. NCheck was designed to be a sister application to NLign as a more user-friendly data entry platform, leaving NLign to be the designated analyses software to be used by engineering. A-10 has fully transitioned to using NCheck for data entry and has seen improvements, specifically reduced training needs and increased participation by field maintainers. NCheck also offers a simplified data structure allowing for ASIP to actively provide partially filled records, referred to as “Jobs”, based upon anticipated induction and maintenance needs. Also, within this data structure a child of the NCheck Job can be predefined to request data from a specific inspection task and is appropriately named “Tasks”. In essence, in NCheck a Job is a specific inspection package, and a Task is specific inspection point in that package. Jobs and Tasks drastically simplifies data entry and is critical to the use of Smart Tools. While these improvements are critical, the transition to NCheck did require time and resources with thoughtful planning and significant data restructuring.

The metadata captured for SSI-related maintenance consisted of the metadata described above with the paper logbooks. However, the digital framework made it possible to request other important information, such as repair types and metadata associated with technical support requests. NLign also makes it easy to share pictures and videos in real-time, eliminating the timely and prohibited process of using individuals' smartphones and email. With a successful implementation of SSI data capture and vast improvement of data quality, discussed further below, it was decided to expand the digital thread and utilize NCheck to capture additional maintenance processes and touchpoints.

Today, A-10 ASIP uses NCheck to expand the FMD by capturing maintenance data from TCTO inspection, ACI, Hog Back fuselage structural repair, field phase inspection, field paint/corrosion inspections, blend measurements, and general maintenance discrepancies. With the expanded use of NLign and NCheck into additional touchpoints throughout the A-10, a growing need materialized for integrations or syncing capabilities with other digital thread platforms. Through enhancement requests from A-10 ASIP, NLign Analytics has developed several soft-integrations to provide data syncing and automated record creation. Currently, A-10 utilizes a soft-integration with three USAF systems: Teamcenter, Impresa, and PDMSS. The soft-integration between Teamcenter is currently only used to sync ETAR meta data and A-10 part specifications but is certainly the more critical of the three and has potential for significant positive impacts as it is fully utilized. The soft-integration with Impresa and PDMSS has allowed for ASIP to automate the creation of Jobs and Tasks in NCheck and partially populate fields saving time for maintenance and ensuring the correct inspection packages are assigned.

Additionally, NLign software platform has become the data repository for many engineering-related activities. Engineering repair dispositions and support analysis are the primary sources of engineering-related data that are continually growing. Test and teardown data, strain-gauge data from full-scale fatigue tests, EWA production non-conformance data, patch tracking data, and historical Engineering Technical Assistance Requests (ETAR) are additional data types that can be utilized in the software's analysis tools.

As mentioned earlier, ASIP engineers were forced to chase through multiple resources to find relevant serialized information, often finding gaps in the data. While Teamcenter's service life module (SLM) will soon be posed as the official repository for serialized information, NLign was chosen to house the information for ASIP needs until SLM is in production. In addition to the major 9, more than 30 serialized components (e.g., flight controls) are tracked with the digital thread and NLign. A dataset has also been established to filter through the serialized information and provide a snapshoot of the current configuration for each aircraft. This dataset is a pillar of the prognostic tools and will be discussed further below. A screenshot of the current configuration dataset can be seen in Figure 4.



ID: 228692

*Type: Aircraft Current Configuration (A-10 SN Tracking)

*Document ID:
Relations:
Attachments:
Tail Number: [redacted]
Serious Risk?: [redacted]
Date Arrival/Departure: [redacted]
Depot: [redacted]
Home Base: [redacted]
Arrival/Departure: [redacted]
Components Carrying Risk:
COT - Last Depot Recorded: [redacted]
COT (Hours): [redacted]
Date COT Updated: [redacted]

Corrosion Data

*Updated From Field Paint Inspections

Date Last Painted: [redacted]
Date of Last Paint/Corrosion Inspection: [redacted]
Average Paint Score: [redacted]
Average Paint Thickness: [redacted]

Aircraft Component Serial Numbers

LH Nacelle Serial No: [redacted]
RH Nacelle Serial No: [redacted]
Horizontal Stab Serial No: [redacted]
LH Vertical Serial No: [redacted]
RH Vertical Serial No: [redacted]
WCP Serial No: [redacted]
WCP Skin Type: [redacted]
LH WOP Serial No: [redacted]
LH WOP Skin Type: [redacted]
RH WOP Serial No: [redacted]
RH WOP Skin Type: [redacted]
RH Decel Leading Edge: [redacted]
LH Decel Leading edge: [redacted]

Figure 4: An example of active aircraft serialized configuration in NLign.

Prognostic Data Requirements

Developing models to accurately anticipate damage or maintenance needs requires high-quality data that is decisive. These two requirements seem simple, but they take more work and require significant human resources to amass the data and warrant its accuracy. The digital prognostic capabilities and models discussed here are contingent on a massive historical and up-to-date information library.

The data collected for A-10 ASIP is required to chronicle the structural health of the A-10 when combined with advanced engineering analyses. This requirement means the data must be specific and meaningful to provide a synopsis. For example, to use fatigue damage data in an analysis, five main attributes are required: damage type, location, orientation, layer/material, and inspection method. Collecting the correct data reasonably and with a reduced effort from the individual authoring the data requires significant data structuring and architecture. Currently, A-10 has two full-time data-analyst managing the data architecture for NLign. Some of the primary responsibilities of these data analysts are listed below.

- Develop and maintain data structures (data forms, fields, and lists)
- Configure and maintain system integrations.
- Maintain data security and data access.
- Implement computer object models to provide data links.
- Develop data models and integrate them into user dashboards.
- Develop report templates.
- Provide user training.

Additionally, A-10 has a full-time engineering technician to ensure that the data inputted into the FMD via the NLign Analytics platform meet data quality requirements. SSI, TCTO, and serialized tracking data are the only data types that currently undergo daily data evaluation. SSI data is often scrutinized hourly for fidelity. Categorizing the data quality for A-10 is reasonably straightforward; data coming is assigned one of three categories: usable, usable with assumptions (UWA), or unusable. However, the protocol for assigning these categories is more complex and often solely at the engineering technician's discretion. An attempt to summarize the process is given in the bullets below.

- Verify serial numbers and inspection packages are correct and anticipated.
- Ensure inspection locations are marked appropriately.
- Evaluate damage findings for completeness.
- Evaluate measurements to ensure they are reasonable.
- Verify that the entire inspection package per component is completed.

When discrepancies are found in the data, it is the engineering technician's responsibility to resolve them by communicating with NDI technicians, mechanics, supervisors, and engineers. In some cases, such as a serial number dispute, resolving the discrepancy can require extensive historical research and participation from multiple parties at the depot and field. Once the data is given a quality assessment, it will be assigned a status of ASIP reviewed to signify that a given inspection can be removed from the workflow and moved into the FMD.

Tracking and maintaining evidence that an inspection was completed with or without fatigue damage findings is as important as maintaining data quality. As a safety measure, A-10 requires that all mandatory inspections are digitally accounted for within NLign and have been ASIP confirmed before the responsible parties can absolve finical obligations and collect revenue forwarding. Production planners can determine the status or what inspections still need to be completed for a specific serial number through an NLign dashboard or utilizing a customized Excel report generated using NLign's report-generation wizard. The exported report allows for easy distribution to external parties that may not have the software. An example of the report is shown below in Figure 5.

	294	295	296	297	298	299	300
1	SELECT SERIAL NUMBER →	[redacted]					
2		SSI Name	Status		SSI Name	Status	
3		W1 LH	Inwork		W30 LH	Complete	
4		W1 RH	Inwork		W30 RH	Complete	
5		W2 LH	Inwork		W30R LH	Complete	
6		W2 RH	Complete		W30R RH	Complete	
7		W3 LH	Inwork		W31 A Zone1 LH	Complete	
8		W3 RH	Inwork		W31 A Zone2 LH		
9		W4 LH	Complete		W31 A Zone3 LH		
10		W4 RH	Inwork		W31 A Zone4 LH		
11		W5 LH			W31 A Zone1 RH	Inwork	
12		W5 RH			W31 A Zone2 RH		
13		W6 WS0			W31 A Zone3 RH		
14		W6 WS23 LH			W31 A Zone4 RH		
15		W6 WS23 RH			W31 B LH		
16		W6 WS66 LH			W31 B RH		
17		W6 WS66 RH			W32 Thin LH		
18		W7 LH	Complete		W32 Thick LH	Complete	
19		W7 RH	Complete		W32 Thin RH		
20		W8 LH	Complete		W32 Thick RH	Complete	
21		W8 RH	Complete		W34 LH	Inwork	
22		W9 LH	Complete		W34 RH		

Figure 5: SSI status report for A-10 center wing panels generated with NLign.

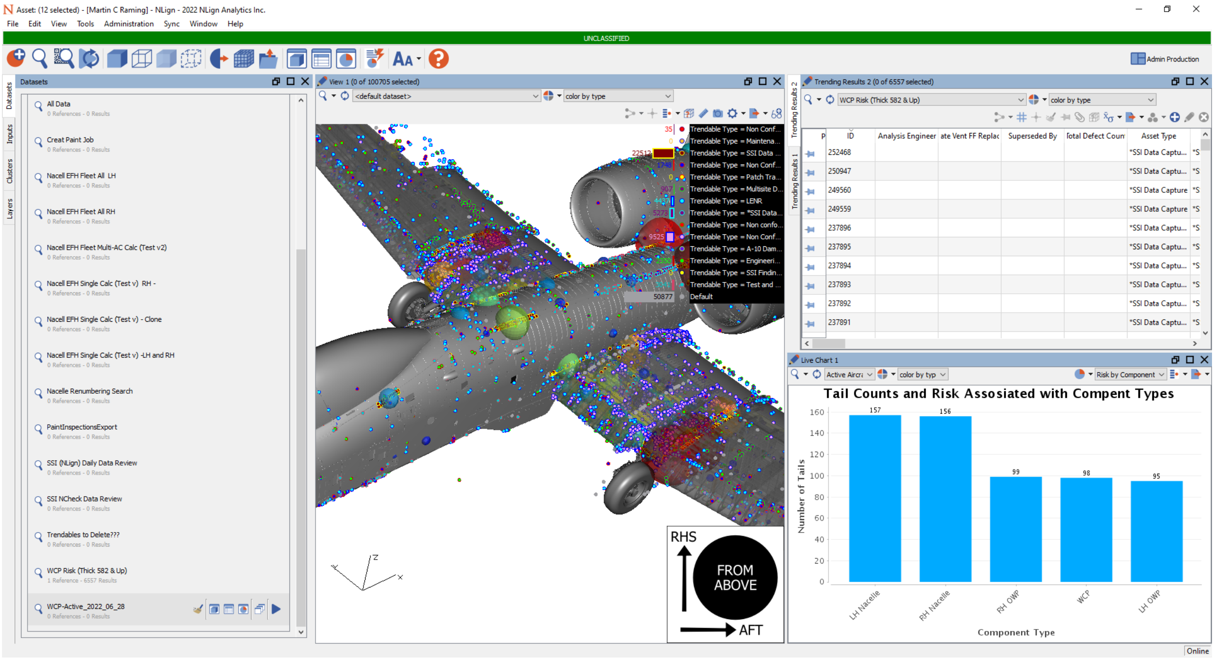
Field data in the digital thread currently does not receive a quality review by ASIP and is evaluated using conditional rules present in the software. Field records require a digital signature and to be marked complete by the data author. These actions cannot be completed unless the data meets the evaluation criteria set by the A-10 NLign data analysts. Ideally, this data would receive the same scrutiny, but there is a lack of funding to support this effort, and the incoming field data is deemed less critical to ASIP.

Prognostic Data Model

According to Caesar et al. [9], it is necessary to provide structure, context, and relationships to data since data alone is insufficient to convey technical statements to be utilized in engineering decisions, highlighting the importance of an accurate data model. The current data model implemented in NLign provides these needed attributes in various ways.

The data structure is enforced chiefly by tools internal to NLign and set up by data analysts. There are multiple layers to the data structure, typically organized by the nature of the recorded inspections. For example, SSI data records are configured to have the name of the inspection as a parent while the children would be any damage findings.

Context to the data can be provided in multiple ways. One powerful method is to utilize the 3D environment available in NLign. Data points are given coordinates that match aircraft coordinates and can be displayed on a 3D Model. The data can be color-coded based upon criteria of a field or clustered and given a diameter to represent nearby data points. An example of using the 3D model to identify hotspots on the A-10 wing can be seen in Figure 6 below. This prognostic tool was recently used by ASIP engineers to identify potential ACI locations to evaluate for implementation at the depot. Context can also be found with the metadata results displayed in a table view which can be manipulated to create figures and charts also shown in Figure 6. For the prognostic dashboard in NLign a combination of these utilized to provide context needed.



All Data
0 References - 0 Results

Creat Paint Job
0 References - 0 Results

Nacell EFH Fleet All LH
0 References - 0 Results

Nacell EFH Fleet All RH
0 References - 0 Results

Nacell EFH Fleet Multi-AC Calc (Test v2)
0 References - 0 Results

Nacell EFH Single Calc (Test v) RH -
0 References - 0 Results

Nacell EFH Single Calc (Test v) - Clone
0 References - 0 Results

Nacell EFH Single Calc (Test v) -LH and RH
0 References - 0 Results

Nacelle Renumbering Search
0 References - 0 Results

PaintInspectionsExport
0 References - 0 Results

SSI (NLign) Daily Data Review
0 References - 0 Results

SSI NCheck Data Review
0 References - 0 Results

Trendables to Delete???
0 References - 0 Results

WCP Risk (Thick 582 & Up)
1 Reference - 6557 Results

WCP-Active_2022_06_28
0 References - 0 Results

<default dataset>
color by type

35 Trendable Type = Non Conf...
0 Trendable Type = Maintena...
22512 Trendable Type = SSI Data ...
1748 Trendable Type = Non Conf...
0 Trendable Type = Patch Tra...
907 Trendable Type = Multisite D...
4437 Trendable Type = LENR
5273 Trendable Type = *SSI Data...
0 Trendable Type = Non confo...
9525 Trendable Type = Non Conf...
Trendable Type = A-10 Dam...
2350 Trendable Type = Engineeri...
0 Trendable Type = SSI Findin...
3041 Trendable Type = Test and ...
50877 Default

WCP Risk (Thick 582 & Up)
color by type

P	ID	Analysis Engineer	ate Vent FF Replac	Superseded By	Iotal Defect Coun	Asset Type	
	252468					*SSI Data Captu...	*S
	250947					*SSI Data Captu...	*S
	249560					*SSI Data Capture	*S
	249559					*SSI Data Capture	*S
	237896					*SSI Data Captu...	*S
	237895					*SSI Data Captu...	*S
	237894					*SSI Data Captu...	*S
	237893					*SSI Data Captu...	*S
	237892					*SSI Data Captu...	*S
	237891					*SSI Data Captu...	*S

Active Aircr
color by typ
Risk by Component

Figure 6: Context applied utilizing a 3D environment to project data onto a model to identify hotspots.

Configuring relationships between data records is one of the most important aspects of a prognostic data model. It is the relationships of serialized tracking, production discrepancies, NDI, repairs, corrosion assessments, and technical orders that can provide a holistic assessment of the health of an aircraft/fleet. Figure 7 shows the data flow enforcing these relationships via the prognostic data model. These relationships, of course, provide context as well. Data flows live from active maintenance activities and are tied to historical records through serialized tracking. It should be noted that flight hours are only actively tracked for aircraft, requiring COT for components to be calculated based on the history of the aircraft the component was flying on.

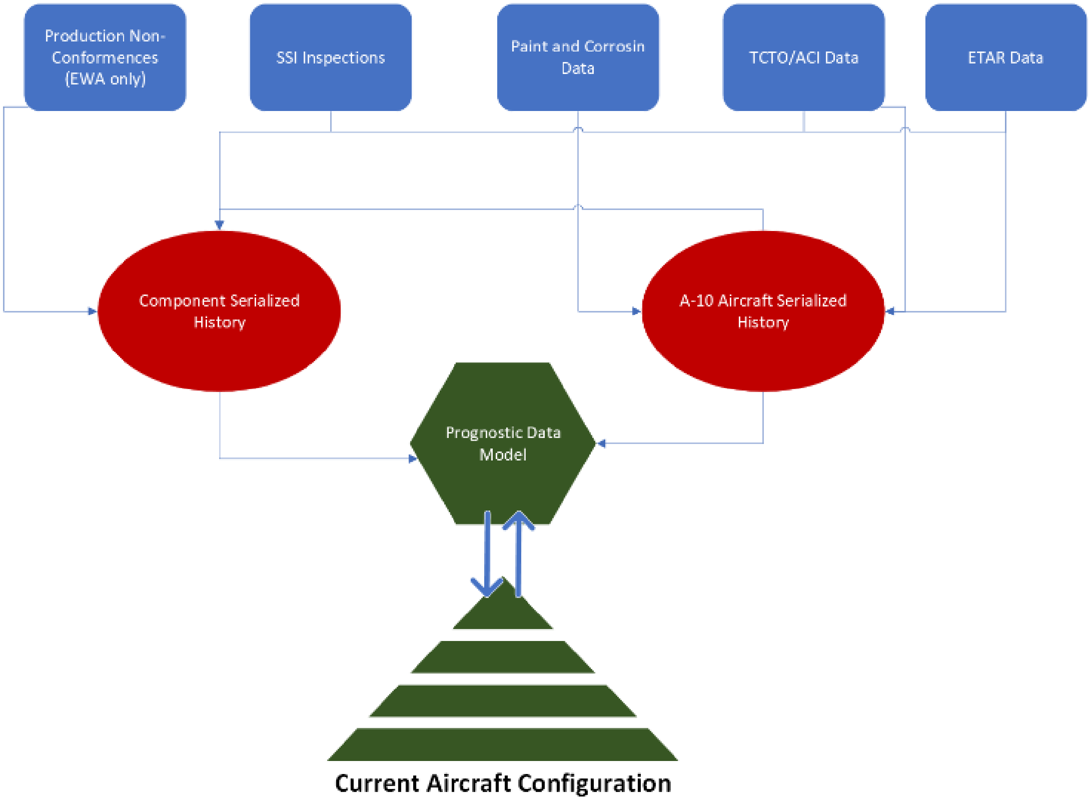
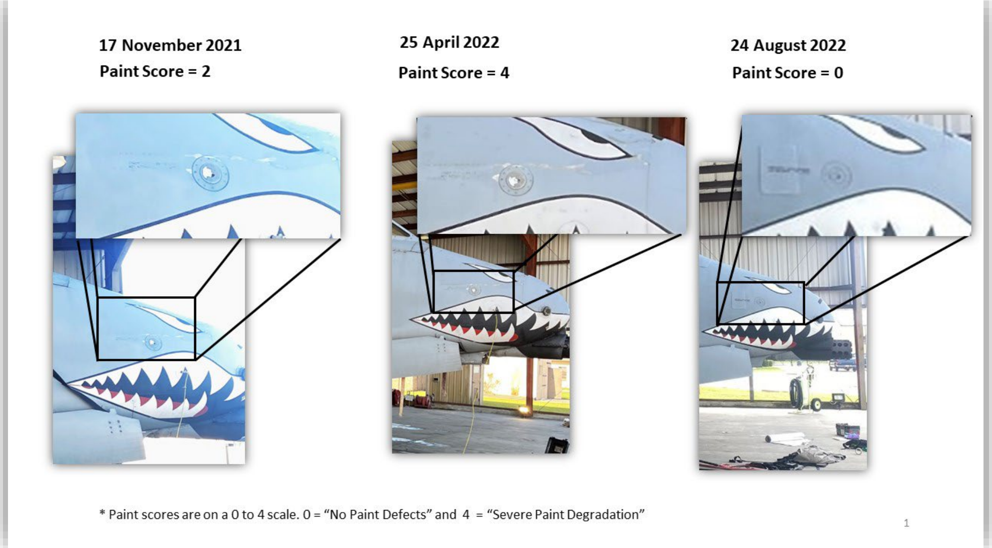


Figure 7: Data flow for the prognostic data model.

Shown at the top of Figure 7 is maintenance-related data from five different touch-points that feed metadata needed for the prognostic data model. From these five touch points there is data from fatigue-related damage, production discrepancies, corrosion damage, and engineering rigor. All of these data types are necessary to proactively provide a holistic interpretation of the structural health of the A-10.

Corrosion related data is one of the most recent data types to be incorporated. In 2020 ASIP deployed NCheck to the field units to digitally capture paint and corrosion-related data. The original intent of capturing field paint and corrosion inspection data was to provide the A-10 Corrosion Prevention Advisory Board (CPAB) feedback on inspection requirements and perhaps improve inspection metrics. Later, it became apparent that metadata from these inspections made it possible to provide a baseline of corrosion and paint conditions and perhaps correlate corrosion effects on structural integrity.

Figure 8 shows images taken during three separate paint inspections of the same area on an individual aircraft; also shown is the associated paint score. The images were taken six months apart starting in November of 2021. This example is valuable in conveying the variability in paint scores. Perhaps, more importantly, this example demonstrates the data captured provided an awareness to ASIP that for more than six months, this specific aircraft was flying with areas of bare metal. The areas of damage/corrosion can then be mapped, as shown in Figure 9, to a model using NLign's damage mapping tools. This type of mapping data can then build on the database that would comprise the digital twin of this aircraft. This information is vital for guidance in corrosion prevention and could also be used in future failure analysis.

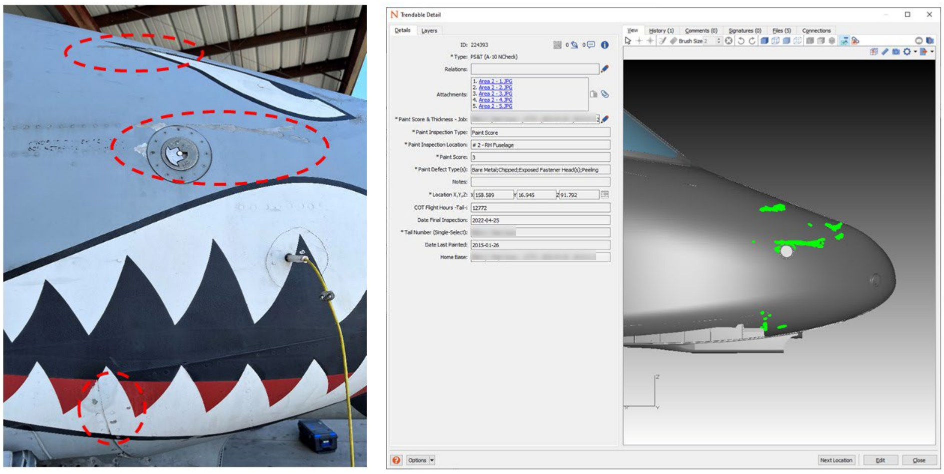

17 November 2021
Paint Score = 2

25 April 2022
Paint Score = 4

24 August 2022
Paint Score = 0

* Paint scores are on a 0 to 4 scale. 0 = "No Paint Defects" and 4 = "Severe Paint Degradation"

Figure 8: Paint inspection scores and corresponding images taken 6-months apart.



ID: 224393
* Type: PS&T (A-10 NCheck)
Relations:
Attachments: 1. Area 2 - 1.JPG 2. Area 2 - 2.JPG 3. Area 2 - 3.JPG 4. Area 2 - 4.JPG 5. Area 2 - 5.JPG
* Paint Score & Thickness - Job: [redacted]
* Paint Inspection Type: Paint Score
* Paint Inspection Location: # 2 - RH Fuselage
* Paint Score: 3
* Paint Defect Type(s): Bare Metal;Chipped;Exposed Fastener Head(s);Peeling
Notes:
* Location X,Y,Z: X 158.589 Y 16.945 Z 91.792
COT Flight Hours -Tail-: 12772
Date Final Inspection: 2022-04-25
* Tail Number (Single-Select): [redacted]
Date Last Painted: 2015-01-26
Home Base: [redacted]

Figure 9: Paint defects and corrosion annotated on models utilizing NLign's damage mapping tools.

Smart Maintenance Tools and the Digital Thread

The future of the digital thread for A-10 has many moving parts that will play a role for more engineering solutions. One of the more significant projects is centered around implementing smart tools on the maintenance floor. A smart tool is considered "smart' once a tool is connected to the digital thread, giving the tool the ability to read data for guidance and write data to provide context for the tool's use. Implementing smart tools has the potential to provide a significant amount of relevant data to provide a more complete picture of maintenance operations. Smart tools also have the potential to significantly reduce the data entry burden on maintenance groups since they can rely on the tools to provide the necessary data.

Currently, A-10 is piloting smart tools for SSI inspections for the A-10's center wing panels. This joint effort started in 2016 as a RIF between Hill Engineering, FTI, NLign Analytics, and the USAF. The project's main goal is to enable a digital thread with coldworking tools to take full credit for the benefits of coldworked holes in fatigue damage analysis, prolonging depot inductions, and improving aircraft availability. In order to take full credit, ASIP needs to prove the "correct hole" was cold worked "correctly." A digital profile of the tool's location and the puller pressure during coldworking operations can provide the proof needed. This current project leverages NCheck's 3D environment with Hill Engineering's Integrated Maintenance System + (IMx+) to get this digital profile of the tool. IMx+ is a system of hardware and sensors developed to link the tool to the digital thread and is capable of providing the physical locations relative to a virtual location on a model in NCheck.

While the project focused on coldworking events, there is undoubtedly an endless potential for smart tool applications input to the digital thread. NDI applications are an additional area that A-10 is planning to implement smart tools, specifically for eddy-current inspections. Again, the requirements for NDI smart tools would be spatial position and tool read-out. While there are significant benefits to such smart tools, it will be important that a correct data structure is implemented to provide context to make the vast amount of data usable.

DISCUSSION AND RESULTS

Many of the issues present in a paper-based system can be resolved by implementing a digital thread with additional benefits. By implementing NLign and NCheck to digitally collect SSI data the lack of continuity between maintainers and engineering was eliminated, changing the cultural perspective of the data's importance. The impacts of a digital transition were significant regarding SSI data quality compared to before the beginning of the transition. Figure 10 shows the data quality trend of fatigue cracks findings from 2017 to 2022. In 2017, one year before the digital transformation, only about 15% of the data was considered usable. In 2019, a year after NLign was implemented, there was a noticeable increase, with nearly 95% of data considered usable. Since 2018 data quality has improved and remained near 100% good usable data. Also shown in Figure 10 is an alternative way to view this improvement through the value of the data per dollar spent to capture the data. The effort to collect this data is monetarily expensive for both the ASIP and the maintenance organizations; for every dollar spent in 2017 to support data collection, only 15 cents of value was realized through the data. Also, the data is likely more valuable once cost avoidance made possible by the digital thread is considered.

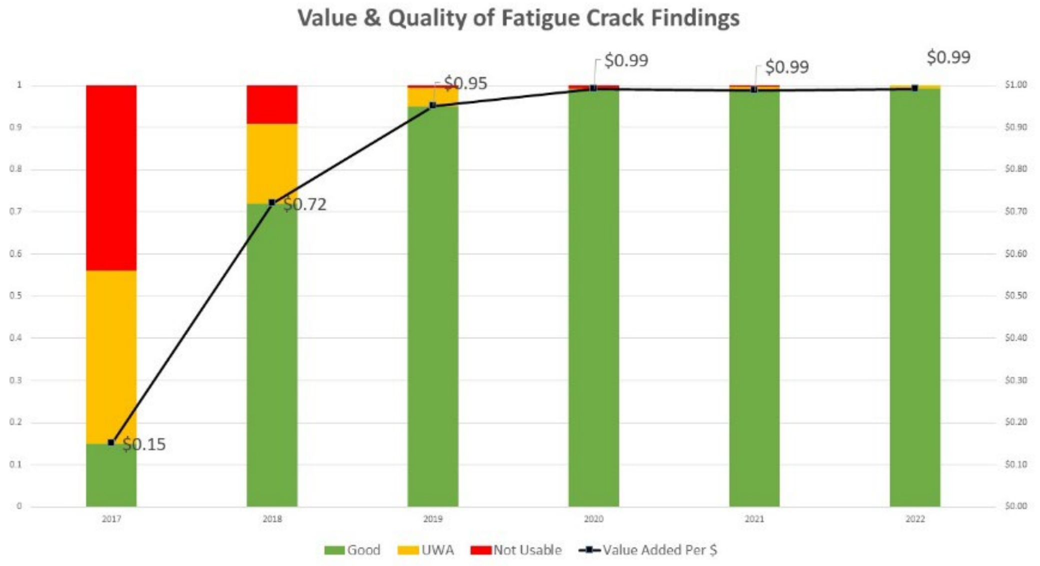


Figure 10: Data quality of fatigue crack findings after the digital transformation.

Perhaps more critical than data quality improvements is the prognostic capabilities the digital thread makes possible. These digital thread prognostic tools allow engineers to make predictions based on a holistic interpretation of data, allowing for directed and proactive maintenance actions. A pointed and proactive maintenance approach leads to millions in cost avoidance compared to the historical timed interval maintenance.

Additionally, efficiency has been realized from time savings resulting offered by the digital thread. One example of this can be noticed with liaison engineers providing technical assistance. Liaison engineers typically start a response for an ETAR by performing research of similar ETARs; if a analogous historic ETAR is found when compared to the current ETAR being worked, the engineer can append the historical disposition to the current disposition, quickly finishing the response. Before implementing the digital thread, liaison engineers would have to sort through multiple systems, which were often uncontrolled, typically resulting in hours of research and very little relevant information found. Through the digital thread, liaison engineers can typically find alike ETARs to append in minutes and have confidence in the data as it is controlled. Additionally, the engineering rigor for current and future ETARs is fully captured in the digital thread, expanding the database to allow more appended responses.

Lessons Learned from Implementing a Digital Thread

While the benefits of implementing a digital thread for an aging aircraft are numerous, specific costs and challenges may often get overlooked in the excitement of current digital engineering conversations. Implementing digital thread software correctly often requires more resources and time than the original assessment. Additionally, there are often obstacles that take time to anticipate beforehand. A-10 ASIP currently has two full-time data analysts and one full-time engineering technician to implement a single digital thread system. The need for this support staff often surprises other weapon systems when looking to make the digital transformation. In reality, there is a need for even more personnel to ensure the vision of the digital thread can be fully implemented for this system, and this need will only grow as more data is collected.

Implementing the digital thread at the field unanticipated obstacles were encountered that were not always present at the depot. Access to adequate hardware was a consistent issue encountered during the field deployment of NCheck. Except for a single field unit, the A-10 SPO needed to provide hardened tablets for the field units to capture data with NCheck. Additionally, the hardware procurement and exchange processes are complicated and time intensive due to USAF policies. The provided hardware must also be imaged and inventoried by the local unit's equipment custodian instead of the depot, or the hardware cannot be managed locally. Network access issues are also a consistent problem in the field, which has led the developers of NCheck to create an off-network solution. When offline, NCheck will cache data as it is entered to sync it later once a network connection is re-established.

The adage "garbage in, garbage out" certainly applies to collecting data, but it is also possible to have meaningful and valid data as input but fail to provide a desired output. As is the case with the more than 6,300 corrosion images taken by A-10 field units over the past two years. The images are taken and attached to data records in NCheck as part of a TO requirement; however, it is impossible to automate corrosion detection on these images with the current software. Additionally, it would be too time intensive for such a large volume of images to do manually. Therefore, A-10 is researching image processing software options to automate corrosion detection and limit variability within images taken to enhance the current prognostic tools and proactively prevent corrosion within the fleet.

Cultural change on the shop floor is the most significant obstacle A-10 has faced and continues to face while implementing a digital thread. Despite ASIP’s request and provided training as well as requirements being included in TOs, data was not coming in from the shop floor. When confronting the issue, shop personnel give many reasons, but the most common response is, "The way we have always done it works fine." In addition to setting requirements, presence from leadership requesting action is also needed to achieve data entry compliance. Requesting leadership intervention is often met with resistance, requiring a series of meetings to convey the benefits of the digital thread before any action is taken.

In some cases, data was not being entered in the field because of a lack of IT support; the units could not get updated software, allowing them to bypass the data entry requirements. Lastly, the frequent change in personnel inherent to active-duty military makes it challenging to ensure knowledge is passed down. The release of NCheck has eased issues related to the lack of knowledge transfer as the application is designed to be user-friendly and semi-intuitive for users.

Conclusion

Implementation of the digital thread for a legacy aircraft is not a trivial feat; however, the benefits of a digital thread dwarf the costs of implementation. As a result of the digital thread, A-10 ASIP has a library of fleet data that can be used to accurately guide ASIP engineering activities like fleet/aircraft risk and prognostics, validation of damage tolerance analyses, corrosion prevention, analytical condition inspection (ACI) selection, and engineering liaison support. The future of aircraft sustainment will heavily rely on digital engineering solutions; therefore, it is vital for all parties involved to be included in the path toward a digital future cohesively instead of internal grandiloquence.

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