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AUGMENTED REALITY FOR AIRCRAFT FATIGUE NON-DESTRUCTIVE EVALUATION

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Abstract

This paper describes a framework aimed at progressing proactive condition-based maintenance using structural health monitoring data and augmented reality for non-destructive evaluation (AR-NDE) of aircraft with fatigue damage 'hotspots'. The framework is an initial proof-of-concept developed using a full-scale decommissioned Pilatus PC-9/A trainer aircraft and a Digital Twin (DT) Unified Finite Element model of the aircraft and several in-flight dynamic loads recorded with strain gauges. Fatigue index mapping of the aft fuselage and empennage structures are generated into a 3-D model file and uploaded to a web-based software (Vuforia) where a Head-Mounted Display Microsoft HoloLens can download the model and project it onto the PC-9/A within the user's spatial environment. Results show that maintenance tasks related to the Aircraft Structural Integrity Program could be simplified with the use of augmented reality (AR) by assisting in the rapid identification of damage 'hotspots', while trials give confidence in the performance of AR in the usage and ease of operation. However, processing of DT data requires several hours and would need to be more efficient for use in everyday operations. A case study of three flights ranging in the severity of dynamic structural loading shows how maintenance procedures with AR-NDE provide greater awareness of fatigue damage to the airframe and has the potential to save time during inspections. Future work will focus on alignment with stakeholder requirements and maintenance procedures to ensure end-user acceptability of AR.

Keywords: Augmented Reality, Fatigue, Structural Non-Destructive Evaluation, Aircraft Maintenance

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Nomenclature

e	=	deviatoric strains
γ	=	engineering strains
n_i	=	cycles at i^{th} applied stress level
N_i	=	cycles to failure at i^{th} applied stress level based on S-N curve data
ε_{eq}	=	maximum distortion energy criterion von Mises equivalent strain
D	=	accumulated fatigue damage fraction

Terms

DAQ	=	Data Acquisition, referring to Structural Health Monitoring system units
MFDR	=	Modal Frequency Decomposition and Reconstruction
S-N	=	Wöhler curve - applied stress (S) against number of cycles to failure (N)
VSE	=	Virtual Sensor Expansion

1. Introduction

Augmented Reality is an emerging enabling technology, supporting better comprehension of complex tasks while also enhancing in-situ decision-making for maintenance practitioners [1]. The emergence of Augmented Reality (AR), in industrial applications, offers the potential for visualisation of Digital Twin (DT) models, intuitive task familiarisation and immersive remote communication for frontline practitioners in aircraft maintenance [2]. In this context of aircraft sustainment, AR is defined as using DT data with the support of devices, such as tablet devices (e.g., Apple iPad) and Head-Mounted Displays (HMD) (e.g., Microsoft HoloLens), enabling maintainers to interact with digital 3-D aircraft models that are augmented or overlaid onto full-scale 'real-world' aircraft within a person's spatial environment.

In the current state-of-the-art AR has had limited implementation into aircraft sustainment, given the with Technology Readiness Levels (TRL) typically reaching 6 [3] or lower depending on the application, although early adoption has been found for training purposes. An example of where an HMD could be used for hands-free remote video communication with more experienced maintainers showed how a complex maintenance task could be safely carried out by less experienced aircraft technicians on the ground [4]. Furthermore, proof-of-concepts utilising DT technology of aircraft components, in this case [5], an air brake, demonstrated that damage assessment using an HMD could simplify and increase the efficiency of a maintainer. An HMD enables interfacing with the real component, while also deriving new information from the combination of maintenance data and remote collaboration. Human-Machine Interface (HMI) is among the top influencing factors for inspection performance and the accessibility of visual information [6]. Inspection tasks that require access to the airframe internal structure, often by means of removing obstructing panels or components, can be limiting in visual instructional information, which leads to time-consuming, costly maintenance and demands more experienced technicians [7].

Furthermore, such inspections are generally in the event of unscheduled maintenance. Such cases, require hours of detailed examination by maintainers, often including visual damage checks of the external and internal structure for buckling, warping skin and loose, sheared, or missing rivets [8].
This is significant for non-normal flight events, such as hard landings, severe rudder movement, overspeed and excessive g-loads, all of which require specialist inspections and are time-consuming maintenance procedures. This leads to the motivation for developing the framework and contributes to the academic state-of-the-art through:

- Integration of aircraft SHM system data and DT technology to visualise fatigue damage, however with the requirements of an end-user in mind, such as maintainers and engineers.
- Enhancing the support of aircraft structural damage inspections with improved visual information, providing a tool in addition to a “bright light source, x10 magnifier and mirror” [8]. Developing a supplementary aid for Aircraft Structural Integrity Program (ASIP) maintenance tasks [9], helping to identify damage growth as early as possible.
- Demonstration of an AR experience with a full-scale ‘real-world’ aircraft, aligned to maintenance procedures and tasks. As a result, generate stakeholder feedback to progress towards an in-practice application for end-users.

The subject of this framework is the Pilatus PC-9/A aircraft and relevant aspects of the ASIP, which includes associated Safety-By-Inspection (SBI) maintenance tasks [10]. The Pilatus PC-9/A is a decommissioned Royal Australian Air Force (RAAF) trainer aircraft, now repurposed as a research testbed parked at RMIT University in Melbourne, Australia. The aircraft maintenance documentation and relevant maintenance logs are available to the authors, including results from on-board Structural Health Monitoring (SHM) systems (strain gauges and accelerometers). This includes a Unified Finite Element Method (UFEM) model capable of producing the DT of the aircraft and performing structural fatigue analysis.

The approach to individual aircraft tracking is the subject of a previous paper [11] and was made possible by OPERAND (Operational Load Analysis and Asset Diagnostics), a multi-physics analysis suite for aircraft structural diagnostics and prognostics tools based on the integration of data-driven methods and model-based approaches. The development of OPERAND is the result of continued collaboration with the Australian Defence Science and Technology Group (DSTG) and RMIT University, primarily developing innovative techniques for operational modal analysis and system identification, which is further described in the paper by Levinski et al. [11]. It should be noted that in the subsequent section, the framework leverages OPERAND and the PC-9/A UFEM DT, serving as a continuation to develop this concept into a framework for proactive condition-based maintenance and for maintainers to use in non-destructive evaluation.

2. Augmented Reality Non-Destructive Evaluation Framework

2.1 Overview of AR-NDE Framework

The Augmented Reality Non-Destructive Evaluation (AR-NDE) framework combines the previously mentioned OPERAND and Pilatus PC-9/A UFEM to generate a DT AR experience for fatigue 'hotspot' non-destructive evaluation. The framework steps are summarised in the flow chart shown in Figure 1, illustrating how the in-flight data is processed for fatigue analysis and the supporting information required to generate the final AR-NDE step. In section 2.2, a brief explanation of the underlying theory is provided, including calculations to arrive at the accumulated fatigue index maps. In section 2.3, the augmented reality software and hardware used are explained, as well as a more in-depth description of the development of the AR-NDE process.

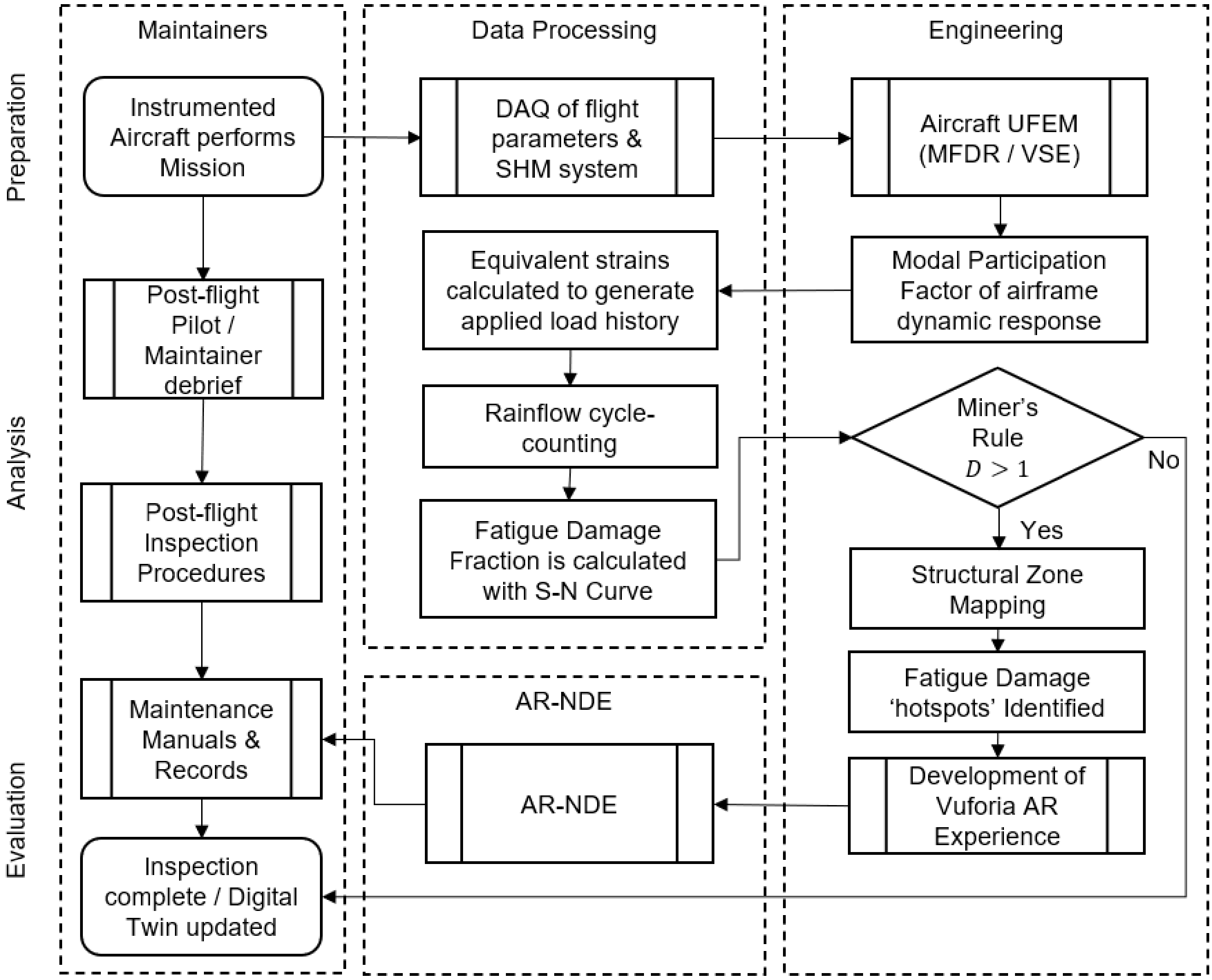


Figure 1 – Flow chart of Fatigue Damage 'hotspot' process for Augmented Reality Non-Destructive Evaluation (AR-NDE)

The framework contains three major steps. The initial step involves the preparation of the data acquired from the SHM system, which may include strains, accelerations, indicated airspeed, angle-of-attack, etc., thus compiling a derived dataset of in-flight dynamic loading conditions. On the engineering analysis side, the DT or UFEM processes the strain data to generate the modal participation factor for the flight, which is multiplied by the equivalent strains to determine the applied load time-series history. The accumulated fatigue damage is calculated and complied into an index map, which is used on the DT model for deployment as an AR experience to a maintainer HMD on the ground or for further engineering analysis. The maintainers can carry out their inspection procedure with the HMD or refer to Instructions for Continued Airworthiness (ICA) documentation. AR-NDE is intended for both engineers and maintainers in the event of unscheduled maintenance inspections. The use of the AR-NDE framework is tested in a case study detailed in section 3.

2.2 In-flight dynamic loads to Accumulated Fatigue Damage Analysis

In this section the methods used to determine the accumulation of fatigue damage are briefly described in the underlying context of a PC-9/A aircraft flight. This covers the method from strain gauge instrumented aircraft to a generalised fatigue damage index map for 'hotspot' identification. As noted in the introduction section, the strains measured during the missions carried out by the Pilatus PC-9/A test aircraft are obtained from an expanded dataset of measured high-resolution strains and virtual strain signatures to produce strains at each node of the numerical digital twin model. The scope of this paper is to focus on the end-user application, although it is important to understand the novel technique used to generate the UFEM combining displacements and known structural mode shapes via Modal Frequency Decomposition and Reconstruction (MFDR). This is detailed in a separate paper by the co-authors [12].

However, it should be noted that the critical product of this method is in calculating the amount of loading across the entire airframe, beyond the limited number of strain gauges at points on the aircraft. This initial step generates a modal participation history for the flight, describing how strongly a mode, 'preferred' displacement of aircraft structure, contributes to the signal response over time. This can be represented in the form of a large matrix x-by-j:

$$Modal\ Participation\ History = \begin{bmatrix} M1_1 & \cdots & Mx_1 \\ \vdots & \ddots & \vdots \\ M1_j & \cdots & Mx_j \end{bmatrix} \tag{1}$$

where x is the primary mode shape and j denotes the time step. This enables more of the aircraft structure to have a virtually expanded value of strain. The expansion is by linear superposition of the principal modes, enabling the limited measurement strain information to expand to other locations on the airframe. This enhances a maintainers ability to identify different fatigue damage ‘hotspots’ in locations not instrumented and with potentially unanticipated loads.

For aircraft with primarily ductile metal airframe structures, it is critical for maintainers to know cumulative fatigue damage over the life of the aircraft, impacting aircraft operational readiness and sustainment costs. Aircraft can undergo intense variable amplitude loading even within a single flight, and fatigue behaviour of the structure depends on the interaction between loading sequence, material characteristics and component geometry, and generalised damage rules are typically used to determine accumulated fatigue damage.

The linear damage rule still used decades on is the Palmgren-Miner’s rule, or Miner’s rule for short. It should be noted that this approach is generalised, and numerous non-linear damage models are capable of producing superior results, however typically only for specific datasets [13]. Miner’s rule hypothesises that fatigue damage is likely to occur where the accumulated cycle ratio of loading to failure over many levels of the applied stress is equal (producing a result of one or greater). Miner’s rule is described as follows:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = 1 \tag{2}$$

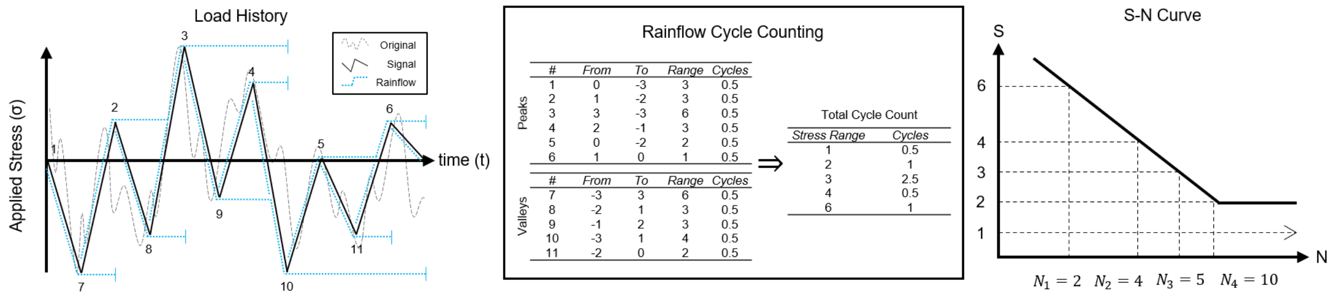
where D is the fatigue life utilisation ratio, n_i is the number of loading cycles at the i^{th} stress level, N_i is the number of loading cycles to failure for the i^{th} stress level based on the S-N curve data, and k is the number of stress levels in the analysis. Miner’s rule is an industry standard for fatigue of metal structures based on the endurance approach due to its simplicity; given the application in this research for assisting fatigue ‘hotspot’ identification, it is a suitable generalised rule in the current scope. It should be noted it is most useful for crack initiation life, although factoring in pre-existing cracks or manufacturing discontinuities is beyond the scope of this paper.

To effectively use Miner’s rule for fatigue ‘hotspot’ prediction, a signal processing step is required to go from strains to the load history and finally to determining n_i, the number of loading cycles the aircraft structure undergoes. The ductile metal of the aircraft structure is assumed to yield under complex loading, and therefore the application of the Maximum Distortion Energy Criterion (von Mises theory) is a suitable approach; it is calculated in the form of the equivalent von Mises strains ε_{eq} according to:

$$\varepsilon_{eq} = \frac{2}{3}\sqrt{\frac{3\left(e_{xx}^2 + e_{yy}^2 + e_{zz}^2\right)}{2} + \frac{3\left(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2\right)}{4}} \tag{3}$$

where e_{ij} represents the deviatoric strains and γ_{ij} the engineering strains, which are calculated directly from the aircraft UFEM data matrix and multiplied by the modal participation history equation (1).

The Rainflow procedure is a cycle-counting method that stores time-series signals in a form suitable for fatigue life prediction of structures. The Rainflow counting method was developed by T. Endo and M. Matsuishi in 1968 and used to extract closed loading reversals or cycles. The name "rain flow" comes from the similarity to the flow of rainwater falling on a pagoda roof and running down along the edges. While the method used in this paper is in the form similar to ASTM E1049-85 documented in [14,15]. The equivalent von Mises strain time-series data is post-processed using the iterative Rainflow procedure: i) firstly, local extrema (min/max turning points) are identified in the signal time history, and ii) subsequently, the loading cycles are extracted in a reduced load history enabling the random loading to be counted. The load history is represented in a simplified example in Figure 2, showing the cycle counting with the corresponding S-N Curve used in determining the total accumulated fatigue damage according to Palmgren-Miner's rule:



	#	From	To	Range	Cycles
Peaks	1	0	-3	3	0.5
	2	1	-2	3	0.5
	3	3	-3	6	0.5
	4	2	-1	3	0.5
	5	0	-2	2	0.5
	6	1	0	1	0.5
Valleys	7	-3	3	6	0.5
	8	-2	1	3	0.5
	9	-1	2	3	0.5
	10	-3	1	4	0.5
	11	-2	0	2	0.5

Total Cycle Count

Stress Range	Cycles
1	0.5
2	1
3	2.5
4	0.5
6	1

$$D_1 = \frac{n_1}{N_1} = \frac{1}{2} = 0.5 \qquad D_2 = \frac{n_2}{N_2} = \frac{0.5}{4} = 0.125 \qquad D_3 = \frac{n_3}{N_3} = \frac{2.5}{5} = 0.5 \qquad D_4 = \frac{n_4}{N_4} = \frac{1}{10} = 0.1 \quad (4)$$

$$Total\ fatigue\ damage\ fraction\ is\ D_{Total} = D_1 + D_2 + D_3 + D_4 = 1.225 \quad (5)$$

$$\therefore As\ D_{Total} > 1\ fatigue\ damage\ is\ expected\ to\ occur$$

Figure 2 – Rainflow Cycle Counting and Palmgren-Miner's rule approach example

The accumulated fatigue damage fraction is calculated for every grid point of the UFEM, which enables the values to be mapped across the structure to visualise damage 'hotspots' for the aircraft. The fatigue damage 'hotspots' dataset is passed through the natural log for better interpolation of fatigue index maps and all data points that are equal to or greater than zero are highlighted, as this is where fatigue damage is expected to occur, while data points less than zero are returned as not a number (NaN). The processing of the in-flight dynamic responses can produce 2-D and 3-D visualisations of the resulting fatigue damage distribution of the dynamic strains for use in the AR-NDE framework detailed in the case study found in subsequent sections.

2.3 Developing Augmented Reality Experience

AR in the context of aircraft maintenance inspections is still in the exploration phase, and as such, there are no standards or guidance on how AR can work in practice. Therefore, the case study in section 3 makes comparison to the PC-9/A revised ASIP and how AR can be used for inspection of the structure in the event of fatigue damage. To develop the AR experience, the 2-D schematics and 3-D fatigue damage index maps are imported into a PTC product Vuforia Studio, an AR content platform. Some 3-D models are first processed using Microsoft 3D Builder and/or Blender to convert into readable formats by Vuforia software. Once compiled in the Vuforia Studio with supporting menus and the aircraft outer mould line, which is used for tracking, the AR experience is uploaded to the Vuforia webservice. In this study, the HMD Microsoft HoloLens II is used with Vuforia View (AR engine) installed, where the AR-NDE experience is launched to interface with the aircraft. In Figures 3 and 4, the development process is shown for AR-NDE in practice on the PC-9/A.

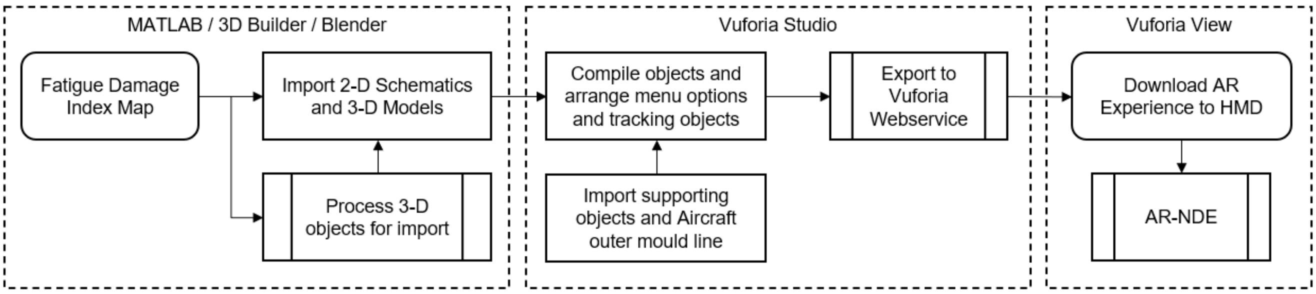


Figure 3 – Flow chart of Augmented Reality experience development process

(a) (b)

(c) (d)

Figure 4 – (a) Decommissioned PC-9/A testbed aircraft at RMIT University; (b) Researcher performing AR-NDE inspection of PC-9/A aft fuselage and empennage using HMD; (c) HMD AR view of Frame 9 Fatigue Damage Index Map positioned in-situ on real aircraft; (d) HMD AR view of full internal empennage structure Fatigue Damage Index Map overlaid on aircraft.

3. Fatigue Damage AR-NDE Case Study

The PC-9/A trainer aircraft performed a series of test flights for operational loads monitoring program, and there are several flights from the test program with varying loading conditions, which have been down-selected for use in this case study. A selection of three flights with low, medium and high load conditions are used to demonstrate the AR-NDE framework. The three flights selected have the following flight parameters that show variation in aircraft loading; note that the data is randomised and normalised to protect the information source.

Table 1 – Summary of PC-9/A flight parameters dataset used in the case study

Flight	*Date*	*Flight Parameter Conditions (rms)*	*Severity Rating*
1	1/JAN	AoA 15 deg, IAS 130 knots	Medium
2	5/JAN	AoA 5 deg, IAS 140 knots	Low
3	1/APR	AoA 10 deg, IAS 160 knots	High

The severity rating for the three flights is based on the comparative flight parameter conditions and the flight routine performed by the pilot. For example, the manoeuvres performed in flight 3 are at the edge of the envelope with severe buffet loading, experiencing high-speed rudder kicks, spins and wind-up turns, compared to flight 2 which is a baseline flight with largely steady low-speed manoeuvres. The flight datasets acquired from the test aircraft used in this study are pre-processed by engineers with the necessary parameters to perform the first step in the accumulated fatigue damage process, which is detailed in section 2.1. The following step is generating the fatigue damage index maps. Section 3.1 shows the results of processing these for the three flights.

3.1 Results – Processing

Critical to the viability of this process is the framework for generating the fatigue damage 'hotspots', and this is underpinned by the methodology as outlined in section 2.2 and the computational resources available. As such, the processing run times were measured for the three major scripts, measuring the time to take pre-processed flight dataset and generate the Fatigue Index Maps for all three flights. This is completed using a High-Performance Computing (HPC) station with 2 CPUs, 44 core processors (2.10GHz) and 64GB of RAM. The average run times across the three flight datasets are summarised in Table 2. The overall run time includes the manual steps required to set up the scripts and export files. The total run time per flight dataset is 13 hours 36 mins, with the largest run time duration being the fatigue analysis using the iterative Rainflow cycle counting method and due in part to the matrix output size with, on average, approximately 7 million rows and 17 columns of time-series data. Although this requires significant computational resources, it was done remotely, and the exported file sizes are below 50 megabytes, thereby not eliminating the potential for 'real-world' applications.

Table 2 – Summary of results for fatigue damage index mapping process (mean of flights)

Process routines	*Run time (hours)*
1. Generating modal participation histories, output matrix (~7,000,000 x 17)	~1.5
2. Equivalent strains calculation, Rainflow Cycle Counting and Miner's Rule	~12
3. Mapping fatigue index and exporting files 2-D schematics and 3-D models	~0.1
Total run time per flight:	~13 hours 36 mins

3.2 Results – Schematics and Models

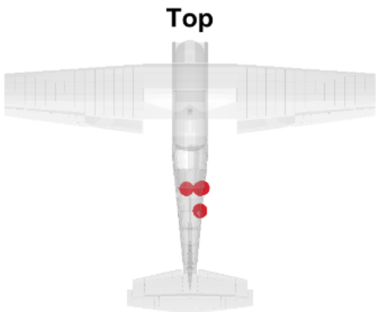
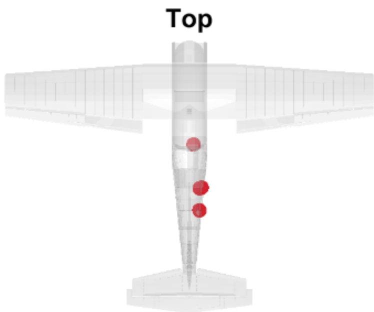
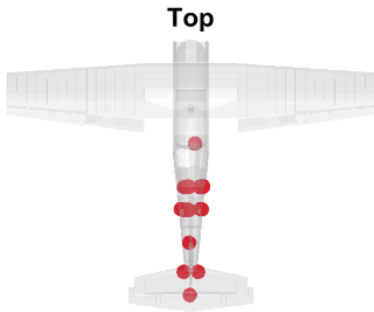
The exported files from section 3.1 are compiled into an AR experience. An initial step is carried out to enable both engineers and aircraft maintainers to evaluate this information, which is shown in Table 3 and Figure 5. Table 3 is a summary of the three flights showing the number of fatigue damage 'hotspots' in relation to the aircraft in a top view. The fatigue damage 'hotspots' are the result of a damage fraction greater than one, as described in section 2.1. The index mapping shows a colour range of values from the natural log distribution for Miner's rule damage ratio, from median to maximum values cutting out less significant lower values.

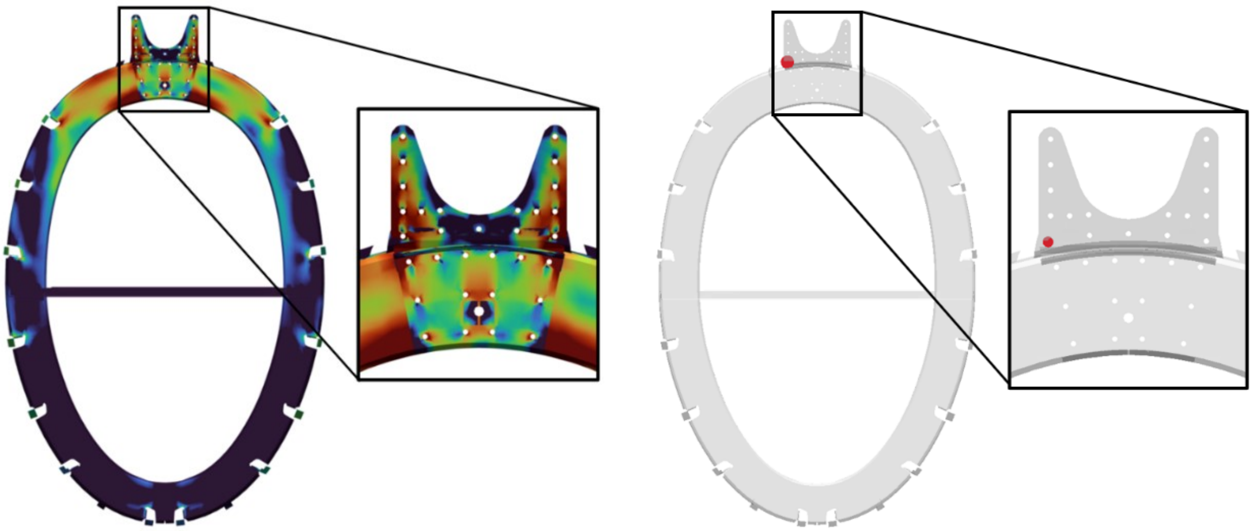
The results show that for the low and medium severity flights (2 and 1), the aft fuselage is expected to have fatigue damage in 18 and 25 elements, respectively. In comparison, the high severity flight (3) has 172 elements showing fatigue damage 'hotspots' across the aft fuselage and empennage. This is consistent with the hypothesis that for more severe flight load conditions, the fatigue damage is expected to be higher with more 'hotspots' warranting inspection for any yield or potential crack growth.

The results show consistent and good agreement across the three discrete flights, where the same ‘hotspots’ are clustering together in areas with known fatigue damage.

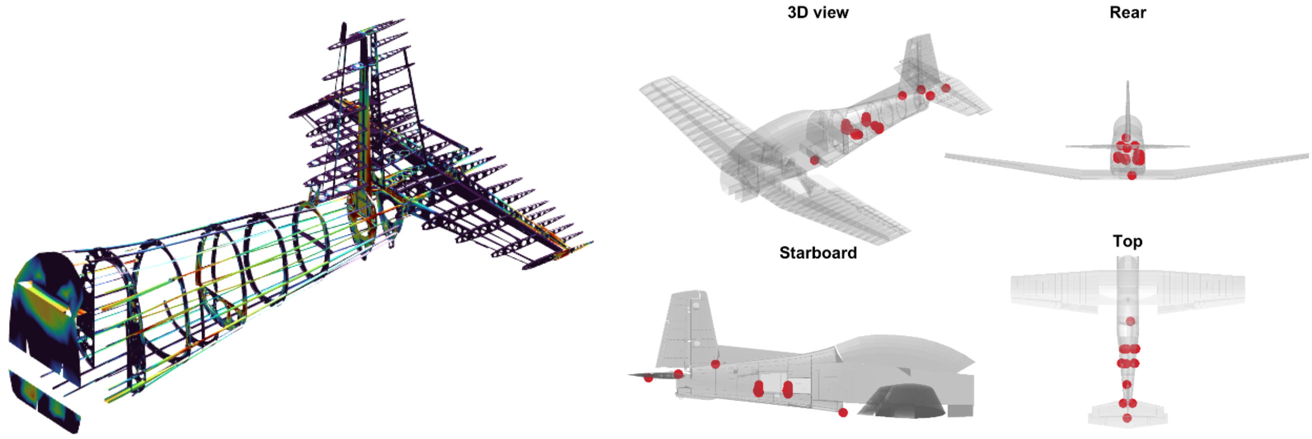
The two comparative views shown in Figure 5 highlight how two levels of analysis can be visualised to suit the end-user, be it an engineer or maintainer. For example, Frame 9 shown in (a) has a fatigue damage index map spectrum (warm to cool colours), indicative of the areas where damage fatigue could arise over time, with the warmer colours having a greater expectation of fatigue damage. Whereas Frame 9 shown in (b) is indicating a single red dot where the most critical fatigue damage is expected to occur, requiring no interpretation or judgement step in a maintenance procedure other than showing the location required for General Visual Inspection (GVI). This can be expanded to the aft fuselage and empennage in a three-view schematic in (d); or a 3-D index map in (c) for engineering analysis.

Table 3 – Summary of the number of fatigue damage ‘hotspots’ shown in top view

Flight 1	*Flight 2*	*Flight 3*
25 ‘hotspots’	18 ‘hotspots’	172 ‘hotspots’
		



(a) (b)



(c) (d)

Figure 5 – Flight 3 in-flight dynamic responses of the PC-9/A aircraft processed for an engineering view (a, c) and maintainer view (b, d).

4. Discussion

From the AR testing, results demonstrate confidence in the AR visualisation process and provide new end-user interactions, warranting further investigation for use as an inspection tool. AR performance parameters such as object tracking, visual resolution and lighting, satisfied the environmental conditions; however, poor alignment of components exists and requires adjustment between the model and physical aircraft. Furthermore, it was identified that the AR-NDE framework provides potential solutions to two of the PC-9/A ASIP deficiencies [10], such as SBI and static Instructions for Continuing Airworthiness (ICA) lacking some detail, as described in the following Figure 6:

ASIP Deficiencies

Unclear structural inspection policy and gaps in fatigue certification

- Consolidation of SBI Locations

Structural configuration not accurately captured

- Fleet Inspections
- ICA Revisions
- Complex Processes

ASIP Recovery AR-NDE Solutions

- Rapid application of DT data for individual aircraft fatigue analysis
- Simple SBI, assisting maintainers in identifying damage 'hotspots' more intuitively and on full-scale aircraft
- Reduce familiarisation time by serving instructions in-situ, with options for remote collaboration to communicate with more experienced maintainers

Figure 6 – PC-9/A ASIP Recovery using AR-NDE Solutions

The potential solutions that the AR-NDE framework could have provided in the PC-9/A ASIP recovery are underpinned by the advantages of a readily accessible DT and the performance of an AR device to visualise in-situ critical structural fatigue information, which can be seen in Figure 4, showing the fatigue index map of internal structure overlaid on PC-9/A, allowing rapid identification of structural ‘hotspots’. While the positioning of damage-critical aircraft frames can be clearly shown in Figure 5 b), isolating the component and potentially reducing the need to remove access panels during the inspection.

Furthermore, a quantitative desktop study of the PC-9/A maintenance manuals, see Table 4, found that 12 flight-line airframe item checks (tasks done before and/or after flight) could benefit from the AR-NDE framework. Similarly, a total of 42 items for interval schedule maintenance and 21 steps for unscheduled maintenance procedures could be supplemented with AR-NDE. Reducing repetitive visual inspections and increasing the effectiveness of damage checks. In addition, cracks are categorised based on grouping and number of rivets impacted, which determines frequency of inspection (from 100 hours to before flight), further adding to the maintenance burden if not identified early. It should be noted that this would need to consider further risk assessments and change management before implementation and is rather intended to only demonstrate potential areas for improvement.

Table 4 – PC-9/A maintenance manual procedures with relevant airframe inspections

Procedures	*Count*
1. Flight-line Inspections - Airframe	12
2. Maintenance Plan / Service Bulletins / Airworthiness Limitations	27 / 3 / 12
3. Unscheduled: hard or overweight landing / tail down landing / overspeed / severe rudder movement / aircraft collision	21

A qualitative analysis of the maintenance manuals found that the AR-NDE framework could assist two common procedures in unscheduled maintenance: i) general examination of the external structure, and ii) removal of access panels to inspect internal structure.

Procedure

A. Remove rudder (Ref. 27-20-01).

B. Examine vertical stabilizer skin for distortion and loose, sheared or missing rivets.

C. Examine vertical stabilizer spar-to-fuselage frame attachment for distortion, and loose, sheared or missing rivets.

D. Examine rudder attachment fittings for distortion and cracks.

(a)

External Structure

(1) Examine complete wing, engine compartment, fuselage and horizontal stabilizer skin for buckling or warping and for loose, sheared or missing rivets.

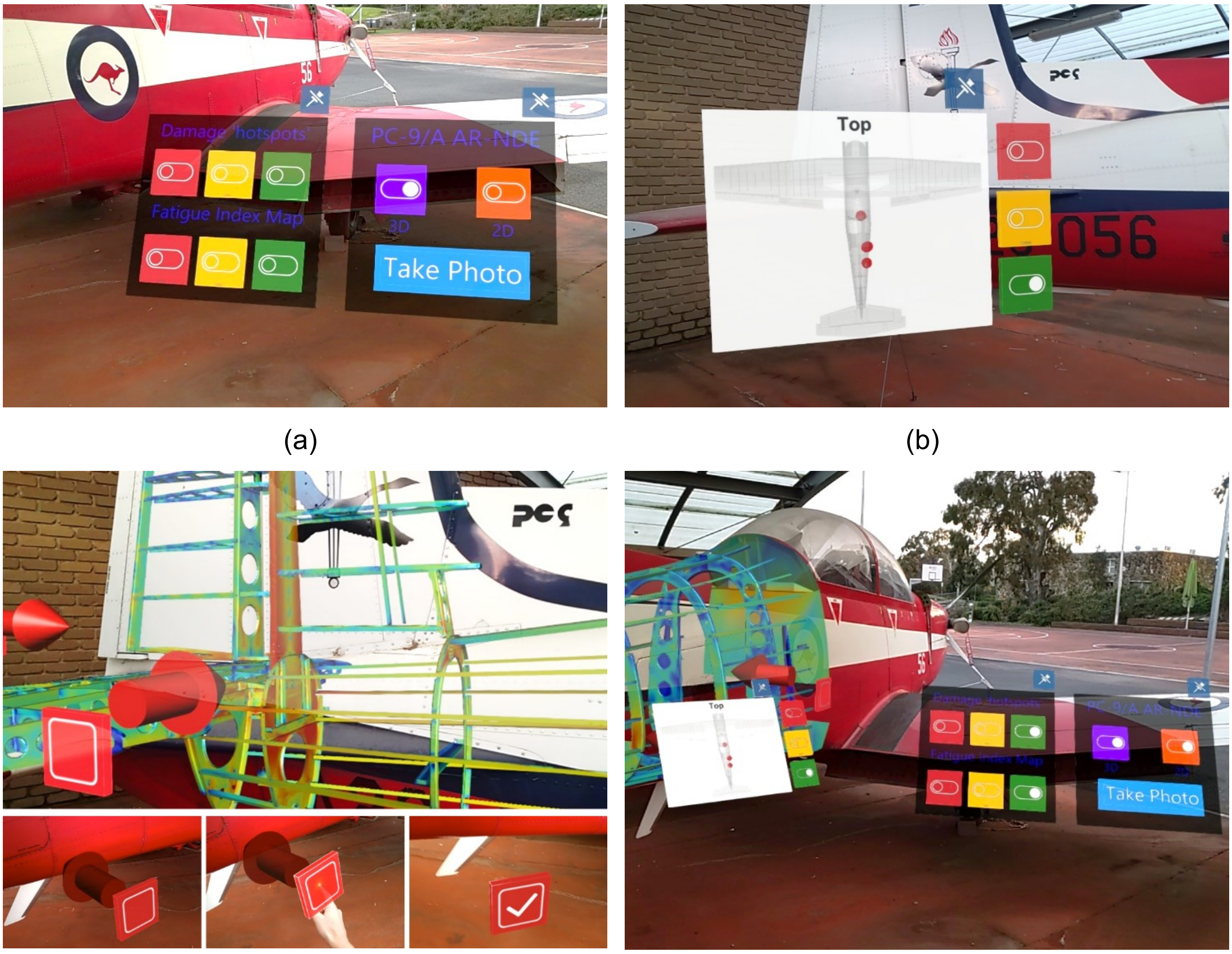
(2) Remove access panels EL1, ER1, F13 and F14 and examine horizontal stabilizer attachments for damage, distortion and cracks. If structural damage is found, do an Alignment and Symmetry Check (Ref. 05-57-01, Page Block 201).

(3) Install access panels EL1, ER1, F13 and F14.

(b)

Figure 7 – Example of PC-9 maintenance manuals [8] inspection task with six GVI steps for cracks in the event of (a) severe rudder movement and labour-intensive panel removals in (b) hard landings.

As documented in Figure 7, in unscheduled events, the external and internal structure is often a time-consuming check, requiring maintainers to examine the entire aircraft surface and then remove panels to check internally. AR-NDE can reduce the uncertainty of not knowing where to start or where to inspect and greatly reduce the amount of external area to inspect, in turn increasing efficiency and, through consistency in approach, improve compliance by adding a sequence to check off inspected 'hotspots'. Furthermore, this has the potential to minimise labour-intensive tasks, reduce the number of tasks and lower costs and constraints on specialists such as NDT (non-destructive testing) experts, also requiring aircraft hangar space, jacking of aircraft and removal of components and/or systems.



(a) (b)

(c) (d)

Figure 8 – (a) PC-9/A AR-NDE main menu (right) with the 3-D menu (left) selected, showing both Damage 'hotspots' and Fatigue Index Maps for the three flights; (b) the 2-D menu showing damage 'hotspots' schematic for low severity flight; (c) arrows show inspection points, with checkboxes to record inspection completion; (d) all AR-NDE menus and objects.

4.1 Assumptions and Limitations

This AR-NDE framework is still in the early stages of development across industrial applications, and there are several considerations, from technology to human-machine-interaction. For this study, several manual steps are involved in producing the AR experience, and this is the subject of future work to lean out the process by automating steps. For example, the fatigue damage accumulation process is computational resource-intensive, and this requires an HPC to be effective, limiting the option for edge computing with the HoloLens or other HMD. Initial evaluation of the performance of the Microsoft HoloLens II in the case study established it coped well with variable environmental conditions, although it struggled with object tracking, becoming misaligned with the target when the user was moving around at a slow rate.

The linear damage method, Miner's Rule, used for fatigue damage 'hotspots' could be enhanced specifically to individual aircraft conditions. Additionally, to improve the fatigue damage analysis, including existing damage such as cracks and other variable factors in the structure such as repairs or modifications would generate more accurate results. Additionally, this approach is suitable for analysis of fatigue failure in ductile metals. Given the use of the von Mises yield criterion, this would not suit brittle material failure analysis, such as composite materials.

Requirements and analytical review session on AR for aircraft sustainment were conducted by RMIT University and the Australian Defence Science and Technology Group, involving both academic and industry researchers, including experienced professionals with technical aircraft maintenance expertise. The discussion generated a requirements list addressing where value can be added to support maintainers and improve maintenance performance. Consistent feedback was the requirement to add value to end-users, whether related to training or in-field contexts:

- AR applicability: two main branches were identified: 1) training aid; 2) in-field (ASIP) application
- Maintainer guidance: complex inspection / instructions; right information at right time.
- Maintainer guidance: GVI with less experienced staff, highlight areas of concern in a simple way. Not using fatigue index maps for maintainers but instead having location priority indications, which are easily interpreted and followed by a maintainer.

The SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis chart shown in Figure 9 summarises the range of considerations for AR to be a viable tool in sustainment operations and be useful for the end-user application. It is important to note that AR tools such as the Microsoft HoloLens are designed for developers as a platform to test a multitude of industrial applications, and this could be challenged as a 'solution looking for a problem'. Nonetheless, this research aims to leverage AR strengths in communication exchange, visualisation and simplify the transition to digital twin technology.

Augmented Reality, or just Reality for Aircraft Sustainment?	
Strengths	**Weaknesses**
▪ In-situ 3-D Visualisation of aircraft structure ▪ Hands-free Interoperability in the operational maintenance environment ▪ Remote communication between maintainer and technical specialist ▪ Procedure compliance checks for less experienced operators. Recording capability can be used to capture and monitor inspection outcomes ▪ Quality control & tracking. Capturing inspection / maintenance decisions and facilitating record keeping. ▪ Reduce human errors and lower cognitive processing loads ▪ Intuitive, fast and relevant instructional information ▪ Reduce time in familiarisation and increase the accuracy of maintenance tasks ▪ Support pre-/post-flight walk-arounds, compliance, accuracy and obscured areas ▪ Inspection / Evaluation can utilise 3-D digital twin assets at full scale in-situ ▪ Image/Video capture with consistency and ease from a maintainers perspective ▪ An additional tool supporting maintenance in the event of Unscheduled maintenance events (Hard landing / Battle Damage)	▪ Challenging spatial environment can cause poor object tracking performance (e.g., misalignment) ▪ Environmental lighting constrains some visuals ▪ New emerging technology with no regulatory framework ▪ Maintaining additional and costly equipment ▪ Additional training required with technology support personnel ▪ Integration with the current procedure ▪ Existing methods are proven and fit-for-purpose, thus could induce errors ▪ A laptop near aircraft on 2-D screen may achieve similar results ▪ Limited computing performance ▪ Process is time-consuming and not lean ▪ Requires expertise to develop experiences
Opportunities	**Threats**
▪ Environment spatial scanning for obstacle avoidance and safer work conditions ▪ New previously undiscovered hotspots not known to OEM (e.g., critical structural components) can be noted - Qualitative trend of the degradation to Unserviceable ▪ Individual Aircraft Tracking SHM data is available on a per flight basis	▪ Cyber security and connectivity limitations ▪ Privacy of user and control ▪ Workplace Health and Safety and Ergonomics (attached to head and eyes) ▪ Regulation and emerging requirements ▪ Operational incompatibility and environmental hazard

Figure 9 – Augmented Reality in Aircraft Maintenance SWOT Analysis

5. Conclusion

The framework presented in this paper is an early research step in progressing augmented reality application in aircraft sustainment and maintenance practices. The novelty of integrating SHM data in a consistent framework has been demonstrated as a scalable process to support DT NDE. Furthermore, AR-NDE presents aircraft maintainers with a supplementary aid for identifying fatigue damage 'hotspots'. The case study established an inspection process and supported the integration of SHM sensor data visualised in a usable form for maintainers. The computational resources required to generate the fatigue damage 'hotspots' limit the potential for rapid post-flight inspections, although this is a function of resources available to the operator. The paper has also resulted in generating more discussion on the use of AR in aircraft sustainment. The AR-NDE framework could support maintainers reduce complexity in ASIP and visualise fatigue damage 'hotspots', helping to shift towards more proactive condition-based maintenance.

This research is on-going, with the aim of further development towards practical application for maintainers, which will require greater stakeholder collaboration. To achieve this goal, the next steps will involve developing a lean process with aircraft datasets that are in-service. This will enable the determination of the efficacy of this framework and to generate stakeholder feedback on what works in practice, as this can differ in controlled research environments. Currently, this method could be improved with access to maintenance reports (e.g., confirmed crack development and measurements). Furthermore, the approach for calculating fatigue damage will also be further refined and allow for more flights to be concatenated in the analysis to be used at larger interval inspections.

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[6] www.leapaust.com.au
[7] www.ptc.com/en/products/vuforia/vuforia-studio

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8. Copyright Statement

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