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MIXED REALITY FOR AIRCRAFT STRUCTURAL DENT AND BUCKLE NON-DESTRUCTIVE EVALUATION

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Abstract

This paper describes a Mixed Reality (MR) framework for the Non-destructive Evaluation (NDE) of aircraft structures supplementing maintainer Dent and Buckle Chart procedures. The motivation for this research lies in the question of how MR can be used to reduce labour-intensive inspections and supplement aircraft condition-based maintenance. Results demonstrate that state-of-the-art laser scanning can improve manual assessment of dent damage and processes can be automated, helping reduce inspection time and increase accuracy in locating and evaluating damage as well as reduce decision-making time in operations. This paper includes alignment with stakeholder requirements and maintenance procedures to ensure end-user acceptability of MR through verification. Additionally, verification and validation trials have been performed at an Maintenance, Repair and Overhaul (MRO) organizations for an end-to-end evaluation of the NDE framework. This adds qualitative and quantitative results enabling a comparison of the existing procedure using Dent & Buckle Charts and the proposed MR-NDE process for time, accuracy and resourcing improvements to aircraft sustainment and operations.

Keywords: Aircraft Maintenance, Dent & Buckle, Mixed Reality, Scanning, Non-Destructive Evaluation

1. Introduction

Conventional NDE approach for damage in a metallic structure subject to impact is stipulated in the procedure for aircraft Dent and Buckle Charts. The approved Structural Repair Manual (SRM) has an extensive description for assessment of dent damage and how it should be documented. This procedure can be time-consuming, labour-intensive and lack accuracy in the localisation and measurement of dent damage. In recent years, new advanced approaches to dent damage assessment for aircraft have progressed using structured light scanners with good success at a local level, e.g. 8Tree dentCheck[1]. However, their output lacks global (whole of aircraft) localisation. While localisation across the aircraft through a Digital Twin (DT) [1] concept has been explored [2], also relative to damage and proximity to stiffened structures in [3]. Such capabilities are in commercial development, however in a manual step process, for example by company AerinX[2] and dent & buckle[3], Airbus is trialling a digital approach to the SRM in the form of a mobile or tablet device application named Airbus for Mechanics [4]. This approach includes a questionnaire to documenting damage at the point of occurrence to triage and organise the maintenance organisation, however it is still a labour-intensive process.

Mixed Reality (MR) has proven to be a beneficial technology that can support implementation of aircraft proactive condition-based maintenance by more effectively delivering maintenance data to

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[1] https://www.8-tree.com/
[2] https://aerinx.com/
[3] https://www.dentandbuckle.com/

the end-user [5]. MR can supplement better comprehension of complex tasks and enhance in-situ decision-making for maintenance practitioners [6, 7]. Devices, such as Tablets (*e.g.*, Apple iPad) and Head-Mounted Displays (*e.g.*, Microsoft HoloLens II) allow interactive digital content to be augmented or overlaid onto real world objects mixing with a person's spatial environment [8, 9, 10]. MR offers a step change in NDE, an additional tool augmenting the end-user's visual maintenance practice, and digitising information for real-time remote collaboration where skilled labour is limited, while removing the paper-based approaches. This can greatly improve maintenance tasks [11, 12]. This is the reason for incorporating MR in the Dent & Buckle charts process. The capability for NDE using DT models, at an individual aircraft level [13] can be rapidly provided to the end-user with in-situ visualization of damage [14], which will help in the Dent & Buckle General Visual Inspections (GVI) processes. Furthermore, the acquired data for damage visualization happens during maintenance activities. In order to improve efficiency, laser scanning system are currently developed [15], [16]. Yet, the information on requirements on laser-scanning solutions is limited. Different studies focus on comparison of 3d laser scans for the use at aircraft structure, [17], [18]. They are limited to hand-hold solutions and focusing on accuracy and precision aspects, only. In order to approach a global and efficient inspection of an aircraft, scalability and process requirements for implementation solutions are still open.

1.1 Research Questions

The focus and application for this research is in the context of digitalisation and process improvement of the Dent and Buckle SRM procedures common to aircraft operations and sustainment programs. The framework is yet to be developed for proactive condition-based maintenance to be coupled with MR to deliver structural anomaly data to end-users. This would enable non-destructive inspections on an individual aircraft level and supplement decision support in operations [19]. This leads to the following research question to be answered:

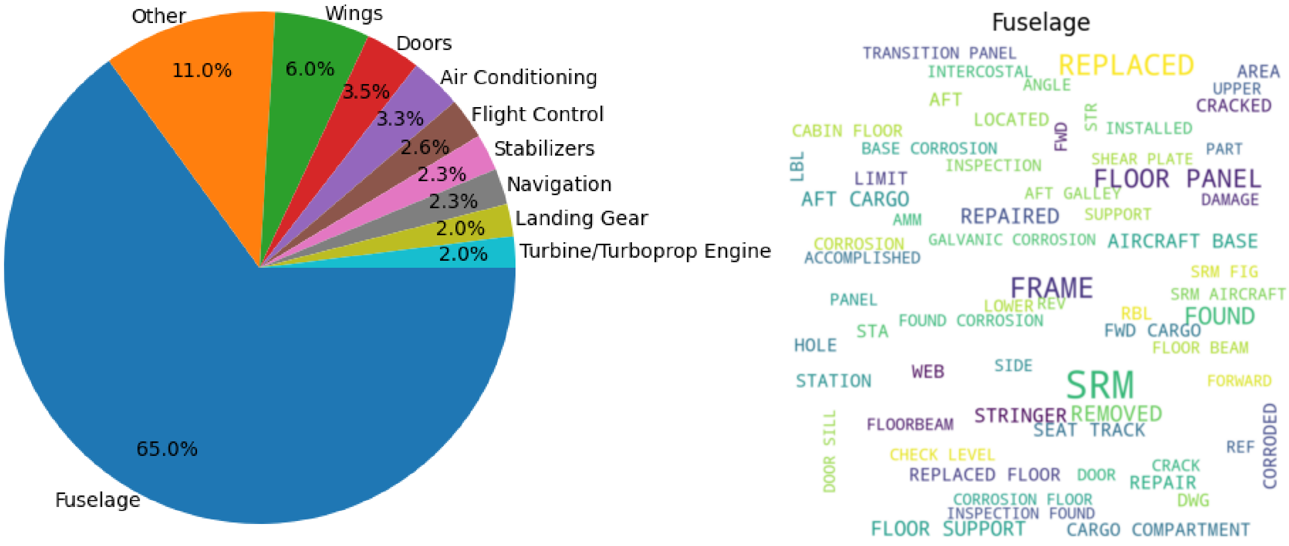
- How can aircraft data be integrated with aircraft structural integrity programs and be deployed to an end-user via Mixed Reality for non-destructive evaluation and assist in proactive condition-based maintenance?

To tackle this research question, the goal is to deliver a framework for maintainers that is capable of being used in non-destructive inspections and integrated into procedures used in structural integrity programs. This requires access to aircraft test models, DT structures (models and datasets) and maintenance technician requirements. The overall objective is to test the technological feasibility and economic sustainability of the proposed framework. The following sub-questions are supporting this analysis:

- What kind of scanning technology is suitable for the characterization of dents?
- What is a suitable MR experience for maintainers during this process?
- What are the benefits of the proposed new process?

The paper is structured in the following sequence. Firstly, the following study elaborates the relevant work, focusing on the industrial relevance for an efficient dent and buckle inspection and the needs stated by airworthiness requirements. Secondly, we propose the innovative loCalize vIsualize documeNt deNt And Buckle chARts (CINNABAR) workflow, describing the applied individual technologies such as data acquisition and visualization to support NDE diagnostics. Thirdly, the results present preliminary proof-of-concepts and the visualization applications are then tested under realistic conditions at the facilities of a commercial MRO organization. Fourthly, the discussion elaborates the strength and weakness of the developments.This paper closes with the conclusions and an outlook.

This paper is part of the CINNABAR project. It introduces the novel framework and analyses the potential, while [20] explains the development of the human-machine interface as well as the visualizations. Lastly, paper [21] prepares and analyses the industrial trial study and [22] examines the benefits for MRO business processes.



(a) (b)

Figure 1 – Based on work by [23], damages of the fuselage are the highest mentioned incidents as illustrated in Figure 1a. The impact of the SRM is indicated by the big font size which equals the overall number of occurrences, represented in the word cloud in Figure 1b.

2. Relevant Work

2.1 Motivation for Improved Dent and Buckle Inspection

First traces on relevant use-cases are derived from the analysis of the service difficulties report prepared by [23]. Aviation regulations require companies to report any operational or structural problems they encounter [24, 25]. The Federal Aviation Administration (FAA) collects these reports in a public database called Service Difficulties Report System (SDRS) [4]. This database includes the following information along with the report itself, which is in free text including the information of the location of the finding. In total, 59,656 reports about the Airbus A320 family from January 2016 to June 2023 are examined. According to 70% of the reports, the problem was found during "Inspection / Maintenance," which could range from a quick check to a major overhaul.

As shown in Figure 1, the findings are categorised according to their respective ATA-chapter. The details of the free text for the fuselage in Figure 1b is illustrated by the word cloud. The font size indicates the frequency of the mentioned word. Apparently, most incidents are mentioned on the floor panel as well as on the frame. The SRM is mentioned as it is the relevant reference for handling and repair of these damages. For the following analysis, the damage category "dent" is considered, only. It is described as follows: "A dent is a damaged area which is pushed in, with respect to its usual contour. There is no cross-sectional area change in the material, area edges are smooth." .

In order to enable new measuring technology and improve their operational efficiency, current inspection tasks are considered and are questioned. The associated inspection tasks [26] for the described use-case in Section 4.of an A320 are covered by the Maintenance Planning Document (MPD) tasks 532165-01-3 for fuselage at frame 24 through frame 35. The inspection frequency must not exceed 4300 flight cycles or 8600 flight hours. The duration of the inspection tasks is estimated to be 2.16 h [27].

This includes the scheduled maintenance, but excludes the unscheduled maintenance which considers the non-routine arising, inspection by demand due to wear, atypical usage, foreign object debris (FOD) or other natural weather events *e.g.*, hailing. As theses occur unpredictably and to overcome time constraints, an efficient inspection is desired.

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[4] https://sdrs.faa.gov/ accessed on 25/10/2023

3. Materials and Methods

The project name CINNABAR is derived from the concept of localising, visualising and documenting dent and buckle chart. In this research a dent is characterised as a damaged area, where the nominal surface area or contour is pushed inwards, to the extent that there is no cross-sectional area change in the material and area edges are smooth. In Section 3.1 the state-of-the art dent and buckle inspection process is explained as well its improvement by the CINNABAR work frame. Different scanning technologies are compared in Section 3.2 In Section 3.3 the mixed reality software and hardware used are explained, as well as a more in-depth description of the development of the MR-NDE process and underlying workflow.

3.1 CINNABAR Workflow

The framework steps are summarised in the flow chart shown in Figure 2, illustrating how digitalisation and MR supplement the preliminary assessment of damage to the point where a maintainer makes a decision based on the scans. The process is started either by a scheduled event such as an MPD task or by an unscheduled event, *e.g.*, due to an undesired impact by Ground Support Equipment (GSE). A Pilot Report (PIREP) or a Maintenance Report (MAREP) starts the documentation process and triggers an evaluation of the found damage.

Three different damages categories exist - permanent (Repair Cat A), permanent allowable damage with operating limits (Repair Cat B), temporary allowable damage (Repair Cat C). SRM first classifies a dent by its dimensional characteristics, namely length, width (W) and depth (D). Apart from other properties, like the type of material and the position with respect to certain aircraft parts or other dents, the measures of width and width/depth (W/D) ratio are the only dimensional ones used to classify the damage as allowable, also referred to as Allowable Damage Limits (ADL) or not allowable, the latter meaning that a repair is needed, immediately or within a certain number of cycles (if some conditions are met). This information is then reported in the dent and buckle chart. Often a representation of the damage is sent to the aircraft manufacturer, who provides detailed instructions about how to conduct the repair [28, 29].

In order to accelerate the process, we propose a scanning technology which performs a detailed 3D scan, followed by a localisation of the damage and finally, assessment of the damage. The decision on how to proceed is based on the current, Standard Operating Procedure (SOP) classification . In order to clarify the decision processes, we propose a mixed reality category which represent a new step towards mixed reality and differentiates from existing decision processes. With the completion of maintenance tasks, a Certificate Return to Service (CRS) is issued.

3.2 Detailed 3D Scan

The CINNABAR proof-of-concept was developed in a laboratory environment utilising a static Boeing B737 left wing section cut-out, a controlled setting for results verification and validation purposes [11, 30, 31, 32], Figure 3 illustrates the relevant results. Scans were performed of the entire structure, before a dent was created in the surface and again scanned to produce the dataset for analysis. In order to create a dent for evaluation a form of drop testing [30, 31] was performed on a static representative aircraft wing structure, consisting of 4-6 mm thick painted aluminium alloy with stiffened regions, as opposed to a Bare Metal Inspection (BMI) . It should be noted that the procedure for creation of dents is outside of the scope of this paper and the inclusion is for the readers context only, while the authors are more focused on the assessment of damage that has occurred, which can include tool drops, bird-strike, foreign object debris FOD, adverse weather, etc. [32].

Various 3D scanners were used during the project, the different methods and advantages of which are described here. Terrestrial laser scanners are suitable for rapid recording of large objects or areas, such as an entire aircraft fuselage. These are usually operated on a tripod and capture the entire space around the scanner in a 360° panoramic image in just a few minutes, whereby the image is only limited by the device itself. The distance between the laser scanner itself and the surface of the

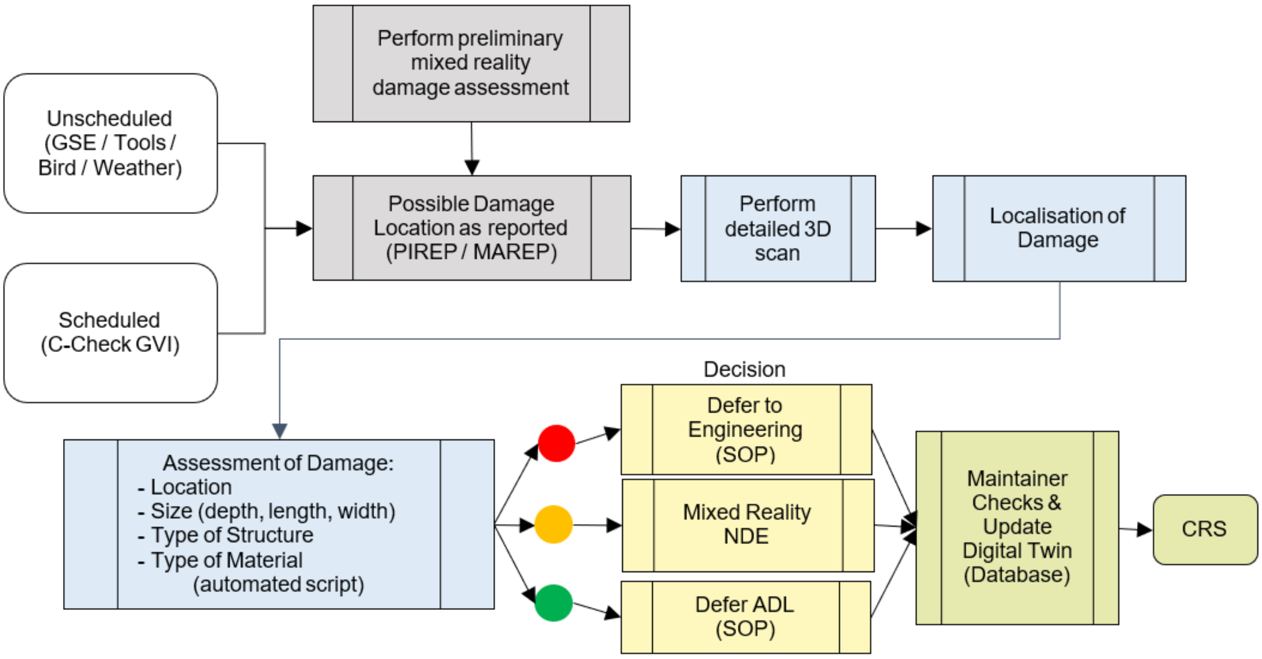
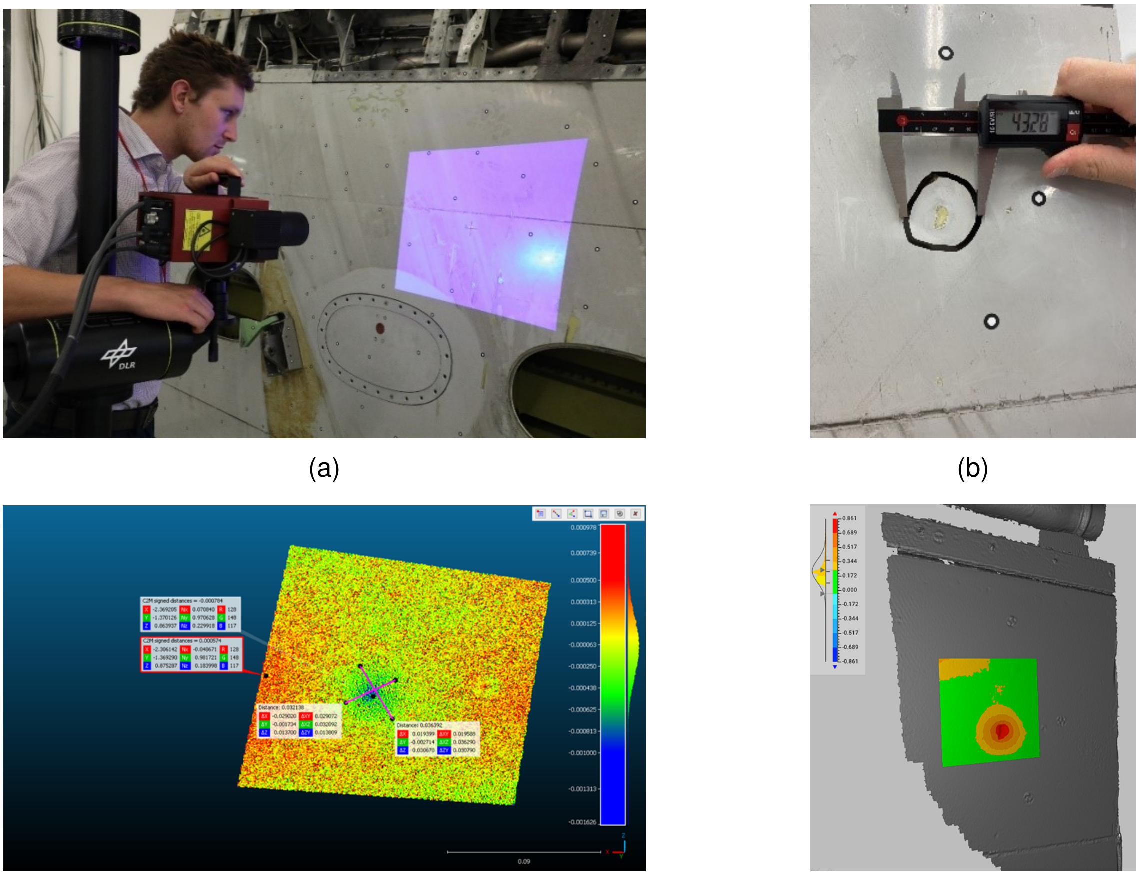


Figure 2 – CINNABAR Workflow

measurement object is determined using a time-of-flight method [33]. In order to capture the measurement objects in their entirety, the scanner must be moved with its tripod around the object. For this project, the RTC360 from Leica Geosystems is used, as shown in Figure 5 (c). This system uses a visual inertial system to register the recordings of the individual positions, which enables real-time tracking of the scanner movements between the recording positions. By using color sensors, RGB color texture values can be added to the individual measurement points [34]. The result is a 3D point cloud that represents the object in the digital space. The accuracy of this system is limited, among other things, by the diameter of the laser beam and is specified by the manufacturer for the RTC360 as 1.9 mm for the RTC360 at a measuring distance of 10 m [34].

One 3D scanning method that offers greater accuracy is the structured-light method. Such a sensor consists of a projector and one or two cameras. The projector projects a pattern, often a striped pattern, onto the surface of the object to be measured. The pattern is distorted by the curvature of the surface. This distorted pattern is detected by the camera sensors and the distance between the sensor and the surface is determined using triangulation in order to reproduce the three-dimensional shape. This method is characterized by its high resolution and high accuracy [35]. However, it can be very time-consuming for large measurement objects. This method can be used with various systems. In addition to smaller, hand-held systems, there are also larger systems that are operated on tripods. For the evaluation of the dents in this project, the Artec EVA from Artec 3D [36] and the Artec Space Spider [37] as a hand-held scanner and an ATOS Compact Scan from Carl Zeiss GOM Metrology GmbH [38] as a larger system are used, which is shown in Figure 3. Both devices record a measuring field defined by the systems with a single image and must be moved for larger surfaces to be recorded. As already mentioned, this method has a higher accuracy, although this is slightly lower for hand-held systems. According to the manufacturer, the accuracy for the Artec Eva system and the Artec Space Spider are up to 0.1 mm and for the ATOS Compact Scan System up to 0.01 mm, which provides a significantly better digital image of the dents on the aircraft. The results are triangulated surface meshes where the original object is described by a finite number of surface points, which are connected by lines to form triangular surfaces.



(a)

(b)

(c)

(d)

Figure 3 – New impact damage on Boeing B737 Wing Section; (a) showing structure light scanning process with reference points on structure and blue light indicating capture area; (b) Dent manually measured using vernier calliper; (c) CloudCompare assessment of dent; (d) Artec Studio 17 Professional dent assessment

3.3 Mixed Reality Damage Assessment

Detailed description in terms of software development of the Augmented Reality (AR) application are analyzed in [20]. The MR application experience guides the end-user through the dent damage assessment process. The dent is measured by intuitively drawing a virtual outline along the shape boundaries using end-users preferred index finger (see Figure 4 (a)). The created shape provides information about the dent dimensions in terms of length and width. As depicted in Figure 4 (b), distances to relevant regions of the structure are calculated, from the dent to the two nearest stiffened parts, either a stringer, rib or frame. With sufficient alignment of the real aircraft with its DT, the position can be calculated and stored. Known dents must be relocated for monitoring purposes and thus a DT can help in the dent searching and the distinguishing process. The preliminary MR damage assessment is performed by combining localisation and measurement procedures. The combination of both position and shape helps in identifying the allowable limits. With the knowledge of the dent limits, the application can support end-users in decision-making. The image can be enriched with meta data, such as dent location and size. In an “offline” inspection process, the created report can be checked and the dent can be evaluated with high precision scanners to create a detailed 3D scan see Figure 4 (c). If end-users find new dents or identify changes in known dents, they can take a picture of the current aircraft section to create a report of the currently inspected dent and its virtually attached drawings Figure 4 (d). Data verification and decision-making can be supported with virtual interaction techniques to reflect decision results back to the DTs database. The functionality to touch and draw virtual shapes on a real surface.

4. Results

4.1 Scanning Technology - Laboratory Results

As shown in Table 1, the preliminary results for the different technologies are compared for the same dent as shown in Figure 3.

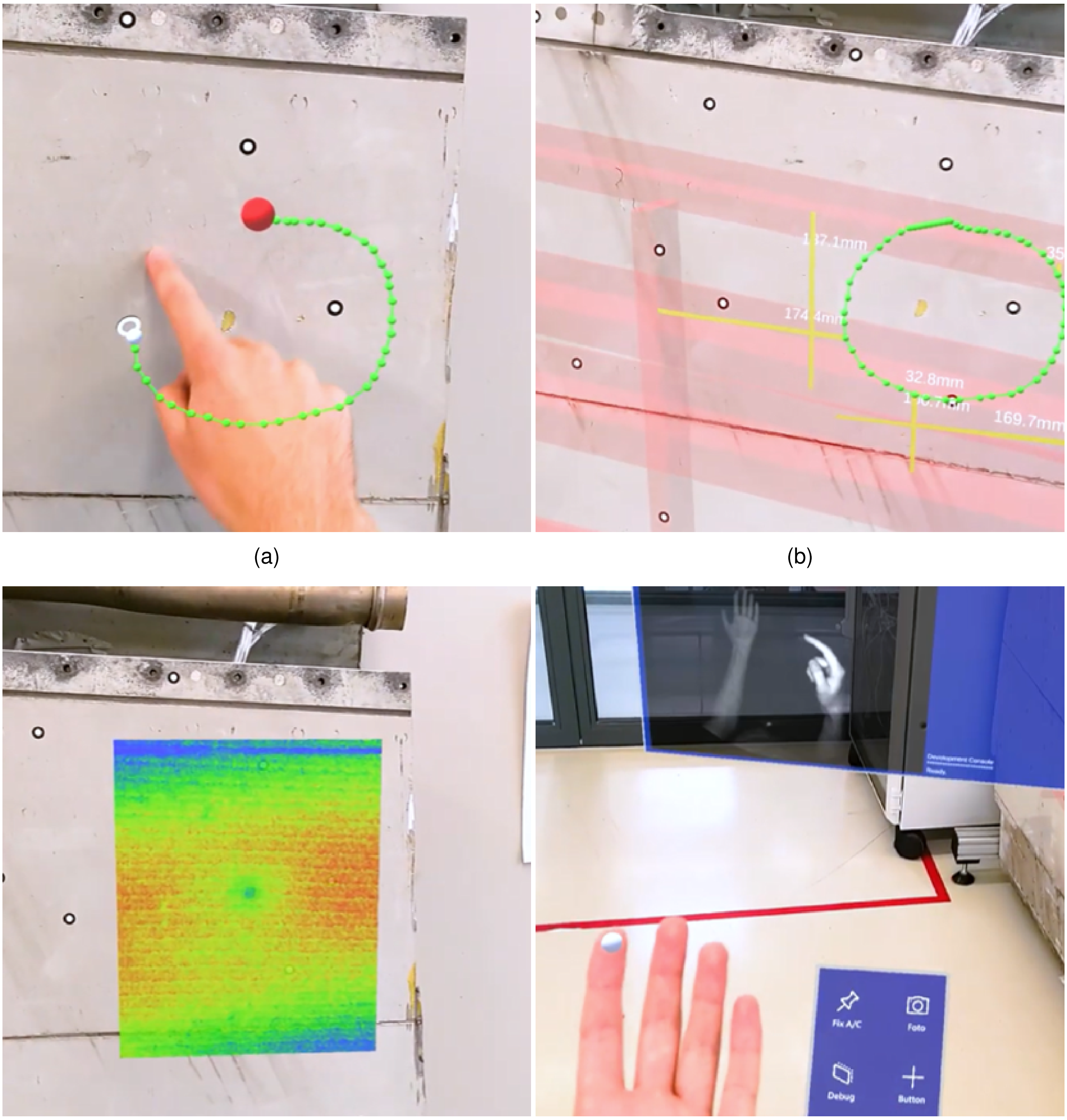
Table 1 – Comparison of technology application for Dent and Buckle Assessment: For fast localization and independent and asynchronous measurement only

Technology	**Measurements** (N=3)				**Time**	**Accuracy**	**Resources**
Type	Length (mm)	Width (mm)	Depth (mm)	W/D	(qualitative)	(qualitative)	(qualitative)
0. Manual	39.37	33.93	1.03	34	Control	Variable	Moderate
1. Hand-held Scanner	38.41	34.65	1.10	32	Fast	Moderate	Moderate
2. Laser Scanner	36.39	32.14	1.36	24	Fast	High	Moderate
3. Fixed-Structured Light Scanner	51.65	44.94	1.66	27	Slow	High	High
4. HoloLens	169.7	137.1	N/A	N/A	Fast	Low	Low

4.2 Scanning Technology - Airbus A320 Case Study

After the first feasibility studies inside the lab, the next objective is to test the developed equipment under realistic conditions. The CINNABAR proof-of-concept framework was verified on the Airbus A320 D-Advanced Technology Research Aircraft (ATRA) at DLR Braunschweig, Germany performing a laser 3D scan of a known dent. According to the existing Dent and Buckle chart the dent is approximately located forward left fuselage at stringer 24-25 between frame 27-28, with parameters length 40, width 30 and depth 0.4 mm. As shown in Figure 5, there is significant variance among measurements and approaches, anecdotally supported by maintainers onsite. The results can be found in Table 2.

Three scanning techniques were employed: two hand-held lasers (Artec Eva and Artec Space Spider) as well as the the Leica RTC360 laser scanner. The laser scanner utilized a 3 mm grid resolution and automated point alignment, requiring 12 scans for full aircraft coverage. The hand-held lasers scanners are focused only on the spot of interest. For better performance foils are placed next to the dent to enhance scanning area without losing tracking. Post-processing involved creating distance maps and analyzing dent dimensions.



(a) (b)

(c) (d)

Figure 4 – Interactive Hololens application for documentation of the found dent; (a) Outlining the contour of the dent; (b) Display of calculated instances to critical structures; (c) Displaying results of 3D Scanner; (d) Photography menu

Table 2 – Results of Damage Assessment at ATRA

Technology	**Measurements** (N=3)			
Type	Length (mm)	Width (mm)	Depth (mm)	W/D
0. Manual D&B Chart	40	30	0.4	75.00
1. Hand-held Scanner (Artec EVA)	34.33	41.33	0.4	103.33
2. Hand-held Scanner (Spider)	37	46	0.35	131.43
3. Terrestial Laser Scanner	31	20	0.15	133.33

4.3 Mixed Reality User Study Results for Damage Assessment at MRO Organization

For the validation of the visualization and human-machine interface with the mixed reality application, an initial validation is conducted at an MRO Organization in Germany. Here multiple industrial qualified aircraft maintainers are presented with the MR applications and motivated to test this on a mobile fuselage panel of an Airbus A330-330 stringer 13-17 Frame C57-C59. Due to industrial constraints, the number of trial participants (N=3) is limited, however due to their professional experience and their work routine in an industrial environment, their feedback is rated as highly qualified.

First of all, the most experienced participant was instructed to inspect and measure the dent as shown in Figure 6. Table 3 lists the results in terms of the direct comparison between the manual and assisted damage assessment of a mobile fuselage panel and presented at the Hangar of an MRO Organization.

Table 3 – Results of User Study: Damage Assessment

Technology	**Measurements**				**Time**
	Length (mm)	Width (mm)	Depth (mm)	W/D	[mm:ss]
Manual	70	60	1.8	33.33	12:59
HoloLens	74	55.5	N/A	N/A	3:59

In the following semi-structured interviews, the participants were encouraged to familiarize themselves with the application as well as describing their observation while operating with the Hololens at the fuselage panel. The technology assessment for the MR application is detailed in [20] and [21]. Both works stress the requirements regarding the reliability and validity. Furthermore, following aspects are analysed : Integration into current workflow, consideration of resources (time and costs), and as human factors and environmental aspects (*e.g.*, wearable device or free hand interaction). In addition, system requirements in terms of finding dents, measuring, and user-interface design (*e.g.*, information input) and its visualizations are identified as requirements and described. In terms of process improvement, localization and navigation are defined. In terms of the design of the digital twin, connectivity is required. Significant key observations are listed in Table 4.

5. Discussion

5.1 Discussion on 3D Scan Technology

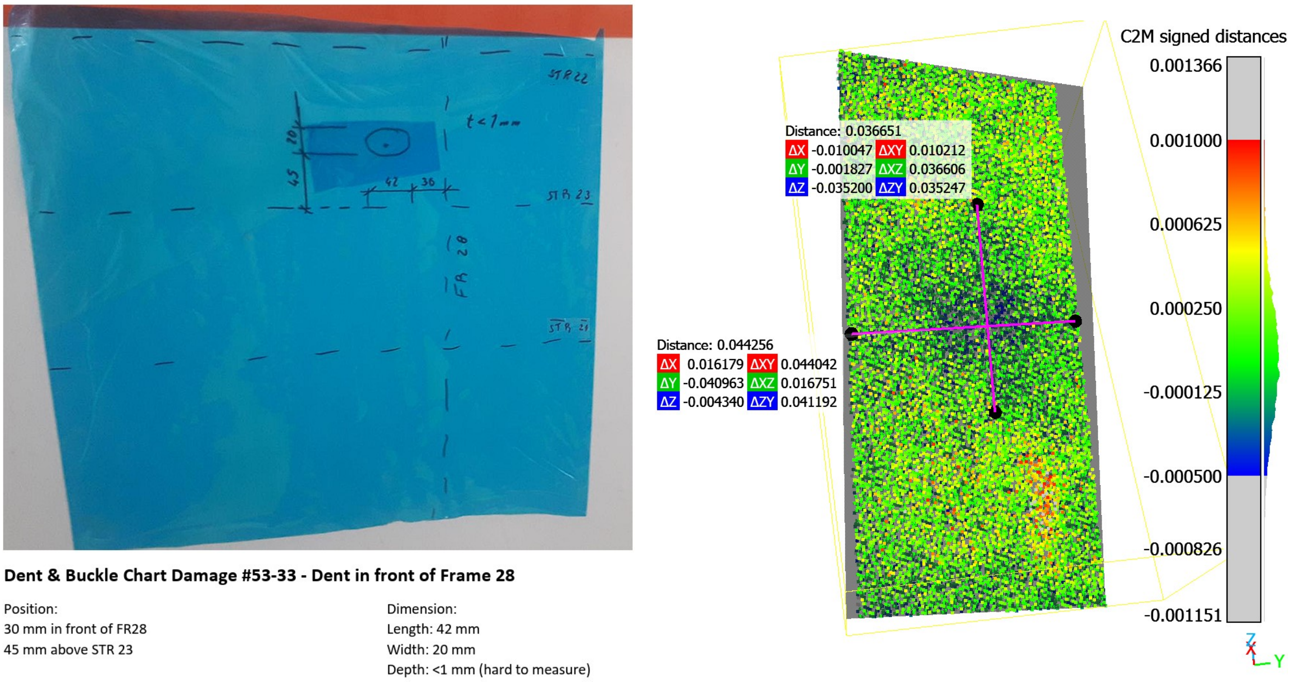
The different technologies applied here have respective advantages and disadvantages, which will be discussed in this section and a preferred technology discussed for the CINNABAR framework. This study trialled different approaches to the assessment of dents in both representative and actual aircraft structures, providing a suitable basis for a qualitative comparison within the context of dent assessments and as such have the following qualities in Table 5.

The reported solution is in the dimensions of centimeters, which matches reports like [39].The requirement put by Airbus as relevant is higher by definition in millimeters. Either an improved localisation technology is required which asks for higher preparation and installation time. This is considered unacceptable for MRO processes.

Laser scanning provided fine measurements but encountered visibility issues, failing to cover all parts during scans. Hand-held scanning, with its foil technique, improved scanned area coverage. However, post-processed models did not detect dents, necessitating adjustments in foil application

(a) Airbus A320 D-ATRA in Hangar at DLR Braunschweig being scanned by Laser scanner imaging.

(b) Dent 30 mm in front of Frame 28 and 45 mm above Stringer 23 on D-ATRA



Dent & Buckle Chart Damage #53-33 - Dent in front of Frame 28

Position:
30 mm in front of FR28
45 mm above STR 23

Dimension:
Length: 42 mm
Width: 20 mm
Depth: <1 mm (hard to measure)

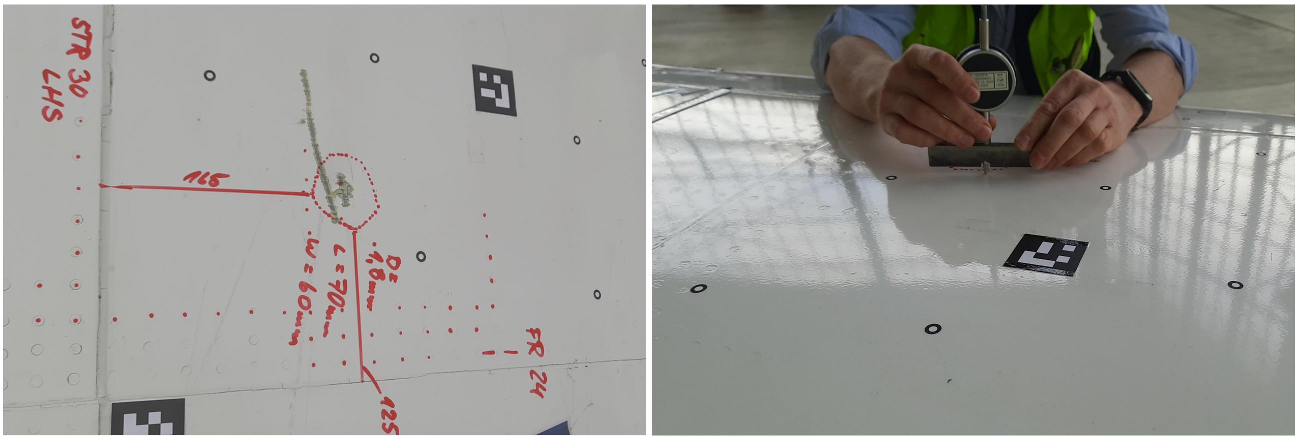
(c) Manual dent assessment procedure

(d) Analysis of point cloud scan using open source CloudCompare 3D point cloud and mesh processing software.

Figure 5 – Damage scanning and assessment at D-ATRA

Table 4 – Table: Key observations of user study interviews at MRO Organizations

I. Technology Assessment	
Strength	· Interactive usability with documentary such as SRM is helpful for evaluating the damage assessment. · Global Localisation is rated as very beneficial feature. · Automated dent assessment is appreciated as well as link to critical structures.
Weakness	· Low resolution of the Hololens is criticized and described as "too coarse".
II. Process Assessment	
Strength	· Crew members having access to a detailed DB (database) chart can aid in understanding aircraft status and maintenance requirements. · Hololens application can guide the maintainer through assessment procedure and an extended version may enhance decision based on history data establishing and decision making rules.
Weakness	· Existing flow chart of SRM is reported to be "fault prone" due to its visualization and lacking additional information. · Additional mental work load due to anticipated consequence of a false decision. · Complains about the cumbersome interactions with the SRM pdf files for the different sections of the aircraft.
III. Inspection and Diagnosis	
Strength	· Growing interest in automated dent localization to streamline repair processes, allowing maintenance crews to focus their efforts efficiently. · Scanning algorithm could give solution to assessment of rounded structures such as wing edges, where traditional inspection methods may prove inadequate. · Invisible tracing of dents, in particular for airlines that prepare sticker-free solution.
Weaknesses	· MRO organization uses small stickers which mark detected dents. This visual mark eases the process as it informs involved personnel about a known existence of a dent. However, this simple state-of-the-art technical solution may lead to a cluttered vision.
IV. Data Governance and Digital Twin	
Strength	· State-of-the-art technology offers a solution for rapid dent assessment but it fails to interconnect these to further meta-models or other resources automatically.
Weakness	· Addressing dent repairs, there is a need for systems to accurately track and manage damage information, ensuring that data on dents remains in the system even after panel replacement. · There is a noted concern about the inflexibility in data requests at the central hub, highlighting the need for more adaptable processes to cater to specific operational needs. · Ensuring flexible accessibility of data across various platforms and devices is crucial for effective decision-making and adaptable operational efficiency.



(a) Inspected dent and scratch on fuselage panel close to STR 30 and Frame 24. The outline of the dent is indicated with a dotted circle.

(b) Manual measurement of depth: The measurement assessment takes around four times longer than an digitized measurement by means of a Hololens, yet it misses the depth measurement.

Figure 6 – Trial study for AR application on Airbus A330 panel section with industrial maintainers

Table 5 – Evaluation of different Scanning Technologies

1. Hand-held structured light scanner	
Pros	· Portable hand-held structured light scanner (approx. half of a millimetre) · Fast scanning at a local level
Cons	· Lacks precision for global model creation and has a small capture volume · Requires processing to remove noise and produce suitable mesh for comparison
2. Terrestrial laser scanning	
Pros	· Rapid scans (several minutes) and easy to operate (approx. half of a millimetre) · Portable pieces of equipment · No preparation of object needed and tolerant to minor movements
Cons	· Lower resolution (*e.g.*, depth of damage) is difficult to capture · No current process to characterise damage · Captures point cloud requiring additional processing step for contour comparison
3. Fixed structured light scanner	
Pros	· High resolution (approx. tenth of a millimetre) · Reliable outputs · supports damage characterisation (*e.g.*, depth) based on contour reconstruction
Cons	· Labour intensive – calibration (often several times) · Lengthy preparation (*e.g.*, placement of marker references) and processing · Bulky equipment, requiring ideal conditions (*e.g.*, no movement)
4. Microsoft HoloLens 2	
Pros	· Ease of use · All-in-One System · Hands-free
Cons	· Resolution inadequate (max. $\sim$10mm accuracy) · Requires reference to aircraft for (self-) localization

and post processing parameters. Lessons learned highlighted the importance of reference structures and careful post-processing parameter selection.

5.2 Discussion on Challenges and Potentials of CINNABAR Workflow

Digitization of processes are realised in increments. Their priority and order is open to discussion, depending on the constraints of the technology, but similarly limiting the performance requirements of the operated technology. The discussion delves into the fusion of advanced technology and investigates the impact at a top level. Specifically, exploring the integration of interactive usability with resources like the SRM, aiming to optimize damage assessment procedures. Additionally, examination of the role of localization tools in this context. It must be stressed that due to limited resources, the results represent a trend. The major findings are listed in the following Potentials & Challenges (P&C):

- **P&C I - Global Localization of Dent:** Accurately locating and assessing the extent of dents or buckles is crucial. The difficulty often lies in the complex geometries and inaccessible areas of structures. Traditional methods might not provide the necessary precision or may be too time-consuming. Advances in sensor technologies and imaging techniques, such as ultrasonic testing or 3D scanning, offer the potential to improve localization accuracy and speed, providing more detailed information about the damage.
- **P&C II - Documentation of Processes:** Maintaining thorough documentation is essential for compliance and quality control but can be labor-intensive and prone to human error. Digital tools and software solutions can streamline this process, enabling automatic data capture and storage. This not only improves efficiency but also enhances the traceability and repeatability of inspections.
- **P&C III - Mixed Reality Decision-Making Support due to Input from SRM**: Decisions regarding whether to repair a dent or buckle depend heavily on guidelines from the SRM, which can sometimes be ambiguous or not directly applicable to every situation. Integrating artificial intelligence with decision-making processes can aid in interpreting SRM guidelines more effectively and suggest optimal repair actions based on historical data and predictive models. A use-case study comparing AR and electronic document-based maintenance instructions considering tasks complexity and operator competency level [40]. A systematic literature review on operated-centred needs of AR-assisted maintenance is explored in [41].
- **P&C IV - Communication Between Different Stakeholders**: Effective communication between engineers, technicians, quality control, and other stakeholders is critical but often complicated by differing priorities and technical languages. Collaboration platforms and project management tools can facilitate better communication, ensuring that all parties are updated and can access relevant data in real-time. Furthermore, the need to enable a standardized wording over various stakeholders with different cultural and career background would enable a smooth process.
- **P&C V - Impact of Previous Repairs on Decision Making**: Previous repairs can significantly influence the decision-making process for new damages. Lack of information about past repairs can lead to sub-optimal or unsafe decisions. Using DTs and maintaining comprehensive digital records of all repairs could provide a complete historical context. This allows for safer and more informed decisions based on the cumulative history of the structure.
- **P&C VI - Availability of Information**: Often, the necessary information for making informed decisions is incomplete or unavailable, which can delay the inspection process and potentially compromise safety. Implementing a centralized database for storing all relevant information and employing advanced data analytics can ensure that necessary data is readily available and actionable.

In summary, while the inspection of dents and buckles presents various technical and operational challenges, leveraging modern technology and data management practices offers significant potential to enhance the efficiency, accuracy, and safety of these processes. These advancements can lead to better outcomes in terms of structural integrity and lifespan, ultimately contributing to cost savings and improved operational readiness.

6. Conclusions

A novel framework has been demonstrated for supplementing dent and buckle chart inspection procedures on aircraft by maintainers, through the development of MR-NDE process utilising rapid laser scanning techniques and digital measurements. Furthermore, this research compares scanning techniques for quality and practical use in operation. The study included a use case on a static Boeing B737 wing section cut-out and in-service Airbus A320. Results show that the laser scanning process can be performed within minutes assessing approximately a $5-10m^2$ surface with millimeter accuracy for locating damage and assessing the length, width and depth consistently.

Further verification and validation of the framework was performed on an Airbus A330 section at an industrial MRO organization, with qualified maintainers. A total of three maintainers provided end-user feedback on the MR damage assessment framework. The maintainers approved the assistance in documentation and time savings, however criticized the low resolution and lack of decision-making support of the mixed reality damage assessment. The MR damage assessment showed potential to reduce process time by a factor of four in comparison to current SRM procedures. Future research aims towards improvement of scanning algorithm and automated dent inspections.

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9. Copyright Statement

References

[1] Hendrik Meyer, Ann-Katrin Koschlik, and Florian Raddatz. Digital twin concept for aircraft components. In *Proceedings 33rd Congress of the International Council (ICAS)*. Stockholm, 2022.

[2] Michael J Scott, Stephan Koschel, Wim Verhagen, Oleg Levinski, and Pier Marzocca. Augmented Reality for Aircraft Fatigue Non-destructive Evaluation. In *Proceedings 33rd Congress of the International Council of the Aeronautical Sciences (ICAS 2022)*, page 18, Stockholm, Sweden, September 2022.

[3] G.O.C. Prado, P.A. Silva, F.M. Simomura, and K.L.O. Pereira. Shm with augmented reality for aircraft maintenance. In *31st Congress of the International Council of the Aeronautical Sciences (ICAS)*, 2018. Accessed: 2024-06-10.

[4] Airbus. Srm damage assessment. `https://aircraft.airbus.com/en/newsroom/news/2021-05-srm-damage-assessment`, May 2021. Accessed: 2024-06-10.

[5] The International Air Transport Association (IATA). From aircraft health monitoring to aircraft health management: White paper on AHM. Nov 2023.

[6] Henrik Eschen, Tobias Kötter, Rebecca Rodeck, Martin Harnisch, and Thorsten Schüppstuhl. Augmented and virtual reality for inspection and maintenance processes in the aviation industry. *Procedia Manufacturing*, 19:156–163, 2018.

[7] Ildikó Horváth. An analysis of personalized learning opportunities in 3d vr. *Frontiers in Computer Science*, 3, 2021.

[8] Ronald T. Azuma. A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, 6(4):355–385, 1997.

[9] Julie Carmigniani, Borko Furht, Marco Anisetti, Paolo Ceravolo, Ernesto Damiani, and Misa Ivkovic. Augmented reality technologies, systems and applications. *Multimedia Tools and Applications*, 51(1):341–377, 2011.

[10] Julie Carmigniani and Borko Furht. Augmented reality: An overview. In Borko Furht, editor, *Handbook of Augmented Reality*, pages 3–46. Springer, New York, NY, 2011.

[11] Sebastian Utzig, Robert Kaps, Syed Muhammad Azeem, and Andreas Gerndt. Augmented reality for remote collaboration in aircraft maintenance tasks. In IEEE, editor, *2019 IEEE Aerospace Conference*, pages 1–10. Big Sky, MT, USA, 2019.

[12] Wim J. C. Verhagen and Richard Curran. An ontology-based approach for aircraft maintenance task support. In *20th ISPE International Conference on Concurrent Engineering*, pages 494–506.

[13] Oleg Levinski, David Conser, Carl Mouser, Stephan Koschel, Robert Carrese, Michael Candon, and Pier Marzocca. An innovative high-fidelity approach to individual aircraft tracking. In *AIAA Scitech 2020 Forum*. American Institute of Aeronautics and Astronautics, 2020.

[14] Guest blog: How rmit university uses augmented reality & digital twin technology for nextgen aircraft sustainment \textbar product design software, 2021.

[15] MRO Business Today. Changing dynamics of aircraft inspection technology: Mro innovation of the month.

[16] 8Tree. Press release -avinxt integrates dentcheck® in automated robotics system. 8tree extends its automation inspection portfolio by partnering with avinxt for robotic aviation inspection system. 2023-11.

[17] Irina Bodrova. Model of decision support system with artificial intelligence for aircraft fuselage damage assessment. In Igor Kabashkin, Irina Yatskiv, and Olegas Prentkovskis, editors, *Reliability and Statistics in Transportation and Communication*, Lecture Notes in Networks and Systems, pages 37–49, Cham, 2023. Springer International Publishing and Imprint Springer.

[18] Pierre-Hugues Allard, Fraser, Jean-Simon, Fraser, Jean-Simon, and Jérôme-Alexandre Lavoie. Improvement of aircraft mechanical damage inspection with advanced 3d imaging technology.

[19] Michael J. Scott, Wim J. C. Verhagen, Marie T. Bieber, and Pier Marzocca. A systematic literature review of predictive maintenance for defence fixed-wing aircraft sustainment and operations. *Sensors (Basel, Switzerland)*, 22(18), 2022.

[20] Thore Keser, Rahel Schmied-Kowarzik, Ann-Kathrin Koschlik, Michael J. Scott, Rebecca Rodeck, and Wende. Cinnabar project: Augmented reality workflow for aircraft dent & buckle inspection. *34th Congress of the International Council of the Aeronautical Sciences, 2024*.

[21] Rahel Schmied-Kowarzik, Thore Keser, Lina Kaschub, Ann-Kathrin Koschlik, Rebecca Rodeck, and Gerko Wende. Cinnabar project: Examining requirements for user acceptance of aircraft structure inspection in augmented reality. *34th Congress of the International Council of the Aeronautical Sciences*, 2024.

[22] Johanna Aigner, Ann-Kathrin Koschlik, Hendrik Meyer, Florian Raddatz, and Gerko Wende. Cinnabar project : Cost-benefit analysis of digital processes for non-destructive inspections of aircraft structures.

34th Congress of the International Council of the Aeronautical Sciences, 2024.

[23] Emy Arts, Hendrik Meyer, Florian Raddatz, and Gerko Wende. [poster] identifying maintenance, repair and overhaul events based on ads-b data. *Journal of Open Aviation Science*, 1(2), 2023.

[24] Department of Transportation Federal Aviation Administration. Code of Federal Regulations. Code of federal regulations - title 14.

[25] European Union Aviation Safety Agency. Commission implementing regulation (eu) 2015/1018.

[26] Airbus. 53-21-00-210-802-a - general visual inspection of fuselage external surface, from stringer 23 lh/rh to crown centerline, except areas covered by belly fairing.

[27] Airbus, editor. *A320 MAINTENANCE PLANNING DOCUMENT: REVISION: 43 DATE: MAR 31/17*. 2017.

[28] Srm 51-11-11 - description - description - allowable damage (002).

[29] Pasquale Lafiosca, Ip-Shing Fan, and Nicolas P. Avdelidis. Aircraft skin inspections: Towards a new model for dent evaluation. *Insight - Non-Destructive Testing and Condition Monitoring*, 65(7):378–383, 2023.

[30] R. C. Rice, J. L. Jackson, J. Bakuckas, and S. Thompson. Metallic materials properties development and standardization (mmpds), 2003.

[31] D20 Committee. Test methods for determining the izod pendulum impact resistance of plastics.

[32] Ulf Paul Breuer. *Commercial Aircraft Composite Technology*. Springer International Publishing, Cham, 2016.

[33] George Vosselman and Hans-Gerd Maas, editors. *Airborne and terrestrial laser scanning*. Whittles Publishing and CRC Press, Dunbeath, Caithness and Boca Raton, 2010.

[34] leica Geosystems. Leica rtc360 3d laser scanner -leica geosystems.

[35] Hamid Laga, Hedi Tabia, Mohammed Bennamoun, R. B. Fisher, and Yulan Guo. *3D shape analysis: Fundamentals, theory, and applications*. Wiley, Hoboken, NJ, 2019.

[36] Artec 3D. 3d-objektscanner artec eva | der beste strukturlichtscanner, accessed on 24.05.2024.

[37] Artec 3D. Industrial 3d scanner space spider 3d: scanning in high resolution, accessed on 24.05.2024.

[38] Carl Zeiss GOM Metrology GmbH. Atos compact scan: Precise 3d scanner | flexibility, mobility.

[39] Florian Kern, Thore Keser, Florian Niebling, and Marc Erich Latoschik. Using hand tracking and voice commands to physically align virtual surfaces in ar for handwriting and sketching with hololens 2. In Yuichi Itoh, Kazuki Takashima, Parinya Punpongsanon, Misha Sra, Kazuyuki Fujita, Shigeo Yoshida, and Tham Piumsomboon, editors, *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*, pages 1–3, New York, NY, USA, 2021. ACM.

[40] Vincent Havard, David Baudry, Benoit Jeanne, Anne Louis, and Xavier Savatier. A use case study comparing augmented reality (ar) and electronic document-based maintenance instructions considering tasks complexity and operator competency level. *Virtual Reality*, 25(4):999–1014, 2021.

[41] Joel Murithi Runji, Yun-Ju Lee, and Chih-Hsing Chu. Systematic literature review on augmented reality-based maintenance applications in manufacturing centered on operator needs. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 10(2):567–585, 2023.