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Digital Twins for Aircraft Structural Inspections: Enhancing Dent Detection

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Abstract

This paper investigates the development of Dent and Buckle Digital Twins (D&B DT) for aircraft structures aimed at enhancing the accuracy and efficiency of damage inspections. By utilising 2D and 3D data sources from different scanning technologies, detailed digital models of aircraft structures are generated for damage assessment. Key features in this methodology include the development of dent detection algorithms, localisation, and assessment of dents as well as the generation of D&B DTs. Integrating computer vision techniques enables automatic highlighting of dents and missing rivets, narrowing down the region of interest. Commercial-Off-The-Shelf (COTS) software offers a proprietary algorithm for the damage characterisation that works with proprietary 3D structured light scanners. This study addresses this constraint by proposing a solution using open-source software for dent detection and to use more efficient, less labour-intensive scanning outputs. The Digital Twin (DT) functions as a digital representative and its capacity for multi-source data fusion overcomes the deficiencies of single technology analysis. A necessity for this is the identification of metadata for the DT assembly. The presented case study includes a detailed parameter extraction, automated dent highlighting, and DT generation for an aircraft wing structure with impact damage.

Keywords: 3D scanning, Aircraft inspections, Computer vision, Dents, Point clouds, Dent & Buckle, Digital Twin, multi-source data integration

Introduction

The structural integrity of aircraft must be guaranteed, and it must be re-evaluated after damage events. The Structural Repair Manual (SRM) provided by the Original Equipment Manufacturer (OEM) gives clear instructions for damage assessment and repair processes. The required maintenance inspection tasks include a manual visual inspection of the aircraft hull for dent and buckle (D&B). Relevant parameters of the damage characterisation are geometric parameters such as width (W), length (L) and depth (D) of the damage. To assess this damage, additional parameters are required such as the approximate global localisation in reference to the overall aircraft structure e.g., stringer and frame numbers. Motivated by the need to reduce manual labour involved in visual inspections, non-destructive testing (NDT) approaches, such as 3D scanning, can enable efficient alternatives. Research on different 3D scanning devices for dent inspection was developed and tested with the first prototype in project CINNABAR [1]. This involved a comparison of hand-held devices as well as terrestrial and laser scanners. As a general result, a trade-off between accuracy, process performance e.g., scanning time and portability are identified. Yet, none of the selected technologies were able to fulfil these criteria sufficiently. To exploit its full potential of an automated workflow, current trends from computer vision offer promising techniques. The required features are separated into damage detection, damage localisation, and damage assessment. In a collaboration between the German Aerospace Center (DLR), the Royal Melbourne Institute of Technology (RMIT) University and the University of Naples Federico II, the following research question shall be answered: *How can automated algorithms be developed to detect small impact damage e.g., D&B on aircraft structures from scanning data?* The first objective of this research is to enhance automation in aircraft structural inspections by developing and implementing advanced systems to streamline repetitive tasks, such as visual inspections for impact damage and structural anomalies. In particular, the research aims to improve damage detection and localisation by utilising cutting-edge scanning technologies to accurately identify and pinpoint small damage, including dents and buckles.

Background

New approaches for dent detection have been discussed during recent years. Different scanning technology carrier concepts are investigated in academia such as UAV cameras [2–4] or improved portable devices like 8-tree[1]. Yet, the dent must first be detected and located manually. Lafiosca et al. [5] employ a synthetic dataset based on Boeing's SRM and surface fitting strategies to convert 3D data into 2D. They demonstrate the potential of computer vision for dent segmentation, but highlights the need for real data and further detailed information. The authors of [6] develop a computer vision algorithm based images from a camera mounted on a UAV carrier. The captured data is used to fine-tune a pretrained TensorFlow[2] model. Although their results are promising, they stress the impact of perspective distortion when estimating the size of the defect from a non-perpendicular angle. Similar work by [7] focuses on the detection of defects like missing rivets, eroded rivets and other general damage (scratch, rust, paint-off, etc.) by using computer vision like YOLOv8 architecture[3]. For damage assessment conventional geometric information such as width, length and depth are requested by the SRM. The authors of [8] propose a 7-parameter model to describe dent shapes on aircraft surfaces, utilising high-fidelity data from 3D scanners. Such processes can be difficult for engineers or technicians to interpret the results without additional training.

Methodology and Case Study

Figure 1 illustrates the proposed research methodology for damage inspection. It is applied to a case study, which focusses on a laboratory specimen Boeing B737 wing section. The feasibility of the automated damage inspection consists of three functionalities: detection, localisation, and assessment. In addition, the results for the generation of a D&B DT are prepared by the definition of relevant metadata, describing the structure of data. Each module is developed individually by one of the research partners. The sequential connection between the modules displays the digital thread, the connected flow of data and used technologies. It should be noted that for this research and developmental stage they are discrete methods and it is intended for production to have them integrated in a sequential workflow. The choice of technologies is based on the MRO process requirements such as time, quality and technology availability. A scan for the primary detection algorithms is based on 2D data by focusing on reflections and shadowing. Optical measurement technology with 3D scanners is used to characterise dents and buckles more thoroughly. The detailed data of the dents is determined using a structured light sensor, which is characterised by its high accuracy. For this project, a Zeiss ATOS Compact Scan[4] with the corresponding Zeiss Inspection Optical 3D software is used for an initial localisation and

[1] dentCHECK: www.8-tree.com
[2] Tensorflow: www.tensorflow.org
[3] YOLOv8: github.com/ultralytics/ultralytics
[4] Zeiss ATOS: zeiss.de/messtechnik/systeme/optische-3d-messtechnik/3d-scannen/atos/atos-compact-scan.html

reference characterisation of the damage. Terrestrial laser scanners are more efficient at capturing large objects, such as the outer surface of an aircraft, but at the same time lack high precision. Laser Scanners are placed on a tripod and capture the entire area around the scanner in a 360° panoramic image in just a few minutes. For this project, the RTC 360 from Leica Geosystems[5] is used, which has a visual inertial system that takes over the registration of the individual recording stations.

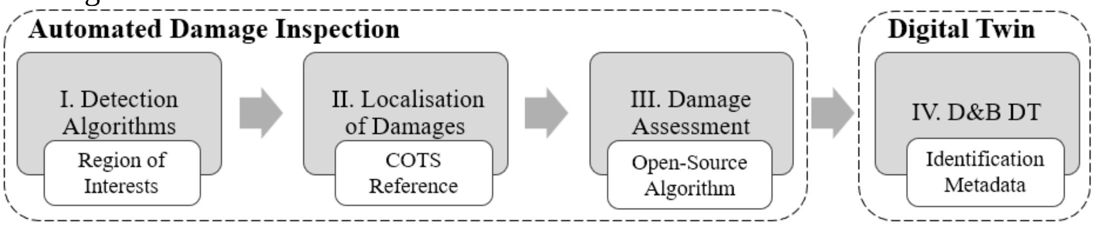


Fig. 1: Research Methodology for damage inspection and generation of D&B DT

I - Dent Detection

The procedure for developing an automatic machine learning dent detection algorithm begins with collecting high-quality RGB images of aircraft components. This dataset contains industrial data and specific specimen images ranging in resolution from 14 to 30 megapixels. Regions of interest (ROIs) are annotated to highlight different types of damage such as dents, missing rivets and corrosion. A data partition results in 80% of the images allocated to the training set and 20% to the test set. To enhance the diversity of the training data, common data augmentation techniques e.g., geometric and colour space transformation among others are applied. In addition, fine-tuning technique is utilised to leverage pre-trained models [7] using existing large aviation image datasets to produce task-specific outputs to improve the accuracy of the detec

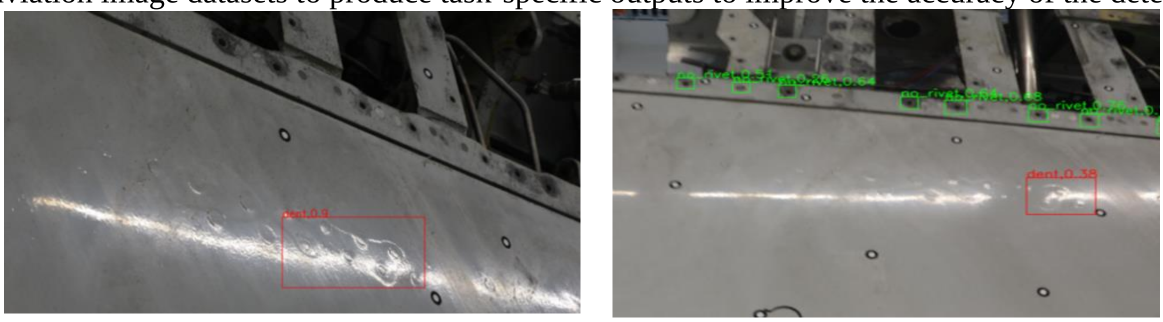


Fig. 2: Detected ROI areas: Bounding boxes for dents (red) and missing rivets (green).

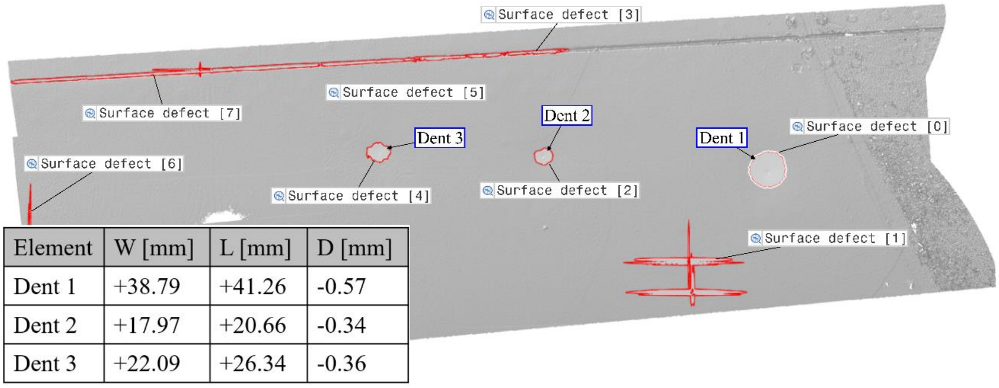
tion results. The trained deep learning models are evaluated for their ability to classify various types of damage, including dent detection with the YOLOv8 architecture, achieving different accuracy levels for different damage types. From the testing phase, it emerged that there are limitations to the model's performance as shown in Fig. 2, due to the minimal dataset of aircraft-specific dents. The training and test images typically feature larger dents related to significant impacts. However, it was found that the model can identify surface roughness like rivet lines well, which is useful in identifying the stiffened regions, important for subsequent damage assessment and it performed well detecting missing rivets.

II - Dent Localisation

To inspect the scanned surfaces for dents, a function within the software Zeiss Inspect Optical 3D is used. This function searches for unevenness and dents, up to a certain defect size. The max defect size parameter determines the length with which the surface is continuously analysed and is set to 100 mm, noting this value was arrived at after initial parameter sensitivity

[5] Leica RTC360 3D-Laser Scanner: leica-geosystems.com/de-de/products/laser-scanners/scanners/leica-rtc360

analysis. Aforementioned function employs a virtual stone which rolls over the surface. All areas with deviations towards the grinding stone are classified as dents. Filters can also be set to filter out large defect areas or areas that are small. The results, e.g., D, L and W, are transferred to a table and exported for further analysis. All these working steps are automated in a script within the software, which leads to standardised results. The result for the classification of the dents taken with the Zeiss Atos Compact Scan



Element	W [mm]	L [mm]	D [mm]
Dent 1	+38.79	+41.26	-0.57
Dent 2	+17.97	+20.66	-0.34
Dent 3	+22.09	+26.34	-0.36

Fig. 3: Output COTS Software Zeiss Inspect for Dent Inspection based on grinding stone dent algorithm and highlighted damage (dent 1-3) including artefacts.

can be seen in Fig. 3. A list of all detected dents and other imperfections are exported in a tabular form and marked on the surface mesh in an image. Other areas have also been identified as defects, such as the joint between two sheets on the skin of the wing. These areas require visual inspection to process only the information of the actual dents. The 3D data can be used to determine repeatable parameters for the individual dents, enabling data to be standardised and less variable.

III - Damage Assessment

This section presents a Python-based approach for surface deviation assessment, intended as an open-source option to COTS solutions for identifying dents on the lower wing section surface. The high-resolution scans are processed using key libraries such as Open3D, NumPy for numerical computations, Matplotlib for visualisation and Scikit-learn for clustering with DBSCAN (Density-Based Spatial Clustering of Applications with Noise). Wang et. al. [9] propose a point cloud method for detecting and characterising aircraft skin defects by employing a region-growing segmentation algorithm to analyse geometric features. However, a different approach is required to utilise point cloud outputs from large surface area laser scans with reduced data and fidelity. The surface was aligned to a standard numerical reference plane using least squares and deviations were calculated by fitting slightly curved surfaces across overlapping segments of the point cloud. The script divided the surface into curved plane segment with a length of 150 mm, a width of 1,500 mm and an overlap ratio of 0.9. A curvature factor of -0.015 was applied along the z-axis to account for non-planar surface deviations. Significant deviations were identified using thresholding above 0.2 of normalised deviation and clustering was performed using the DBSCAN algorithm with an epsilon parameter of six and a minimum cluster size of five points, with large cluster sizes excluded. The algorithm processes the scan, downsampled to one million points, taking only a few seconds on a consumer grade computer to successfully identify the three major dents, as shown in Fig. 4, with corresponding W, L and D values. By integrating clustering, this approach provides a comparative assessment and a fast method for assessing dents. However, it requires development to be a robust solution. Future improvements could include adaptive parameter tuning for DBSCAN to handle varying point densities and enhanced surface fitting techniques to account for complex geometries. This would ensure less variability in results, while scaling up the algorithm to handle point cloud to point cloud comparisons or analysis of large surface scans.

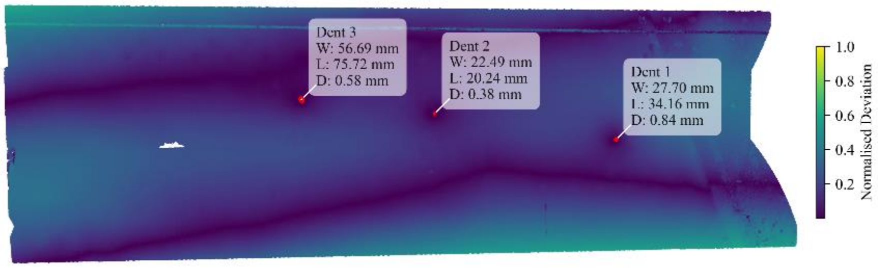


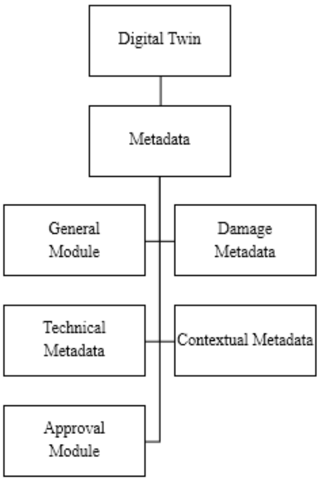
Fig. 4: Output of dent assessment based on 3D data - The cluster of red points corresponds to the detected dent and details annotated.

IV – Generation of the D&B Digital Twin

The DT serves as a virtual representation. Key components of DT modelling include, among others, assembly and fusion of relationships [10].This approach enables data integration and contextualising diverse data sources, overcoming the limitations of single technologies to provide holistic insights. Metadata plays a crucial role by providing interoperability. A data management approach is adopted from [11], using MongoDB and HDF5. MongoDB, a NoSQL database, efficiently handles via metadata parameters e.g., file paths, smaller point cloud data. HDF5 is used, a hierarchical format designed for scientific data. The proposed general metadata as shown in Fig. 5a includes basic details about the point cloud and its link to aircraft inspection task, describing dents and the point cloud. Equipment metadata records how the data was generated and processed. Contextual metadata connects the point cloud to maintenance efforts, while approval metadata outlines responsibilities and decisions. Fig. 5b presents an example.

Discussion

The dent detection based on 2D shows promising results. The best results were achieved with correct lighting, showing contour deviation of the specimen. Yet, the algorithm is not yet robust since irregular light reflection is sometimes identified incorrectly as a deformation. For more robust results, additional images are required and perhaps a specific lighting standard within the image is required. The acquisition of 3D data by the structured light sensor and the automated evaluation of this data enables a standardised evaluation of the dents, free of subjective influence variability and human error. The misalignment observed in comparison with COTS software for 3D damage assessment highlights several critical issues and considerations: Care should be placed in the development of the algorithms to ensure such as the misaligned artificial plane that assumes a perfect fit but fails to account for geometric curvature. This simplification introduces significant errors. To address this, it is essential to incorporate accurate geometric data, such as CAD models, into the alignment process to account for complex shapes and curvatures. In a DT context, techniques like point stamp analysis can enhance dent identification by distinguishing them from artefacts such as sediments or adhesive residues, improving damage assessment accuracy. A key challenge with unstructured point clouds is the uniform treatment of all points, which results in inefficiencies and the processing of irrelevant data. To address this, it is recommended to focus on ROIs based on functional relevance. This prioritisation improves computational efficiency and ensures resources are directed toward the most relevant regions, enhancing the interpretability and utility of the 3D data in a digital twin framework.



Type	B&D Assessment
ID	617707d88169c370c15c6b77
Name	Damage Assessment
Title	Damage Inspection – FOD after hailing
Parent ID	617707d68169c370c15c6c4f
Data ID	614191cc44ca142e54e3f0cb
Created by	MRO Department - Rudolph, the Raindeer
Created at	30. Nov 24, 10:20 UTC
Project	Flugzeugwartung, Inspektion 2024
Position of the Dent	FR21-23 STR 3-4 L/H
Maximum Depth	0.4 mm
Size of the Point Cloud	200.000 Points, 15 MB
Format	.PLY
Capture Technology	Terrestrial Laser
Processing Steps	CloudCompare
Criticality	To be defined
Storage Location	Cloud-Speicher, Ordner "Inspektion_Nov_2024"

Fig. 5: a) Metadata hierarchy; and b) Attributes for the metadata of the D&B DT.

Conclusion

This research focusses on the development and comparison of dent detection, localisation and assessment methods for 2D and 3D data tested on a laboratory aircraft wing section. The ensembled approach includes the use of a deep learning computer vision model, enabling detection of dents on the wing. Subsequently, the 3D scans for dent assessment achieve good results comparing a COTS software result and open-source point cloud clustering algorithms. To overcome limitations of single technologies, digital twinning combines the distributed data and analysis interconnected by relevant metadata. This more accurate representation of the wing creates a novel system for enhanced defect detection e.g., classifying true damage from artefacts.

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