CINNABAR PROJECT
AUGMENTED REALITY WORKFLOW FOR AIRCRAFT DENT & BUCKLE INSPECTION

Thore Keser[1], Rahel Schmied-Kowarzik[1], Ann-Kathrin Koschlik[1], Lina Kaschub[1], Michael J. Scott[2], Rebecca Rodeck[1] & Gerko Wende[1]

[1]German Aerospace Center (DLR), Hamburg, Germany
[2]RMIT University, Melbourne, Victoria, Australia

Abstract

Conventional aircraft Dent & Buckle inspection is a manual and time-intensive task. The CINNABAR project introduces an Augmented Reality (AR) supported workflow. This paper approaches object tracking on Microsoft HoloLens 2 using retro-reflective markers in the infrared light spectrum to detect the aircraft pose and align augmented visualizations. These guide mechanics through the Dent & Buckle procedure and help with damage searching, localization, and documentation processes. The assessment results show a high potential for time reduction in dent searching operations and acceptance of the introduced AR system.

Keywords: Aircraft Maintenance, Extended Reality Inspection, Non-Destructive Evaluation.

1. Introduction

Aircraft are inspected for dents at least every 8600 flight cycles [1] (approx. once a year) or at unscheduled damage events to maintain airworthiness. As shown in Figure 1, a dent on an aircraft can be characterized as damage, 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 [2]. As these minor defects may impact the overall durability of the aircraft fuselage and wings, their condition is checked and documented regularly.

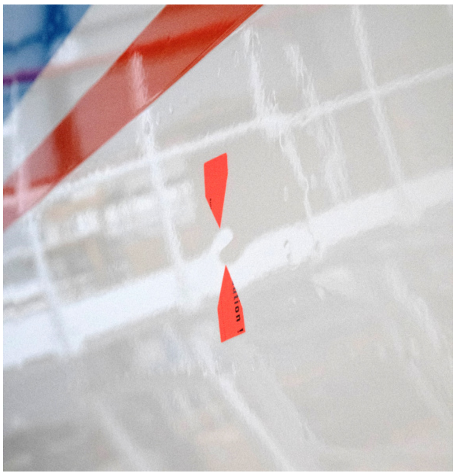

Figure 1 – Dent in aircraft fuselage skin, visible by its distortion of the specular light reflection.

The dent detection process is time-consuming [3] because dents are small and difficult to identify in general visual inspections. Trained staff uses the specular light reflection on the aircraft surface to spot dents; this relies on the maintainer seeing an anomaly in the light reflections when shining a light source over a deformed surface area. Dents are documented in the Dent & Buckle (D&B) chart, where the localization descriptions within the documentation are not precise and susceptible to inconsistency depending on maintainers. Hence, locating existing dents and distinguishing them from new ones is challenging. If new dents are identified, their position is located relative to rivet lines, that mark stiffened airframe areas. Moreover, dents are measured in length, width, and depth [3]. They are checked, located, and documented regularly and repeatedly during line and base maintenance as they affect the aircraft's airworthiness. If a particular aircraft structure is damaged beyond allowable limits, the aircraft might be temporarily grounded [3].

This paper presents an Augmented Reality (AR) supported workflow to help with the localization, measurement, and documentation process. AR as a disruptive technology can improve the Dent & Buckle (D&B) workflow for more objective measures and digital consistency [3]. The goal is to save time while increasing maintainers' user experience during the D&B inspection.
In AR research, a common problem is the identification and detection of objects that are visible in the device's camera streams. Difficulties lie in the process of calculating the position and orientation (pose) of objects in the real world and their relative placement to the detecting camera. This process is necessary to align virtual content, such as hints and arrows, with the object of concern. A suitable alignment increases the abilities of the AR technology to support real-life use cases.
Object tracking based on the visual outlines of the aircraft within the video stream requires performance capabilities that pose barriers for most head-mounted and hands-free devices. Higher performance capabilities require more energy and physical space, which results in higher weight, more heat production, and less battery time. Hence, portable AR devices are built in a balance between those factors and thus require well-performing algorithms.
In AR research, QR-code-like fiducial markers are commonly used to align virtual content with real-world objects. These markers are detectable with low-cost algorithms but are also visually salient for humans. When placed all over an aircraft, those markers are also externally visible, which may be of concern for passengers boarding the aircraft and potentially adverse to the branding and presentation of commercial airliners.
To overcome this issue, it is possible to create markers that blend in with the aircraft's color. Using retro-reflective material, markers in the same color as the aircraft can be created. When viewing the aircraft with its markers under an infrared light source using an infrared camera, the markers become brightly visible (see Figure 2).

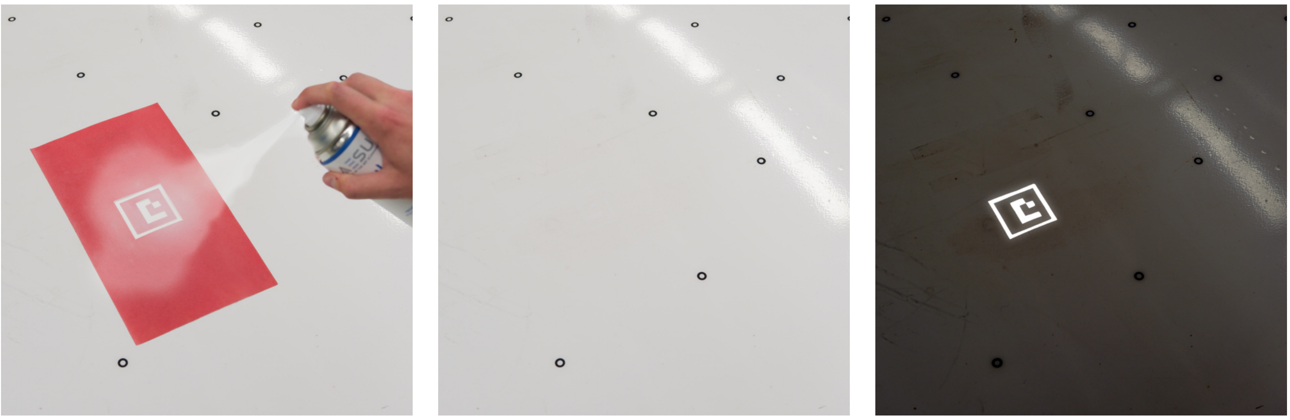

Figure 2 – Process of spray marker creation (left to right): 1) Creating an ArUco marker using a stencil and retro-reflective spray. 2) Removed stencil, leaving an invisible marker behind. 3) Viewing the invisible marker using an infrared camera to process the marker pose and content.

The following section briefly describes current research projects regarding this topic. Next, a summary of the implementation process and its considerations is provided. The implementation is supported by user feedback, outlined in the Preliminary Assessment section. Concluding this paper, the main user study and results are summarized, along with a discussion and an outlook on future progression.

2. Related Work

Augmented Reality (AR) tightly couples the surroundings with digital information [4]. Devices, such as tablets and Head-Mounted Displays (HMDs), e.g., Microsoft HoloLens 2, allow interactive digital content to be augmented or overlaid onto real-world objects mixing with a person's spatial environment [5, 6].
The industrial performance of AR in aircraft maintenance is an emerging and disruptive technology [7]. It can support the proactive condition-based maintenance of aircraft by more effectively delivering maintenance data to the end user [8]. For example, AR can supplement better comprehension of

complex tasks and enhance in-situ decision-making for maintenance practitioners [9]. Moreover, users can localize maintenance tasks significantly faster when exploring real environments enriched with digital information [10].
AR devices rely on several tracking technologies for environmental tracking and object identification. The HoloLens 2 AR HMD uses a Simultaneous Localization and Mapping (SLAM) algorithm for self-localization [11]. When combining SLAM with an external tracking system, drift is introduced, caused by the HoloLens Inertial Measurement Unit (IMU) [12]. An excellent way to overcome drift in tracking external objects is to choose an inside-out system [13], where sensors are mounted on the device itself, and the device creates its own coordinate space, for example, by using HoloLens' built-in sensors. This approach has been evaluated for neurosurgical environments in previous work [14].
Advancing from previous ideas, this paper utilizes the infrared capabilities of HoloLens to create and detect markers that blend in with the aircraft painting layer. Others also research non-visible markers in the form of infrared reflective tags [15], but those are printed into the fabric of objects. In contrast, this project aims to create markers using reflective spray quickly.
AR is a hands-free technology. As seen from medical use cases [12], this is beneficial when working with tools and contaminated hands. The same applies to maintenance processes, where maintainers use their hands for mechanical work or require their hands to be free for tools.

3. Method

In this project, ArUco[1] based markers from retro-reflective material were created. HoloLens 2 cannot detect the markers by default, but by using a custom implementation for the onboard infrared camera, those markers can be used for object tracking.
As depicted in Figure 3, the first major step is to enable HoloLens to detect markers in the infrared spectrum. A plug-in is used to unlock sensor access within the Unity3D game engine [14] and integrate the OpenCV[2] library. ArUco marker detection is performed on the raw infrared camera stream of the HoloLens infrared sensor. Detected marker corners are transformed from 2D image coordinate space to the global 3D world space using the Research Mode API [11].

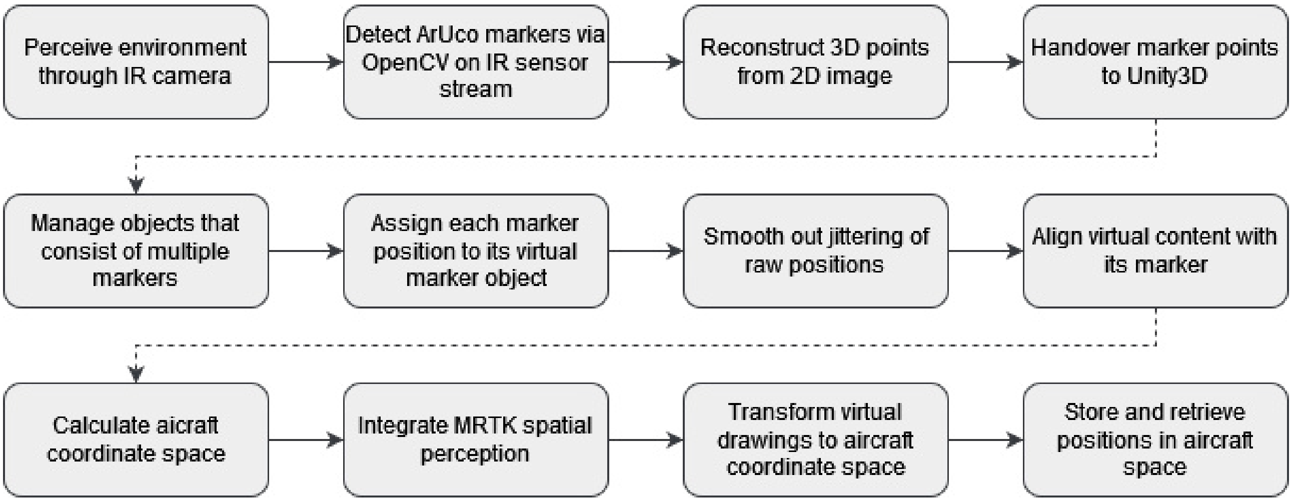

Figure 3 – Technical workflow required for the AR application to process inputs, provide the system functionality to end-users, and render the graphical user interface.

For viewing dents, a management layer is required to align virtual objects with perceived marker positions. The management layer stores each marker's virtual (previous) position and the just-in-time updated (new) position. A relative movement vector is calculated from previous and new positions, which is used to move virtual objects to the detected position and create alignment.
For complex objects, multiple markers are required. With multi-marker objects, some objects could be hidden or face away from the camera. Hence, the management layer determines the tracked

[1] ArUco detection: `https://docs.opencv.org/4.x/d5/dae/tutorial_aruco_detection.html`
[2] OpenCV: `https://opencv.org`

state of each marker and averages relative movement vectors for only the tracked markers. This is implemented using a timeout function that indicates the tracked state based on the last detection time stamp. Averaging the relative movement erases the need to distinguish between single and multi-marker objects.

As the infrared sensor has a relatively low resolution, jitter occurs when marker corners are detected in between pixels. The application uses a combination of *Lerp* and *Clamp* functions to interpolate the movement path and restrict large position jumps. The algorithm can be adapted to a variety of smoothing behaviors by changing the parameters of these two functions.

From the knowledge of marker positions in the global world space, it is possible to construct a local object coordinate system, which allows the storage of dent locations with respect to the aircraft base point. It is also necessary to transform stored dent positions from the aircraft coordinate system back to the global world space to allow HoloLens to visualize the content and allow user interactions. An example of those transformations is the virtual drawing on the aircraft hull, which is implemented using the Microsoft Mixed Reality Toolkit (MRTK) and its Spatial Awareness System[3]. The system yields world coordinates for every drawing point. When storing the drawings or measuring distances to significant structures, these drawings are transformed into aircraft space to allow comparison with aircraft-relevant coordinates.

The local aircraft coordinate space allows for aircraft movement and position changes during and between maintenance checks. Implementing this feature ensures that stored dent positions automatically align with the aircraft in the hangar.

All systems are integrated into a graphical user interface to support the user workflow. It guides the user through the D&B inspection described by Kowarzik et al. [16]. A picture taking algorithm captures the dent and its virtual drawings. The AR application lets maintainers see the aircraft and a highlighted dent overlay. When new dents are identified, users can circle the dent with their finger to automatically detect the position in relation to the aircraft model.

4. Preliminary Assessment

In a first validation step, a proof of concept AR application was presented to trained maintenance mechanics and staff involved in the D&B inspection. This feedback was included in an early development phase to align the features with the needs of mechanics. The assessment was conducted with one maintainer in an oral interview and by observing his work.

Preliminary feedback initiated a change from voice commands to more intuitive touch interactions (see Figure 4) due to challenges in detecting keywords in a noisy hangar environment. Moreover, touch interactions do not require knowledge of the keywords and thus reduce training time.

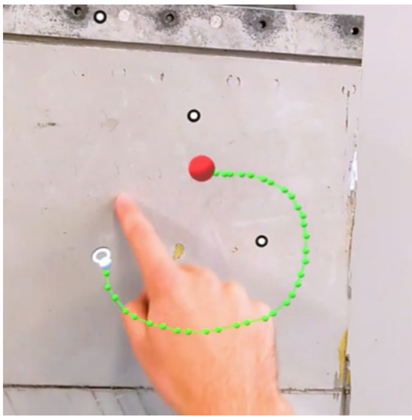

Figure 4 – User proposed touch interaction to locate a dent.

During testing, the user tried to erase drawings using his hand, as one would intuitively scrape chalk drawings on a blackboard. Hence, the implementation of a feature to erase virtual drawings is planned. The feature must be deactivated when users are currently drawing shapes. There are possibilities in using the little finger extension angle to deactivate the erasing function when users show pointing hand gestures to draw with the index fingertip.

The feedback also showed potential for the application, as staff could see the benefits of the proposed system. Localizing functionalities were pointed out to be helpful in the scenario. Furthermore, visualization of limits from the Structural Repair Manual (SRM) overlaid with the real aircraft could enhance decision-making.

[3]MRTK Spatial Awareness System: `https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/features/spatial-awareness/spatial-awareness-getting-started`

5. Main Study and Results

The main validation study took place during an Airbus A320 C-Check in April 2024. Staff from an aircraft maintenance company could test the application and give feedback. Due to restrictions on participant numbers, a qualitative evaluation was conducted. The study contained four main participants, who gave rich feedback and took time to test the application. Seven more participants could attend the interview session for a limited time or did not test the entire application. According to Holzblatt et al., [17], interview sessions were transcribed and evaluated. This process and results are described by Schmied-Kowarzik et al. [16] in more detail.
The retro-reflective marker setup was successfully tested and showed good detection speed and positioning performance. Medium deviation in the rotational alignments was found and expected to originate from the chosen alignment algorithm. Printed markers under good lighting conditions are detectable via the infrared pipeline. Hence, the usage of retro-reflective material is expected to show similar results. The main user study was carried out using conventionally printed markers. Due to logistical problems, spraying the markers using a transparent retro-reflective spray had yet to be tested.
A short introduction to the main results is given in the following sections. Please note that user quotes are not literal speech and have been translated from German to English.

5.1 Information

Maintenance workers constantly exchange information with colleagues, handle documentation, or take action based on their knowledge. For the D&B check, the documentation contains key parameters and guidance on how to check and repair those damages. As seen from Table 1, the documentation poses barriers in locating damages. Information is lost if the paperwork does not contain detailed position descriptions, which results in search operations. At the same time, colleagues hand over incomplete documentation, which requires maintainers to double-check or manually correct damage descriptions within their systems.
A valid and well-implemented communication system consists of taking pictures of damages, including drawings of key data. Distances to nearby frames, stringers, and other significant structures are required measures in those pictures.

Table 1 – Information requirements

No.	Requirement	Example Quotes (with user No.)
1	Users need precise positioning information from the documentation for better damage localization	"We need more precise information to localize damages" (U1), "Damages and their positions are not distinct" (U1), "Localizing damages at the aircraft is often a problem" (U10)
2	Maintainers wish for a better communication and description of damages from colleagues	"We often correct descriptions that were made by pilots" (U1), "Often you receive the description 'damage at fuselage'" (U9)
3	Photos with distances to other structures are required	"The distance to frames and stringers are important" (U10)

5.2 Time

Users state a general time pressure originating from high workload. High workload is created when repairs take longer than expected but the aircraft needs to return to service at a fixed date. The D&B check is a long lasting operation, that users wish to shorten. Hence introduced systems are expected to run quickly with minimal setup time. Requirements from Table 2 reflect the need to be more efficient in work and reduce delays.

Table 2 – Time requirements

No.	Requirement	**Example Quotes** (with user No.)
4	Users wish for a reduced time pressure	"Sometimes we cannot complete our given work for the shift" (U1), "The aircraft needs to fly again, soon" (U10)
5	The time for dent & buckle check needs to be shortened	"From damage detection to decision making may take an hour" (U9), "Finding damages is time consuming" (U1)
6	The system must have a short setup time	"It is very simple: switch on and go" (U10)
7	Systems need to save time	"I think the system reduces work and saves time" (U10)

5.3 Alternative systems

Within the workshop, an alternative damage measuring system is used that can quickly and automatically measure important parameters of dents and scratches. Users describe the system as sometimes unreliable in terms of interconnection to other devices and handling. Although users describe the measurements as of very high quality, the overall use of the system is reduced by errors in the interaction and interconnection domain. As the system is expensive, users state they do not purchase updates. Moreover, the system is complex for some users and requires training. As not all colleagues were trained, only a few are allowed and able to use the system.

Table 3 – Requirements of alternative systems

No.	Requirement	**Example Quotes** (with user No.)
8	The alternative system should run reliably	"The system is genius if it works" (U10), "The system is perfect on a technical level but it is not used because it also suffers from problems" (U0)
9	The alternative system must be less expensive	"We use a workaround because updates are to expensive" (U9)
10	Users wish to use the system without training	"The least know how it works" (U9), "We do not use the system, because people do not have training for it" (U10)

5.4 HoloLens 2

For most maintenance work, maintainers require their hands to be free. Also, with large aircraft, the ground-facing fuselage surface is not reachable without mobile platforms, thus hindering the D&B process. The upper part is always accessed using mechanical lifting equipment. A device that respects distancing aspects, such as HoloLens 2, is reported to be helpful. However, users prefer inputs via interconnected computers, tablets, or smartphones for larger amounts of text. As seen from Table 4, feedback concerning the chosen device is positive.

Table 4 – HoloLens 2 requirements

No.	Requirement	**Example Quotes** (with user No.)
11	Maintainers require their hands to be free for carrying and using physical tools	"It is good, that HoloLens keeps our hands free" (U2)
12	Aircraft hulls need to be reachable	"You need an aerial platform to drive along the fuselage" (U1), "The D&B check is simpler with lower aircraft, its difficult to reach higher ones" (U9)
13	We need more devices like HoloLens	"I'd like to try HoloLens at the aircraft" (U9), "HoloLens performed fluently" (U1)
14	Users wish other modalities like tablets and computers for data input	"We could link the data to smartphones and laptops to type in more information" (U1)

5.5 Connectivity

In aircraft maintenance, many assistance systems are not linked to databases and are not consistently digital. Users wish for more exchange between devices to retrieve and store information seamlessly. This also includes attaching software to current MRO management software. The introduced AR application should follow this lead and connect with databases in use.

Table 5 – User derived links

No.	Requirement	Example Quotes (with user No.)
20	All used systems should communicate with each other	"We did have an app that stored images in the network, that was helpful" (U10), "One should access the system via WiFi" (U10)
21	Systems should sync with existing MRO management tool	"It would be helpful to link ATA chapters" (U9)
22	HoloLens should access existing MRO management tool	"Do you plan to link HoloLens with the management tool?" (U9), "A link to our tool would be great" (U1)

5.6 Localization and navigation

Automatic localization describes the technical ability to automatically store and retrieve a damage position with respect to the aircraft. Users compared this feature with a "GPS"-like system, that helps to visualize known dent positions and provide that information to colleagues. Incorrect damage locations, resulting from erroneous counting of frames and stringers, could be prevented. Moreover, a visualization of restricted areas, where damages are limited or not allowed, is stated to be a helpful addition. As dents are difficult to find (see Table 6), maintainers wish for assistance within the process.

Table 6 – Localization and navigation requirements

No.	Requirement	Example Quotes (with user No.)
15	An automated solution is needed that stores dents with respect to the current aircraft	"This is stored like with a GPS so that others can see this, too" (U1)
16	An automatic and easy localization would improve the workflow	"HoloLens would prevent wrong inputs for frames and stringers" (U9), "Storing damage positions with HoloLens is easy" (U9)
17	We need to visualize restricted areas and limits	"I could walk around the aircraft and see highlighted areas were damages are not allowed" (U9)
18	Damages should be easier to find	"Sometimes we use a torch light and look from all 30 angles" (U10), "It is more difficult to find damages if one is tired during night shifts" (U9)
19	Maintainers wish for help with navigating to documented dents	"Finding the dents was great" (U1)

5.7 Application

The implemented application was easy to use, even if users had no experience with the AR device. However, some interactions, such as drawing on the aircraft surface using the index fingertip, were rather unintuitive. Users also noticed technical difficulties in the drawing functionality. They concluded that the system should improve slightly to fulfill their needs. Hence, the application has to gain trust and prove itself in real use cases. In contrast, taking pictures with the application was reported to be effortless and understandable.

Table 7 – Application requirements

No.	Requirement	Example Quotes (with user No.)
23	The system must be easy to learn	"It is simple to use for externals without experience" (U5, U6)
24	Drawing needs getting used to	"Drawing is like digital signing papers - somewhat strange" (U1)
25	Drawing should work on a technical basis	"Maybe my hand is in the way when I try to draw" (U10)
26	The HoloLens system should improve	"I work with fine structures" (U1), "The system isn't perfect" (U9)
27	The system must be trustworthy	"The system must proof its worth" (U4), "I'd use the system if everything works well" (U5)
28	Taking pictures must be simple	"Bam, now it took a picture" (U1)

6. Discussion

The retro-reflective marker detection pipeline showed to be robust against distracting factors, such as sunlight or unpainted metallic materials that create reflections hindering the tracking process. The markers are quickly detectable by the HoloLens device. As printed as well as sprayed markers use the same pipeline, no differences in detection speed or accuracy are expected. First development tests with prototype retro-reflective markers confirm this. Rotational tracking errors were caused by small marker diameters resulting in a high leverage factor of normal vectors. This difficulty can be corrected in future versions by including longer directional vectors between tracked markers to decrease the effect of single tracking errors on the entire tracked object.

The technology is non-intrusive and invisible for passengers while being an attractive proposition for commercial airlines as the required markers are low in contrast and subtle in color change. As these markers are difficult to see for humans, they could be integrated into the aircraft painting layer for permanent use. These markers enable HoloLens to locate the aircraft and visualize dents more precisely than with the D&B chart. Invisible markers allow the use of AR on uniform areas or where salient markers are not accepted. The markers open possibilities for various AR applications in - but not limited to - the aviation industry.

The qualitative evaluation confirms that users tend to accept the technology as a beneficial assistance [16]. Using conventional paper-based documentation methods, information that is crucial for a fast damage search is lost when workers shorten descriptions. This results in time-consuming and rather frustrating documentation completion and correction. An automatic and objective location of damages using HoloLens would resolve these issues.

The conventional dent localization and documentation process includes counting frames and stringers, as well as manually drawing distances to relevant structures and measuring damage parameters (see Figure 5). With the digitally consistent workflow, a reduction in dent localization and documentation time is indicated. Users report time to be of great importance and time pressure being a challenge in their work. Hence, they require systems that do not need preparation time and shorten the documentation and searching process of the D&B check. With the AR-supported inspection, users could identify existing dents on the aircraft surface and quickly locate new ones. Even though the timings were not precisely measured, time reduction benefits were visible by an approximate factor of three. This indicates a huge benefit in time reduction, cost efficiency, and potentially user satisfaction. A detailed cost-benefit consideration is introduced by Aigner et al., where improvements in time, labor, and quality are evaluated [18].

An alternative system currently in use shows to be exact but is not well-accepted and doesn't provide assistance in localization. Users report difficulties caused by the reliability of the system. In combination with high costs for usage and training, the system is integrated into a workaround workflow while discarding its huge potential. Learnings from this feedback result in requirements like effective interconnection, low cost, and 'switch on and go' functionality for the HoloLens application. These align with the general requirements of learnability, simplicity, and trustworthiness.

The main findings regarding the visual alignment and localization are positively denoted. Users highlight a speed-up in their work processes based on the automated localization of dents and the ability to find dents without searching. They welcome a digital solution to support them with the current work, their documentation, and other paperwork so they can focus on their primary tasks.

Difficulties were found in using the HoloLens device itself, as all users were unfamiliar with the device. However, users reported to understand the interaction techniques quickly. For drawing on the aircraft's outside hull, difficulties originated from the non-optimal hand-tracking and surface detection performance of the HoloLens device itself. The shiny painting layer created reflections that impaired the built-in hand-tracking quality and resulted in incomplete and ineffective drawings of users. Previous research shows that drawing with fingers on HoloLens 2 is only precise to approximately 10mm [19]. However, the precision would suffice for this use case if drawing is used to select areas that do not require high-precision markings. The drawings can narrow down the area where technical post-processing could be applied.

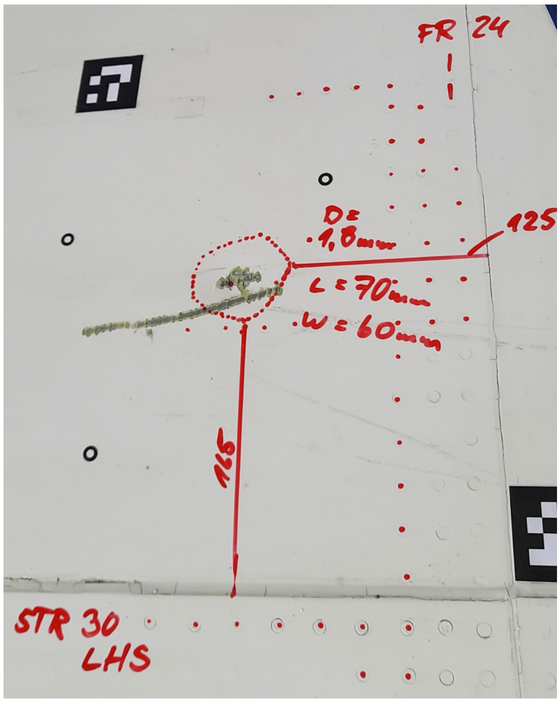

Figure 5 – Conventional manual dent localization and documentation.

If paired with other input devices, like tablets, smartphones, and computers, the HoloLens or HMDs in general, would provide a meaningful addition to the workshop tools. These devices are hands-free and thus enable workers to physically engage with the current maintenance task. Moreover, the device can create an overview effect for users, which is required with larger aircraft or situations where the fuselage isn't close. Visualizing a navigational aid would also reduce the time to distinguish dents from others on the aircraft hull. Additional highlighting of restricted areas and limits would increase the decision-making process and eliminate labor-intensive paperwork.

7. Future Work

Future development cycles can provide a more in-depth analysis of the retro-reflective markers. The creation of markers from spray or in sticker format, as well as their strengths and weaknesses, could be tested. Moreover, the ability to include the markers in the aircraft painting layer needs to be discussed.

The markers enable functionality to automatically save the dent's position by counting virtual stringers and frames, as well as measuring distances to doors and other significant or hidden structures. Additionally, sensitive zones around doors and windows according to the Structure Repair Manual (SRM) [2] can be visualized, supporting in the fast judgment of damage repair necessity.

Pictures taken by users can convey the most meaningful information to colleagues if they include visualization and user drawings. Maintainers could take a photo of drawings and virtual structures in reference to the dent and send those drawings to engineering for further evaluation, thus simplifying the communication of dent locations.

8. Conclusion

The CINNABAR project introduces an Augmented Reality (AR) supported workflow to improve the conventional aircraft Dent & Buckle inspection. This paper presents an object tracking approach on HoloLens using retro-reflective markers in the infrared light spectrum to detect the aircraft pose and align augmented visualizations. The user study shows a high potential for time reduction in dent localization and search time, as well as workflow simplification.

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10. Contact Author Email Address

Thore Keser M.Sc.
mailto: thore.keser@dlr.de
Research Associate at the German Aerospace Center (DLR) at the Institute of Maintenance, Repair, and Overhaul, specializing in Human-Computer Interaction and Augmented Reality research for maintenance in aviation.

Rahel Louise Schmied-Kowarzik M.Sc.
mailto: rahel.schmied-kowarzik@dlr.de
Research Associate at the German Aerospace Center (DLR) at the Institute of Maintenance, Repair and Overhaul, specializing in Human Factors and Extended Reality in the field of MRO.

Ann-Kathrin Koschlik M.Sc.
mailto: ann-kathrin.koschlik@dlr.de
Research Associate at the German Aerospace Center (DLR) at the Institute of Maintenance, Repair and Overhaul, specialising in unmanned aircraft maintenance and predictive maintenance.

11. Copyright Statement

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