# Augmented Reality for Remote Collaboration in Aircraft Maintenance Tasks


**Sebastian Utzig**
**DLR**
**Lilienthalplatz 7**
**Braunschweig, 38108**
**+49 531 295 2479**
**Sebastian.Utzig@dlr.de**

**Robert Kaps**
**DLR**
**Lilienthalplatz 7**
**Braunschweig, 38108**
**+49 531 295 3220**
**Robert.Kaps@dlr.de**

**Syed Muhammad Azeem**
**DLR**
**Lilienthalplatz 7**
**Braunschweig, 38108**
**+49 531 295 2809**
**Syed.Azeem@dlr.de**

**Andreas Gerndt**
**DLR**
**Lilienthalplatz 7**
**Braunschweig, 38108**
**+49 531 295 2782**
**Andreas.Gerndt@dlr.de**



*Abstract*—**In this paper, we present a concept study to facilitate maintenance of an operating aircraft based on its lifelong collected data, called Digital Twin. It demonstrates a damage assessment scenario on a real aircraft component. We propose a graphical user interface that contains menu-guided instructions and inspection documentation to increase the efficiency of manual processes. Furthermore, experts located at different sites can join via a virtual session. By inspecting a 3D model of the aircraft component, they can see synchronized information from a *Digital Twin* database. With Augmented Reality glasses, the *Microsoft HoloLens*, a *Digital Twin* can be experienced personally. In the inspector's view, the 3D model of the *Digital Twin* is directly superimposed on the physical component. This *Mixed Reality Vision* can be used for inspection purposes. Any inspection related information can be directly attached to the component. For example, damage locations are marked by the inspector on the component's surface and are stored in the *Digital Twin* database. Our scenario demonstrates how new information can be derived from the combination of collected data and analyses from the *Digital Twin* database. This information is used to maintain the continued airworthiness of the aircraft. Feedback from domain related engineers confirm that our interface has an enormous potential for solving current maintenance problems in the aviation industry. Additionally, our study provides ideas for the integration of further analysis functions into the interface.**


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## 1. INTRODUCTION

Maintenance tasks in aviation are hampered by low levels of digitalization in terms of legacy systems, paper-based documentation, and poor information exchange among the institutions involved. This has a negative impact on the efficiency and costs of product support and phase-out [1].

Hobbs and Williamson [2] found that 12% of serious aircraft accidents and 50% of engine related flight delays and cancellations were caused by maintenance deficits. Complex routines of aircraft maintenance and repair not only increase costs but also pose a risk to aircraft safety. Due to the long service life of aircrafts and their components, the development of new routines is expensive.

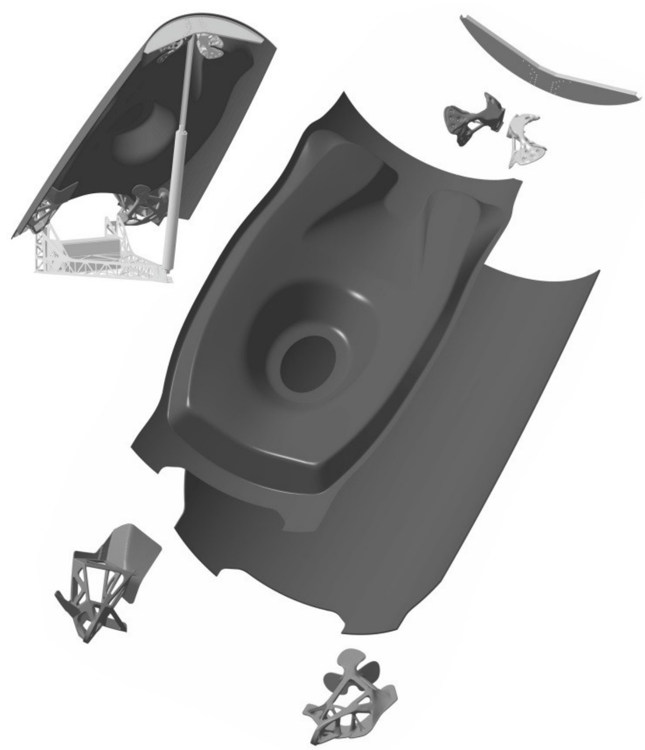

**Figure 1: Assembly of the all-composite-redesign of an EF 2000T air brake**


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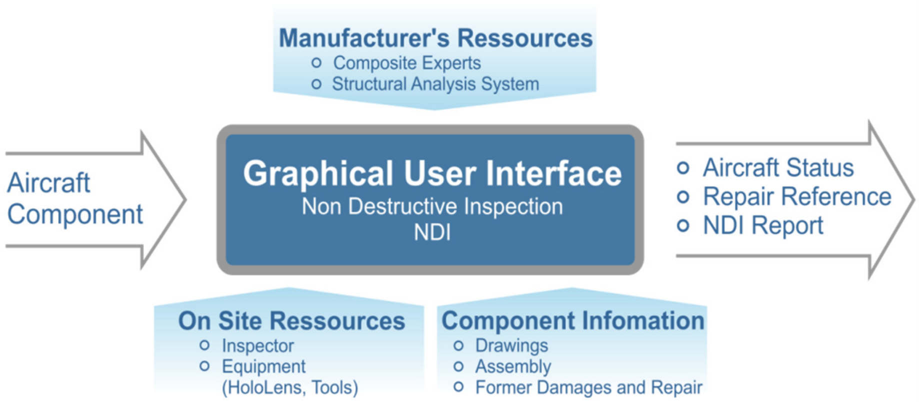


**Figure 2: Information flow during the damage analysis process**

We introduce a graphical user interface for damage evaluation in order to solve this problem step by step. The interface is built for modern Augmented Reality glasses, the *Microsoft HoloLen*s, and takes advantage of their capabilities: They are portable, can be used hands-free and support multi-modal input like voice commands and gestures.

In order to demonstrate our interface in an operational study, we have used the air brake of the Eurofighter EF 2000T. We picked this component since both the physical air brake and its virtual 3D model are available at the German Aerospace Center (DLR). The air brake was developed and built as an alternative composite structure for the conventional metallic design. By using a bonded two-shell construction, the number of components is drastically reduced. Figure 1 shows the single components: Four metal flanges, a frame and the two shells. The composite outer shell is vulnerable to impact damage and is the key subject of the inspection scenario that we present. Visual inspections are the basis for the damage analysis of a composite structure. They can reveal superficial deformations such as dents or cracks. On the other hand, these abnormalities can indicate larger damages inside the internal structure of the composite assembly [3]. The damage is caused by foreign objects that are thrown up along the runway or damage is taken during maintenance and service work. Overloading during operation as well as fatigue, lightning strikes or erosion can also cause damage.

Figure 2 shows all resources and entities involved in our damage evaluation process. They are arranged around the inspection task which is guided by a graphical user interface. The outcome of the evaluation is the inspector's decision on the air brake's operation. During maintenance with the *HoloLens*, the aircraft status is documented in form of a digital damage report. It builds the basis for later repair processes. A repair plan can be worked out and confirmed by a composite expert, who is remotely connected.

The next section will give an insight into work related to *HoloLens* and remote collaboration. Section 3 explains the role of the *Digital Twin* in our inspection scenario. It is followed by the sections *Mixed Reality Vision* and *Remote Collaboration* that combine the *Digital Twin* with Augmented Reality. Next, we apply these techniques in an operational study. The paper concludes with the limitations of our system, future work, and a summary.

## 2. Related Work

Maintenance, repair and overhaul (MRO) of aircraft are highly specialized tasks that are performed by authorized inspectors. They have to document and assess any damage followed by the repair analysis. In order to support the inspector, experts can be involved in the decision process. However, experts may be located at the manufacturer site and are limited in number and availability. Costs for transporting expert and repair teams to remote locations can be avoided considering remote inspection. We investigate whether *Microsoft HoloLens* can support several aspects of these processes.

The *Microsoft HoloLens* is an optical head-mounted display capable of tracking its motion by reconstructing the environment. Displayed content appears fixed in this environment considering the wearer's head motion. Stereoscopic images are projected onto semi-transparent lenses at 60Hz. The light of a rendered image with a maximum resolution of 1268x720pixels[1] per eye is directed into the pupil. Since waveguides are part of the optical system, a light density higher than 2.5 thousand light points per radian[2] is stated to be the actual indicator on display quality. Displayed content may include 3D models, instruction windows or documentation forms. Documentation text can be recorded and photos can be taken with the integrated front camera. Furthermore, the *HoloLens* has a built-in 802.11ac wireless networking adaptor which makes it able to communicate with other devices.

1 https://docs.microsoft.com/en-us/windows/mixed-reality/rendering

2 https://docs.microsoft.com/en-us/windows/mixed-reality/hololens-hardware-details

Using *HoloLens*, a 3D model of an aircraft component can interactively be placed right next to its physical counterpart e.g. to compare them. By directly placing it into the physical component, it gets superimposed in the user's vision. This in-place matching of real objects and their virtual counterparts is also investigated in other domains. Rodrigues et al. [4], for example, discuss *HoloLens'* application for surgery by augmenting medical training. They refer to a technique already implemented by Bajura et al. [5] presenting real-time imaging visualization in human bodies.

Based on *HoloLens* experiences, Rodrigues et al. [4] point out the potential of modern Mixed Reality hardware: It is portable, independent of external (tracking) devices and can be used hands-free. However, it is not yet capable of recognizing and tracking arbitrary objects individually. Rodrigues et al. apply *Vuforia*[3] for marker-based object recognition. It uses *HoloLens'* front camera to find markers, so called image targets. Image targets are printable and can be detected and tracked in 3D using computer vision algorithms. In surgery simulation, an image target can be attached to a mannequin to provide the frame of reference. The target needs to be scanned by the user to initially place the virtual representation of the patient inside the mannequin. Besides surgery training and simulation, Rodrigues et al. address the specific use case of remote guidance. The local user would act based on landmarks and annotations set by a remotely located expert. Furthermore, a surgery of an expert can be recorded and played back for training.

In the research field of Computer-Supported Cooperative Work (CSCW), software systems are classified regarding specific characteristics and how they support collaboration [6]. Remote collaboration can be conducted simultaneously (synchronous) and at different times (asynchronous). Moreover, Penichet et al. [6] add information sharing, communication, and coordination as further system attributes. In order to identify core communication elements for synchronous distributed virtual environments, Piumsomboon et al. [7] [8] depict awareness cues supporting collaboration. Their collaboration framework requires the users to be virtually collocated in a shared environment. In particular, a *HoloLens* user is sharing the reconstructed environment to an expert wearing a Virtual Reality headset. Both can freely move around the shared space without affecting each other. To visualize a remote user, Piumsomboon et al. [7] apply avatars indicating head position and orientation as well as virtual hands and gaze directions. Since *HoloLens* is capable of tracking its orientation inside the shared space, it can transmit the own field-of-view to the expert and vice versa. This provides a remote user's focus of attention. Moreover, eye tracking is applied to involve eye-gaze, which is pointing to focused objects. Results of their usability study reveal that the awareness cues are crucial to improve performance during collaborative tasks. Fundamental research on visual cues as a conversational resource in collaborative physical tasks can be found in [9].

[3] https://vuforia.com/

Oda et al. [10] investigate remote guidance for maintenance and repair. They introduce the remote subject-matter expert (SME) to guide assembly actions on objects in the local user's environment. This requires each relevant physical object in the local user's environment to be modelled and tracked to visualize it in the expert virtual environment. A virtual model is called *proxy* and represents its basic physical counterpart. The SME can annotate and point to the *virtual proxy* while these actions are transferred to the local user's environment. Similarly, avatars and other virtual utilities are presented relative to the tracked object's surface. Some of these approaches for remote collaboration in Augmented Reality have been already introduced by Billinghurst et al. [11].

Oda et al. [10] address the problem of limited tracking concerning heavily damaged objects and arbitrary tools in the local user's environment. In this case, a virtual model might not exist. Here, a video-based approach can be applied [10] [12] [13]. For example, the *HoloLens'* front camera can be used to capture a live video of the local user's perspective. The remote expert can watch the video feed of the user with stereoscopic glasses or any other display device and annotate the video. Collaboration is implemented by augmenting the local user's view with the annotations. But it requires the expert's vision being coupled to the local user. This technique can also be applied to virtual collocation [7] [14]. Here, the expert's and the local user's head positions are coupled in the modelled environment. It supports common spatial awareness but is restricting the expert's mobility. To avoid motion sickness, the head orientations are not coupled.

## 3. DIGITAL TWIN CONCEPT

The concept of the *Digital Twin* intends to optimize and expand the entire value chain of a product with regard to used resources and received profit. The concept was developed in the context of Product Lifecycle Management [15] and gets new boost by the technical and infrastructural possibilities of the on-going digitalization.

The classic development of technical products usually begins with the design of 3D models. In the next step, digital models for structural and functional simulations can be derived. Then, the prototypes for test purposes are built, which provide further information for improved designs and constitute the basis for qualifications. Thus, two basic principles for the realization of the *Digital Twin* already exist, i.e. the physical product and its digital version.

The idea of the *Digital Twin* incorporates a digital version that contains all the information necessary for the manufacturing and qualification of the physical product as well as the geometric-constructive 3D data. Grieves [16] calls this manifestation *Digital Twin Prototype* (DTP).

The term *Digital Twin Instance* (DTI) is used for the data of an individual product [16]. Each DTI contains all information that is generated during manufacturing and operation up to the product's end-of-life. Manufacturing processes provide information for quality assurance, such as sensor data of production processes, non-destructive testing (NDT) and results of functional tests. During operation of an aircraft component, further information is added to the DTI. This includes for example sensor data measuring operating loads, information on damage accumulation, repairs and individual product modifications.

Many of these data fragments already exist for aircraft components today. However, they are often stored on different media (paper documents, individual computer systems and databases) and thus are inaccessible for central digital processing and evaluation.

In order to reach the expected success of the *Digital Twin,* two requirements must be met: Firstly, all collected data and information must be stored in an appropriate environment where it can be accessed by any authorized person or system. This must be enabled regardless of the physical component's location. Secondly, the current status and information must be constantly synchronized between the real component and the *Digital Twin* (see Figure 3).

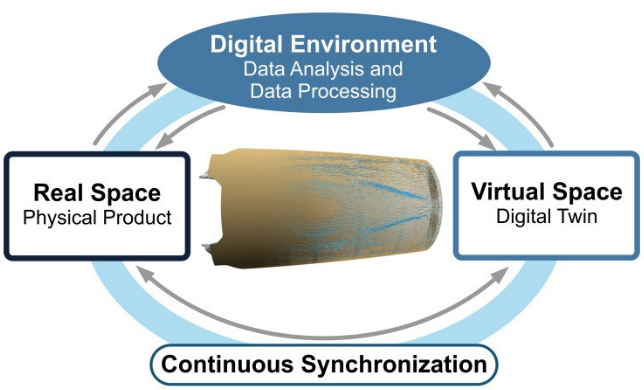


**Figure 3: Overview of basic information management between real products and their *Digital Twin***

Given the two requirements are met, a unified repository and an integrated, multi-domain physics application space can be created applying a *Digital Twin* to a variety of purposes [16]. This includes physical simulation of the component's behavior based on current data or statistical evaluations of sensor data. The online collaboration of engineers based on synchronized DTIs will be discussed in Section 5.

## 4. Mixed Reality Vision

We have designed a graphical user interface to support future inspection and documentation tasks. The interface provides access to the *Digital Twin* database. Its operation requires the inspector to stand in front of the real aircraft component. Essential information about an inspection job is presented by an Augmented Reality application built for *Microsoft HoloLens*.

We introduce inspection windows to display instructions and store damage documentation (see Figure 4). An inspection window can be rigidly attached to the reconstructed environment. This prevents the inspector's view from being cluttered. *HoloLens* even allows placing CAD (computer-aided design) models from the *Digital Twin Prototype* into the work environment. It enables a natural way of inspecting an aircraft's design. In general, CAD models are highly detailed and vector-based. To visualize them on *HoloLens* in real-time, we tessellate surfaces and reduce the details manually in a pre-processing step. Since the CAD model gets recognized as part of the environment, inspection windows can also be attached to it. All virtual content is downloaded from the *Digital Twin* database.


**Figure 4: A blue circle on the component's surface marks a location for damage documentation**

The spatial link between 3D model and documentation can help the user to find damage locations, especially when dealing with bigger aircraft components. During maintenance, for example, small damages can be highlighted on the model surface for later repair. By matching the aircraft component and its virtual CAD model, both can be seen through the *HoloLens* at the same place, here referred as *Mixed Reality Vision*. The highlighted virtual component and damage documentation from the *Digital Twin Instance* can then be found directly on the surface of the real component. The prototype's CAD model does not need to be visualized. The *Mixed Reality Vision* also enables the visualization of hidden parts inside the aircraft component. Based on the CAD, certain model parts can be indicated more precisely.

Our approach uses marker tracking to identify an aircraft component and to track its position and orientation in space. Once the image target is detected, the CAD model is attached to it and the calibration is accomplished. Furthermore, *HoloLens'* tracking is capable of anchoring virtual objects relative to the reconstructed environment. We use a *World Anchor* to stabilize a local coordinate system centered inside the aircraft component. The *HoloLens* operating system handles the stabilization independently.

The interface is not limited to output information. Via voice commands and gesture input, it enables user interaction that is simultaneously performed in the physical and the virtual domain. In particular, every maintenance step with spatial relation to the physical aircraft component is recorded and uploaded to the *Digital Twin Instance*. The spatial relation is indicated by the user's gaze direction. For example, new documentation windows can be attached in case a physical damage is focused and selected by the inspector or during NDT (non-destructive testing, e.g. ultrasonic inspection). The respective documentation window can be filled with voice input, photos, and ultrasound imagery. Given a match with the local coordinate system of the NDT or structural analysis, an in-place visualization of the sensor data directly below the impact can be realized. Every user interaction can directly be fed back to the physical simulation for structural analysis without further ado. Even photos can be projected onto the surface of the CAD model to match the *Digital Twin Instance* with the real air brake's appearance (see Figure 5).


**Figure 5: Photos taken with the *HoloLens'* front camera are projected onto the model surface**

## 5. Remote Collaboration

We propose remote collaboration for maintenance tasks. Inspector and expert can either see an augmented physical aircraft component or its virtual twin at different sites. Both sites are continuously synchronized with the *Digital Twin Instance*. We consider the aircraft component's *Virtual Twin Prototype* as *virtual proxy* [10]. By starting a remote session, inspector and expert can collaborate on the inspected component while seeing each other as avatars. The inspector is acting in front of the physical component whereas the expert, also wearing a *HoloLens,* sees the 3D model and documentation content attached to it.

By bringing all users into the 3D model's local coordinate system, they get virtually collocated relative to the model surface. Since inspection windows as well as the damage documentation are attached to the surface, they can be precisely located in the shared virtual space. Avatars with gaze rays are used to point to common virtual objects even though the physical environments of the users are different. Discussions on focused model and interface parts can therefore be facilitated. However, this approach requires the interface to be aligned with the tracked aircraft component. It is beneficial for the remote expert to visualize the CAD model similarly as seen by the local user. Otherwise the alignment of virtual windows attached to the model surface needs to be mediated between all parties.

The following operational study focusses on synchronous distributed collaboration. Avatars, gaze rays, and voice transmission support the communication between inspector and expert. Via the life synchronization to the *Digital Twin Instance,* the system is capable of sharing information. The graphical user interface coordinates a joint inspection job.

## 6. Operational Study

We present our interface in an operational study which demonstrates the potential and benefits of the *Digital Twin* in a maintenance and repair scenario. It is built for *Microsoft HoloLens* based on *Unity3D*[4] and the *MixedRealityToolkit*[5]. The application's scene contains the composite air brake model.

The purpose of this study is to:

- design an interactive interface suitable for MRO
- learn about the organizational needs for component related data management
- develop profitable applications for MRO in cooperation with engineers of that domain

The following workflow involves all discussed concepts of *Digital Twin*, *Mixed Reality Vision,* and *Remote Collaboration*. Two persons act in separate roles: One of them is the inspector of an aircraft that is in service. The second person is a composite specialist and an expert for certification. She has access to all stored data in the *Digital Twin* database but is located at a distant site.

A regular inspection job was prepared in the inspector's office and then transferred to the *HoloLens*. The action items of the inspection are shown in the main menu. It provides an interface to all other necessary functions as well as a list of former inspections.

[4] https://unity3d.com

[5] https://github.com/Microsoft/MixedRealityToolkit-Unity


**Figure 6: Information panel attached to the airbrake is interpreted as image target**

In order to match the inspection job's scene with the physical component, an image target attached to the air brake (see Figure 6) needs to be scanned. It locks the virtual CAD model including the whole inspection interface in place. A *World Anchor* handles further stabilization of the virtual content so that the image target does not need to be tracked all the time.

The inspection of the air brake starts by selecting "*Start Job*" in the main menu (see Figure 7) via voice command or gaze and gesture input. Since the component's virtual surface does not need to be displayed, only related data is shown. Blue circles appear on the surface of the real air brake marking formerly repaired damages, called findings.

Part of the inspection is to re-check the status of former findings. In order to get detailed information, a *Finding Information Window* can be opened at every finding. It may contain a description, photos, and ultrasonic scan imagery. Our demo application contains two former findings: The first finding marks some scratches on the surface. Ultrasonic scan results as well as the visual appearance indicate a minor surface damage without impact on the structural integrity. The second finding stores repair documentation regarding a former impact damage.

During further inspection, the air brake surface is visually checked. Whenever a new damage is detected, the inspector can create an additional documentation entry. An unfilled *Finding Information Window* appears when the documentation process starts. While a damage description and photos can be attached in the window, a snapshot of the surface is projected onto the virtual air brake and is also stored in the *Digital Twin Instance* (see Figure 5). Finally, ultrasonic scans can be carried out and attached for later damage assessment.

In our case, the inspector alone is not allowed to decide whether the air brake needs to be replaced before continuing flight operations. This decision must be approved by the manufacturer. Thus, a manufacturer's expert needs to be contacted for inspection. Since the expert is not physically present on the site, both start a remote collaboration session wearing the *HoloLenses*. The expert opens the service application and has access to all collected data.

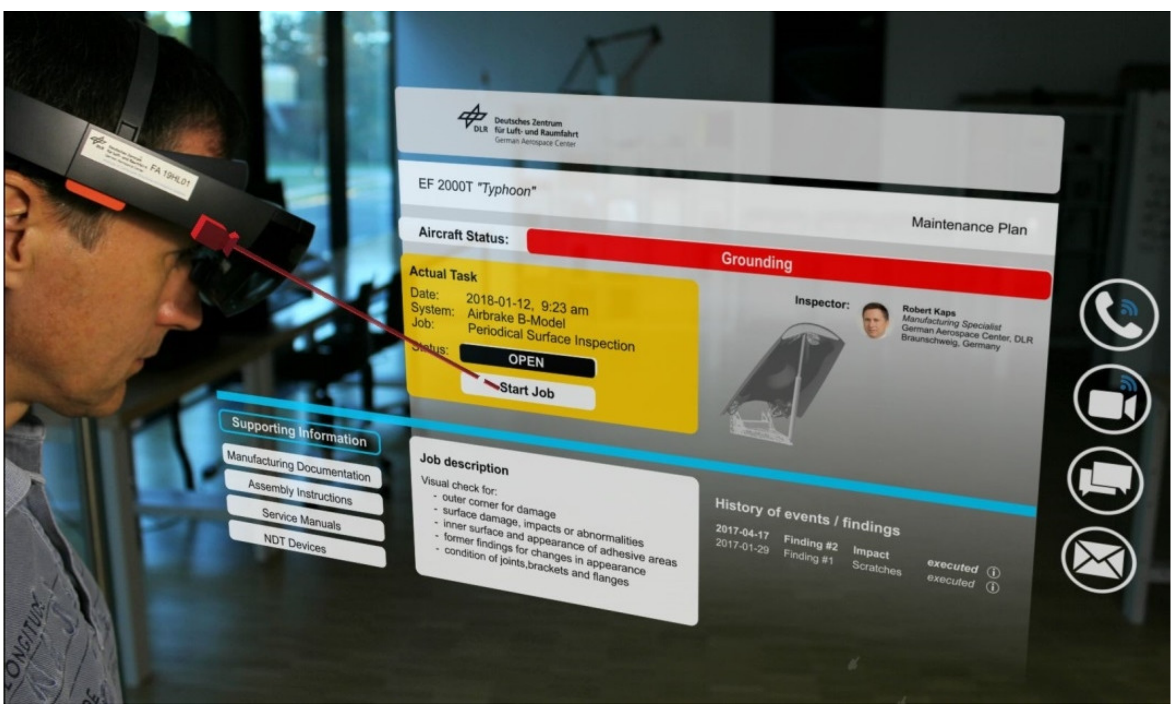


**Figure 7: Inspector's gaze ray pointing to inspection job in the main menu**

This synchronous collaboration session is based on a shared experience collocating inspector and expert around the air brake. While the inspector keeps her *Mixed Reality Vision*, the expert scans the image target to place the CAD model in her office room. Both can see each other as avatars moving around the air brake and the inspection interface. Gaze rays indicate the users' view directions and can hit virtual elements. Next to the virtual air brake, the expert can find the opened *Finding Information Windows* containing damage descriptions. The interface is always synchronized with the inspection. Any interaction on the interface will be transferred to the *Digital Twin Instance*. While the expert examines the virtual air brake and the new finding window, she discusses the damage with the inspector. She opens design and manufacturing documents displayed as windows next to the air brake (see Figure 8). These documents help to identify structural elements that could be affected by the damage.

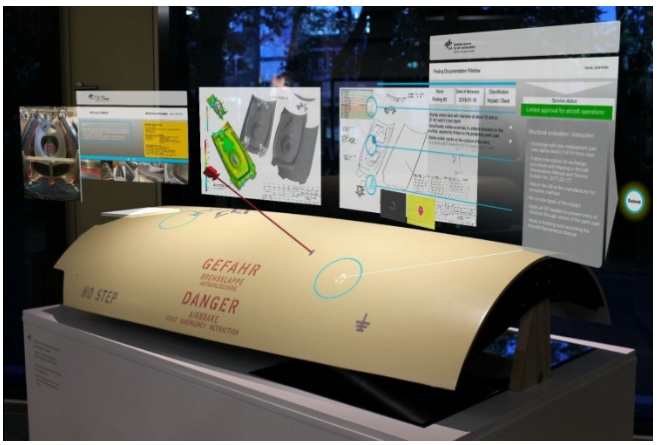


**Figure 8: Expert's avatar (red box) and gaze (red beam) in front of design information and manufacturing documentation windows**

Since both have access to detailed CAD data, hidden parts below the air brake surface can be visualized. In order to assess the damage in place, the expert can cut off a part of the CAD surface and look below the damage. Similarly, the *Mixed Reality Vision* of the inspector allows the augmentation of the real air brake with the virtual interface. The hidden parts appear three-dimensionally inside the real air brake imitating an X-Ray view (see Figure 9). This could assist structural analysis.

In our scenario, the critical bonding area of the two shell elements is not affected by the damage and the expert completes the documentation process. She adds a status report with additional instructions to the new *Finding Information Window*. The report is registered in the main menu where the repair job is listed. On the other site, the inspector receives all these events since her application is synchronized. As no further tasks are listed, the inspector finishes the maintenance by closing the job.

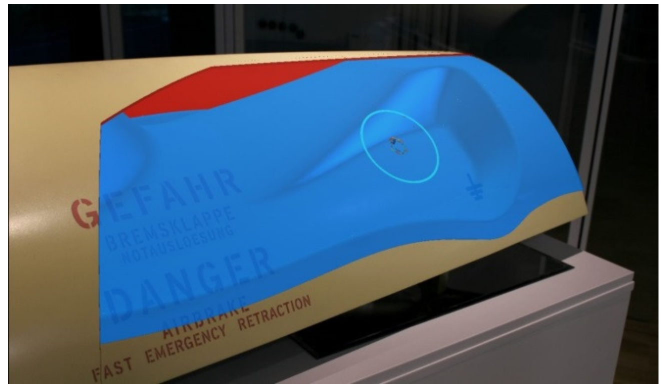


**Figure 9: *Mixed Reality Vision* to display virtual model parts of the air brake below the surface**

## 7. DISCUSSION

In the presented operational study, the inspection of an aircraft component is simulated. It is performed with access to the *Digital Twin* database and the use of Augmented Reality glasses.

The interface presented to the user supports the following aspects:

- discovery of damage locations
- damage documentation
- inspection of external sensor data (ultrasonic scans)
- provision of the information regarding the airworthiness of the aircraft

This scenario involving an inspector and an expert role was presented to a broad specialist audience at various exhibitions. The response was entirely positive. On one hand, it shows us that the emulation of the workflow by the interface reflects the real process. On the other hand, the presented technique is considered to have enormous potential for solving current maintenance problems in the aviation industry. At the same time, various aspects and capabilities were identified that have to be tackled:

*Network Architecture*

In order to perform a realistic remote collaboration session, we will test our application on more complex network architecture. The operational study we have presented is handling communication within a local network regardless of any security concerns. Data encryption and access management will be key elements for industrial use.

*3D Representation*

The information basis on which the expert is supposed to assess any damage is still very limited. Her main information source, the *Finding Information Window*, lacks three-dimensional information. Especially deformed and heavily damaged objects cannot be represented by the *Digital Twin Prototype*. Hence, we have started to incorporate the reconstruction of an aircraft component as part of the physical environment, which is reconstructed by the *HoloLens* on-the-fly. In combination with photos of the surface, a colored three-dimensional reconstruction of an aircraft component can be sent to the expert.

*Asynchronous Remote Collaboration*

Inspector and expert will in practice not be available at the same time. However, asynchronous remote collaboration could be conducted based on the inspection windows and the 3D representation of the aircraft component. Ultimately, asynchronous operation of the *Digital Twin* could facilitate subsequent repair tasks.

*External Tracking*

We also started to investigate outside-in tracking for *HoloLens*. During field experiments, we observed that the *HoloLens* loses track of its position relative to the component's surface. This might happen frequently when working with infrared light reflecting materials or bad lighting conditions and homogeneous surface textures. Furthermore, external tracking could check *HoloLens'* tracking accuracy.

## 8. SUMMARY

In order to improve the efficiency of aircraft inspection tasks, we investigated the potential of the *Microsoft HoloLens* Augmented Reality glasses for damage assessment and remote collaboration.

Using a marker attached to a physical aircraft component, the virtual scene containing 3D model and inspection documentation can be superimposed. This virtual scene is synchronized with the *Digital Twin* database. Therefore, every interaction on the physical component directly updates the *Digital Twin Instance*, which represents all the data collected along the life cycle of one specific aircraft component. A remote expert can see the *Digital Twin Instance* by inspecting all information on the 3D model. Additionally, avatars and gaze rays of all the connected users are visualized during a synchronous remote collaboration session.

In our approach, we have used a variety of HoloLens' capabilities for our aircraft maintenance task. This is approved by a broad specialist audience. The concepts of *Mixed Reality Vision* and *Remote Collaboration* reveal new ways of user interaction and use cases for the *Digital Twin*. By addressing just a particular use case for the *Digital Twin*, its major potential has already been inferenced through our application. These outcomes build the basis for further practical implementations, shaping the idea of digitalization for aircraft maintenance and qualification.


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## REFERENCES


[1] W. J. Verhagen, R. Curran and others, "An ontology-based approach for aircraft maintenance task support," in *Proceedings of the 20th ISPE International Conference on Concurrent Engineering*, 2013, p. 499.

[2] A. Hobbs and A. Williamson, Aircraft maintenance safety survey: Results, Australian Transport Safety Bureau, Department of Transport and Regional Services, 1994.

[3] J. Heida and J. Müller, "In-service inspection and monitoring of composite aerospace structures," in *224 Workshop on Advanced Non-Destructive Evaluation Techniques for Polymer Based Composites in Military Vehicles*, Riga, National Aerospace Laboratory (NLR), 2013.

[4] D. Gasques Rodrigues, A. Jain, S. R. Rick, L. Shangley, P. Suresh and N. Weibel, "Exploring Mixed Reality in Specialized Surgical Environments," in *Proceedings of the CHI Conference Extended Abstracts on Human Factors in Computing Systems*, New York, NY, USA, ACM, 2017, pp. 2591-2598.

[5] M. Bajura, H. Fuchs and R. Ohbuchi, "Merging Virtual Objects with the Real World: Seeing Ultrasound Imagery Within the Patient," in *Proceedings of the 19th annual conference on Computer graphics and interactive techniques*, vol. 26, New York, NY, USA, ACM, 1992, pp. 203-210.

[6] V. Penichet, I. Marin, J. Gallud, M. Lozano and R. Tesoriero, "A Classification Method for CSCW Systems," in *Proceedings of the Second International Workshop on Views on Designing Complex Architectures*, vol. 168, 2007, pp. 237-247.

[7] T. Piumsomboon, A. Day, B. Ens, Y. Lee, G. Lee and M. Billinghurst, "Exploring Enhancements for Remote Mixed Reality Collaboration," in *SIGGRAPH Asia Mobile Graphics & Interactive Applications*, New York, NY, USA, ACM, 2017, p. 16.

[8] T. Piumsomboon, Y. Lee, G. A. Lee, A. Dey and M. Billinghurst, "Empathic Mixed Reality: Sharing What You Feel and Interacting with What You See," in *International Symposium on Ubiquitous Virtual Reality*

*(ISUVR)*, 2017, pp. 38-41.

[9] R. E. Kraut, S. R. Fussell and J. Siegel, "Visual Information as a Conversational Resource in Collaborative Physical Tasks," in *Human-Computer Interaction Journal* , vol. 18, Hillsdale, NJ, USA, L. Erlbaum Associates Inc., 2003, pp. 13-49.

[10] O. Oda, C. Elvezio, M. Sukan, S. Feiner and B. Tversky, "Virtual Replicas for Remote Assistance in Virtual and Augmented Reality," in *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, New York, NY, USA, ACM, 2015, pp. 405-415.

[11] M. Billinghurst and H. Kato, "Collaborative Augmented Reality," in *Communications of the ACM - How the virtual inspires the real*, vol. 45, New York, NY, USA, ACM, 2002, pp. 64-70.

[12] H. Chen, A. S. Lee, M. Swift and J. C. Tang, "3D Collaboration Method over HoloLens and Skype End Points," in *Proceedings of the 3rd International Workshop on Immersive Media Experiences*, New York, NY, USA, ACM, 2015, pp. 27-30.

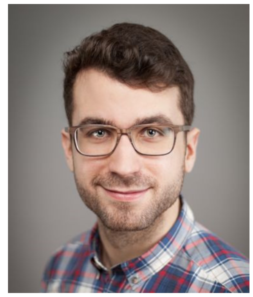
[13] Y. Lee, K. Masai, K. Kunze, M. Sugimoto and M. Billinghurst, "A Remote Collaboration System with Empathy Glasses," in *IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*, 2016, pp. 342-343.

[14] A. Dey, T. Piumsomboon, Y. Lee and M. Billinghurst, "Effects of Sharing Physiological States of Players in a Collaborative Virtual Reality Gameplay," in *Proceedings of the CHI Conference on Human Factors in Computing Systems*, New York, NY, USA, ACM, 2017, pp. 4045-4056.

[15] M. Grieves and J. Vickers, "Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems," in *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, F. Kahlen, S. Flumerfelt and A. Alves, Eds., Cham, Springer International Publishing, 2017, pp. 85-113.

[16] M. Grieves, "Digital Twin: Manufacturing Excellence Through Virtual Factory Replication," Dassault Systèmes, 2014.

## BIOGRAPHY



***Sebastian Utzig*** *received a M.Sc. in Computer Science and Media from Bauhaus University Weimar, Germany, in 2016. He specialized in Virtual Reality and Interactive Visualization and is now researcher at the German Aerospace Center (DLR). At the department "Software for Space Systems and Interactive Visualization" he is investigating the application of HoloLens in scientific environments. Furthermore, he is leading the research on 3D interaction within virtual environments and cooperating with engineers of the aerospace domain.*

***Robert Kaps*** *is a research associate and an expert for Composite Manufacturing Technology at the German Aerospace Center (DLR), Institute of Composite Structures and Adaptive Systems. He received his degree in Aerospace Engineering in 1997 at the Technical University of Braunschweig. He worked in the automotive supply industry as an advanced developer before he continued research work in the field of aeronautical structures at the DLR in 2002. He got his doctoral degree in composite manufacturing technologies in 2010 and until now continued research activities in the field of the industrialization of composite manufacturing and later the incorporation of 3D interaction.*

***Syed Muhammad Azeem*** *is a research scientist at the department "Software for Space Systems and Interactive Visualization" of the German Aerospace Center (DLR). In 2013, he received his degree in Computer Engineering from National University of Sciences and Technology (NUST), Islamabad, Pakistan, and served the software industry in his country for two years. Before moving to Germany in 2017, he received his Master's degree from University of Science and Technology (UST), Daejeon, South Korea, and Diploma from Korea Institute of Science and Technology (KIST), Seoul, South Korea, where his focus was Virtual and Augmented Reality research.*

***Andreas Gerndt*** *is the head of the department "Software for Space Systems and Interactive Visualization" at the German Aerospace Center (DLR). He received his degree in computer science from Technical University, Darmstadt, Germany in 1993. In the position of a research scientist, he also worked at the Fraunhofer Institute for Computer Graphics (IGD) in Germany. Thereafter, he was a software engineer for different companies with focus on Software Engineering and Computer Graphics. In 1999, he continued his studies in Virtual Reality and Scientific Visualization at RWTH Aachen University, Germany, where he received his doctoral degree in computer science. After two years of interdisciplinary research activities as a postdoctoral fellow at the University of Louisiana, Lafayette, USA, he returned to Germany in 2008.*