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Synchronizing aeronautical Digital Twins in complex stakeholder environments via 3D scanning

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Abstract
Digitalization in the aviation industry is driving the transition towards climate-neutral and more sustainable aircraft. A central focus of research is the Digital Twin, a virtual representation of the physical system that continuously collects operational data during operation in order to increase efficiency and optimize maintenance. A challenge arises when different stakeholders such as manufacturers, airlines and maintenance companies create independent Digital Twins, which leads to inconsistencies and contradicts the very idea of a single Digital Twin per system. Isolated IT environments prevent the possible synchronization of information. One approach to synchronizing geometric data is the use of 3D scans. As aircraft cabins are frequently refitted, digital 3D models are often incomplete, if they are available at all. By comparing scans with the initial Digital Twin, modifications can be recorded and updated even if no original data is available. This enables precise documentation of the cabin interior and facilitates the iterative updating of the Digital Twin, which supports the planning and analysis of conversions as well as versioning of modifications.

Keywords Aeronautics · Digital Twin · 3D scanning · Aircraft cabin · Object recognition

1 Introduction

The aviation industry is facing the major challenge of managing the transition to a climate-neutral and environmentally friendly aircraft and a sustainable air traffic. Digitalization can improve efficiency and sustainability in aviation. However, the complete and end-to-end digitalization of the entire aircraft system is still a vision that needs to be implemented and consistently driven forward. In order to take a significant step towards this goal, the German Aerospace Center (DLR) is working on the end-to-end digitalization of aviation, from the preliminary designs through production and operation to the decommissioning of an aircraft [1]. This objective is also set out in the aviation strategy of the German Federal Government [2] and the Helmholtz Association [3]. The DLR itself has set the goal of utilizing its systems expertise and assuming the role of a virtual OEM[1] that understands the complex interactions between the individual subsystems of the aircraft. The aim is to realize new, highly efficient and climate-friendly aviation systems, thereby accelerating the energy transition in aviation [1].

To achieve this goal, all development steps of the complex aircraft system must be understood and digitally mapped. This allows errors to be identified and rectified at an early stage before they affect the entire design and development process. The overall digital representation of a system over its entire life cycle is referred to as the Digital Thread. This contains a large amount of digital data from all phases of the aircraft's life cycle and links them together in a meaningful way. By intelligently linking all information, new innovations are accelerated and the lead times and entrepreneurial risks for new, more environmentally friendly aircraft designs are reduced. In addition to the Digital Thread, the

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term Digital Twin is currently ubiquitous. The Digital Twin is a virtual representation of a physical product that contains all the relevant information of its physical counterpart at a specific point in time. By using a Digital Twin, the complex interactions between the individual subsystems of an aircraft can be understood and analyzed. As it is already done by multiple companies and institutions, including OEMs and suppliers. Section 2.3 describes examples from various companies in more detail and explains how they benefit from Digital Twins.

The cabin plays a special role in the life cycle of an aircraft. This safety-critical subsystem for passengers and crew benefits in particular from new sustainable technologies and energy-efficient production due to the short replacement cycles of 5–7 years [4]. Due to the regular retrofit of the cabin, many changes take place, which also need to be transferred to the Digital Twin. These modifications are often planned and implemented by different companies. This raises the question of how this information can be integrated into the Digital Twin of the aircraft. Optical measurement technology offers a possible solution here, in which high-resolution geometric images of the actual environment are created.

This article first presents the concepts of digital continuity in aviation, focusing on the Digital Thread (Sect. 2.1) and the Digital Twin (Sect. 2.2). Following is a list of examples of Digital Twins applications in aviation and an explanation in Sect. 2.3. This list of the various Digital Twins also shows their challenges in aviation, which are discussed in more detail in Sect. 2.4. Finally, the possible use and benefits of 3D scanning for Digital Twins are discussed in Sect. 3.1. Section 3.2 shows the advantages of 3D data for modification analysis using the example of 3D data captured of the DLR research aircraft ISTAR.[2] This is followed in Sect. 3.3 by suggestions on the preparation of 3D point clouds. Section 3.4 presents different fidelity levels of cabin components for data in Digital Twin applications.

2 Digital consistency in aviation

Digital consistency in aviation describes the digital end-to-end process of an aircraft, starting from the preliminary design through the development and production phase of the system to operation and decommissioning with the scrapping of the aircraft. Digital data and information describing the system is generated during all these phases of its life cycle. The digital consistency is composed of two areas, the Digital Twin, the digital representation of a physical system, and the Digital Thread, which enables the continuity of data and information. These two areas are described in more detail in the following chapters.

2.1 Concept of the digital thread

The Digital Twin, discussed in Sect. 2.2, obtains all of its data, information and knowledge from the Digital Thread. This concept provides the consistent and chronological storage and linking of information and data throughout the entire life cycle of a physical product. The aim is to create a single source of truth which, as a central and consistent data source, ensures the complete traceability of all product-related information over the entire life cycle - from early conception to design, production, operation and decommissioning [5, 6].

A wide range of data flows into the Digital Thread, including modeling and design data, sensor data, control and regulator information, material characteristics, operating conditions, as well as further digital information generated in the various phases of the product life cycle, as shown in Fig. 1. This data is to be intelligently linked and analyzed via a data-driven infrastructure. This not only achieves seamless digital documentation, but also creates a solid basis for data-based decision-making [6].

An important application of the Digital Thread is the close link with the concept of the Digital Twin. While the Digital Twin represents a digital image of a specific product at a specific point in time, the Digital Thread provides the structured database from which the Digital Twin can be generated, updated and further developed. The Digital Thread thus forms the backbone of the Digital Twin, providing the necessary means to generate the technical system architecture of a physical twin and continuously supplying it with up-to-date information [7].

Especially for complex systems as aircraft, the Digital Thread interconnects various digital information, such as digital design data, test results, certification information and operating data. This enables an end-to-end view of the product, which not only increases the quality and efficiency of development processes, but also improves life cycle management [5, 6].

The concept of the Digital Thread described here represents the ideal of a unified and end-to-end backbone. Unfortunately, the reality is quite different: the relevant data is often scattered across the proprietary IT systems of various stakeholders. The challenges arising from this fragmentation are discussed in more detail in Sect. 2.4.

2.2 The definition of digital twins

Digital twins are currently being researched in many fields. The primary focus is on gaining deeper insights into

[2] In-flight Systems & Technology Airborne Research.

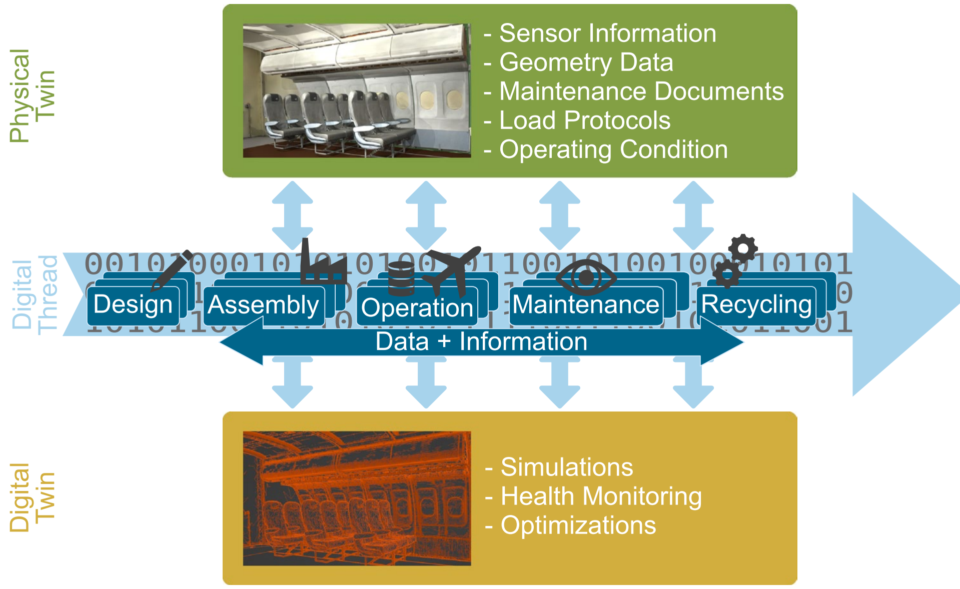

Fig. 1 Illustration of the Digital Twin in connection with the Digital Thread

performance, behavior, and other characteristic features. Digital twins are used, among many other fields, in biomedical research, engineering, atmospheric research. It is intended to serve as a decision-making tool, leveraging a synergistic combination of data and models [8].

There are numerous definitions of a Digital Twin in the literature. However, they all have one thing in common, they consist of three main components [8–11]:

1. the physical product,
2. the digital product and
3. the bidirectional data connection between the physical and digital product.

The physical product provides the information and data on it's structure, condition, and behavior over its entire life cycle, from design until disposal. The digital product describes its physical counterpart virtually, based on the information provided. It is designed to reflect the current status of the physical product at all times, drawing its information via the bidirectional data connection established by the Digital Thread (Sect. 2.1). These three areas, which can also be seen in Fig. 1, are in constant communication with each other and cannot be viewed isolated [12].

The Digital Twin covers the entire life cycle of the physical product, from design through manufacturing and service to the product's disposal [10]. According to Stark et al. [11], the life cycle of the Digital Twin begins only when the physical counterpart is put into operation, based on existing 3D models and data, or after information about the real object has been collected. However, it should already be prepared during the product development and manufacturing phase, as there are already a huge amount of data is generated, and continuously expanded. In this context, the Digital Twin represents a single, manufactured product, meaning that for every *n* manufactured products *n* Digital Twins must be initiated [13].

The Digital Twin describes the digital representation of a clearly identifiable physical or logically existing object or system that reflects its properties, conditions and behavior over the entire life cycle of the product. The foundation for this is the Digital Thread described in Sect. 2.1, as shown in Fig. 1.

With the systems entry into the operation phase, the complexity increases, due to multiple variables and unpredictable factors during the life time [14]. In order to keep the Digital Twin up to date, changes must be regularly recorded and reflected. In addition to manufacturing inaccuracies, geometric changes also include wear and tear or adjustments and modifications by the user [13].

Digital Twins are expected to accelerate the discovery of scientific findings and revolutionize entire industries. Through the dynamic link between physical and digital systems, the Digital Twin takes on a dynamic character that goes beyond previous modeling and simulation methods. A virtual model is created that evolves over time in parallel with the physical system, thereby surpassing the capabilities of conventional modeling and simulation. Key functions include predictive insights, anomaly detection, performance monitoring, and dynamic system simulation. Together, these enable faster scientific insights, improved operational efficiency, shorter time-to-market, and new opportunities for industrial innovation [8].

2.3 Application examples of digital twins in the aviation industry

Many companies and research institutions within the aviation industry have already started developing Digital Twins, some of which are designed for different areas and use cases.

Aircraft manufacturers and maintenance, repair and overhaul companies (MRO) are developing holistic Digital Twins of aircraft that take the entire system into account. For Airbus, Digital Twins are the cornerstone of a transformation towards a more sustainable and efficient aviation industry, which will initially involve creating a Digital Twin in the virtual world alongside the physical product. Airbus sees the Digital Twin "as a dynamic, living virtual replica" that integrates information from design, manufacturing and operations to create a permanently updated image of the physical object or system [15]. First, the Digital Twin enables product development to simulate a variety of real-world scenarios through physics-based models, reducing the need for physical prototypes, improving design and performance validation and accelerating time to market. In the next step, Digital Twins help Airbus to plan production systems by simulating tools, robots and workflows. They use machine data to monitor production processes and supply chains. When the aircraft enters into service and is therefore added to Airbus *Skywise* platform, data and information collected by sensors during operating times flows into the Digital Twin in real time to predict wear and tear, optimize maintenance schedules and reduce downtime [16]. *Skywise* itself is described as a comprehensive and cloud-based data platform that is seen as a central hub for the integration, analysis and use of large amounts of data from various areas of aviation, including development, flight operations and maintenance.

With its *Aviatar* platform, Lufthansa Technik represents a Digital Twin of the entire aircraft, with each component modeled virtually. It is a manufacturer-independent, modular and cloud-based platform for digital aircraft maintenance and operation. Data on the components is recorded by sensors and other measuring equipment in the flying aircraft and sent to the Digital Twin in real time. This means that the condition of the aircraft can be permanently monitored, for example to carry out maintenance before a defect occurs. But it can also be used by airlines for fleet management [17, 18].

In addition to approaches for Digital Twins of entire aircraft, Rolls-Royce, a supplier of aircraft engines, is developing a Digital Twin for engines in order to be able to model potential operating scenarios completely digitally. To this end, sensors are integrated into the real engine in order to pass on the status data to the Digital Twin, enabling it to behave digitally in the same way as the real engine on the aircraft. This enables Rolls-Royce to better predict maintenance, thereby reducing repair times and increasing the safety of the systems. Also, behavior under very extreme conditions can be simulated and examined, which would not be possible with real engines [19, 20].

The airline KLM has teamed up with the company Matterport, which mainly creates virtual images of interiors and buildings, to create digital panorama images of their entire aircraft fleet using camera technology. KLM has identified two user groups for the use of these images. Firstly, they are used for training employees such as ground staff, flight attendants and pilots. An annotated image for ground staff shows the cleaning process and where service trolleys are stowed in the cabin. Pilots use the image for their pre-flight safety checks, where problems can be illustrated. Flight attendants get to know the layout of the cabins in advance and the position of safety components and passenger service items. On the other hand, KLM Business Class travelers can experience the cabin virtually and choose a seat that suits them best [21].

Lufthansa Aviation Training is working together with the ETH Zurich on a Digital Twin for the virtual delivery of training content for safety and emergency cabin training. The aim is to create a virtual replica of an A320 CEET[3] based on existing aircraft and equipment specifications, which complies with the recommendations of International Civil Aviation. It is promised that the "Digital Twin" will display all relevant training content in virtual reality and on a tablet. This will eliminate the need for time-consuming and cost-intensive physical cabin replicas [22].

In addition to the efforts to create digital images of entire aircraft or individual systems, there are also efforts to create a Digital Twin of the infrastructure on the ground. Cologne Bonn Airport, together with the University of the Federal Armed Forces in Munich, is developing a Digital Twin of the entire airport. Initially, the infrastructure and operational processes are being modeled on the airside and landside. It will be used to test various scenarios and make targeted use of synergies. The aim is not only to create simulations, but also to combine them with real-time data [23].

Companies outside the aviation industry are also working on the implementation of Digital Twins. One among many others is Siemens. They see Digital Twins as virtual representations of a real object or process, based on powerful and physics-based simulations. It supports the digital planning and optimization of objects and production systems, reducing the use of physical prototypes. By constantly adapting the Digital Twin to changes in the real counterpart, Siemens sees a "closed feedback loop in a virtual environment". In addition to the Digital Twin for the product, the Siemens

[3] Cabin Emergency Evacuation Trainer.

platform enables the Digital Twins of the product and production to be linked. This supports "the planning and optimization of machines, production lines and entire factories" [24].

An analysis of these examples shows that industry and research are working on the implementation of Digital Twins in aviation. However, there are significant differences in the scope of the systems under consideration. Approaches range from holistic twins at the system level (Airbus, LHT) to specific subsystem models (Rolls-Royce) or Digital Twins of infrastructure (Cologne/Bonn Airport), suggesting that the level of detail in the model depends heavily on the specific operational challenges at hand. With regard to data integration, there is a clear distinction between purely visual representations (e.g., KLM's virtual cabins), which function more as high-resolution virtual models, and dynamic twins based on real-time sensor feedback, such as for predictive maintenance (Airbus, LHT). This indicates varying degrees of maturity, with "active" twins offering direct added value for operational efficiency, while "passive" twins, such as those from KLM or Lufthansa Training, optimize training and marketing. It is also evident that holistic Digital Twin approaches rely on platform-based solutions, like Airbus Skywise or LHT Aviatar, though it remains unclear how data exchange between manufacturers, operators, and service providers is intended to function across these platforms (Table 1).

2.4 Key challenges in implementing digital twins

As described in Sect. 2.1, the concept of the Digital Thread is based on a single, unified data backbone that connects all information across the entire product life cycle. In practice, however, this is often not the case. Instead of a single Digital Thread feeding a single Digital Twin, there are many parallel and isolated implementations, leading to a fragmentation of digital consistency of the system.This is due to the fact that many companies and institutions are working on their own Digital Twin applications, which are based on different requirements and contexts. These parallel initiatives

Table 1 Examples of Digital Twins in the aviation industry

Company/partner	Twin scope	Main benefits	Industry domain	Platform/ context
Airbus [16]	Holistic Digital Twin (Design, Manufacturing, Operation)	Simulation of real-world scenarios during product development, reduced physical prototypes, accelerated validation, production and supply chain monitoring, predictive maintenance, reduced downtime	Aircraft Manufacturing & Operations	Skywise
Lufthansa Technik [17, 18]	Digital Twin of entire aircraft (component-based, modular)	Real-time condition monitoring, predictive maintenance, fleet management, manufacturer-independent	Aviation (MRO)	Aviatar
Rolls-Royce [19, 20]	Digital Twin for aircraft engines	Digital operation modeling, improved maintenance prediction, shorter repair times, enhanced system safety, extreme condition simulation	Aviation (Engines & Maintenance)	–
KLM & Matterport [21]	3D panorama images/digital cabin visualization	Training for ground and cabin staff and pilots, visual safety checks, virtual seat selection for passengers	Airline (Training & Service)	Panoramic images visualization
Lufthansa Aviation Training & ETH Zurich [22]	Digital Twin for virtual safety training (A320 cabin replica)	VR/tablet-based training, elimination of physical cabin replicas, time and cost savings	Aviation (Training & Education)	VR Platform
Cologne Bonn Airport & Univ. Bundeswehr [23]	Digital Twin of airport infrastructure and processes (airside/landside)	Scenario testing, synergy exploitation, integration with real-time data	Aviation (Infrastructure & Operations)	–
Siemens [24]	Digital Twin for products and production systems	Virtual representation, digital planning and optimization, reduced prototypes, closed feedback loop, factory planning	Cross-Industry (Mechanical Eng & Industry 4.0)	Siemens Platform

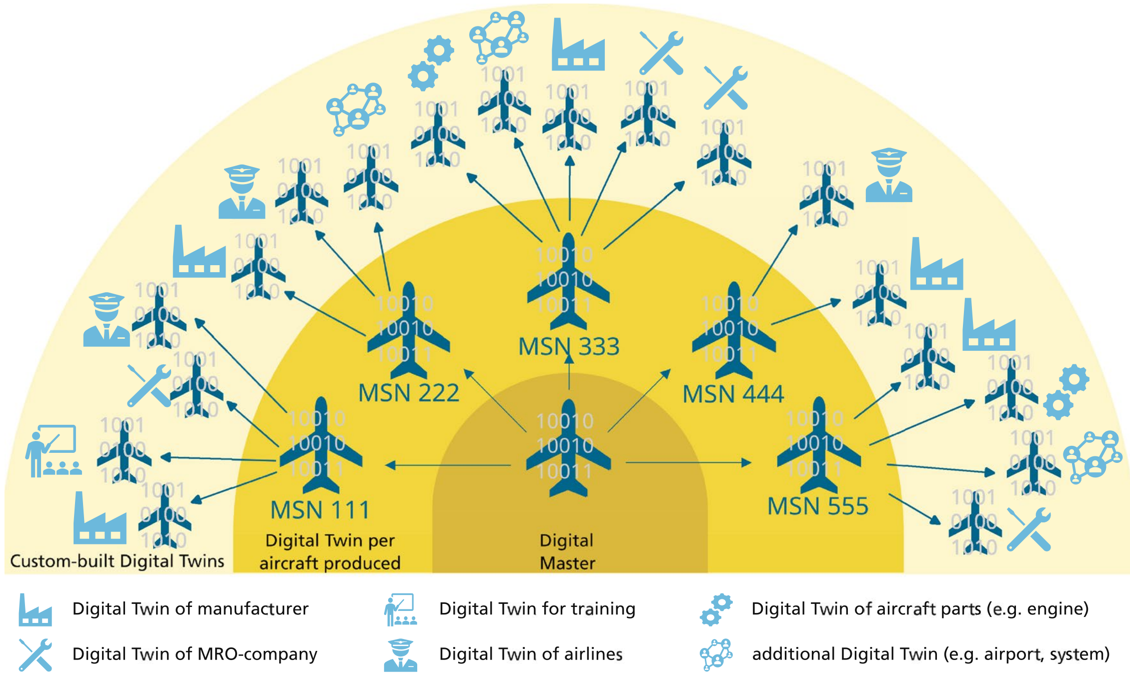

Fig. 2 Fragmentation of the Digital Twins by different stakeholders

Table 2 Summary of the challenges identified in the parallel development of Digital Twins, along with proposed solutions from the literature

		Approaches								
		Moenck [25]	Attaran [26]	Abounaja [27]	Illmann [28]	Naderi [29]	Landon [30]	Sadeghi [31]	Kabashkin [14]	Bae [32]
Challenges	Data ownership	◐	○	●	●	●	◐	○	●	○
	Digital Twin collaboration platform	●	◐	●	○	●	○	○	◐	●
	Data and IT security	○	◐	○	◐	○	○	◐	◐	●
	Ethical aspects	○	○	○	◐	○	○	○	●	○
	Sharing data with third parties	●	○	○	○	○	●	○	○	○
	Data generation and transfer	○	○	○	○	○	○	●	○	●

Legend: ○ not addressed, ◐ partially addressed, ● addressed

and proprietary developments by different companies lead to a wide range of Digital Twin fragmentation throughout the entire value chain, as shown in Fig. 2. Table 2 provides a summary of the challenges associated with the simultaneous development of Digital Twins with different focuses. The horizontal columns group the challenges into five broad categories, while the vertical columns refer to studies that describe approaches to addressing these challenges. The challenges and approaches are described in greater detail below.

According to Stark et al. [11], the digital master, which contains the product geometry and behaviors, is created during the development phase. With the completion of each physical product, a Digital Twin is created for this one product. As the individual stakeholders initiate their own Digital Twin applications from this moment on, or at later points in time, the actual idea that there is a single Digital Twin for a system, in this case an aircraft, which reflects all the information about this one system in digital space, is not fulfilled. There is also the question of who owns the Digital Twin and who has to share which data and information with whom.

In addition to the organizational issue of data ownership, it is also important to consider the challenges of generating data and the large amounts of data that is collected at every stage of operation. Furthermore, amassing large volumes of unfiltered data can negatively impact the carbon footprint, as the additional storage and processing of the data requires large amounts of energy. The sensors installed in various areas and systems in the aircraft must withstand the extreme operating conditions of an aircraft, such as extremely high temperatures in the engine, or high pressure and cold temperatures on the fuselage, and must not fail [25]. Also the real-time transfer of data from the physical into the digital space and back without any communication latency must be considered. Therefore, Bae et al. sees the upcoming 6 G networks as a promising solution for managing big data sets [26]. Further, the question of how to deal with faulty information from sensors that provide wrong values arises, which leads to incorrect decisions being made on the basis of these values. Sadeghi et al. lists possible solutions, such as K-nearest neighbors to filter wrong or false information [25].

Moenck et al. [27] and Attaran et al. [28] also sees this problem as challenges of Digital Twins in aviation. They explain that the large number of different stakeholders involved in the production and operation of an aircraft makes it difficult to implement the system digitally across all phases of its life cycle. The relevant information is often stored on different and proprietary IT systems of the respective stakeholders, which makes continuous integration of the data and its traceability across system boundaries difficult.

An industry-wide standard could enable the exchange of relevant data and information for the Digital Twin, which is collected or provided by different stakeholders, across IT system boundaries. However, the industry is far from a standard, including a regulation for controlling IP-protected and sensitive operational data. This highlights the need for collaboration across company boundaries, from OEMs to suppliers, airlines and MRO companies. A collaboration platform could enable standardized, secure and dynamic data exchange [14, 27, 28]. Beyond the technical challenge of establishing such a platform, the economic value of Digital Twins is still not clearly understood or articulated across the industry. In particular, the upfront costs of developing and maintaining Digital Twins need to be weighed against their expected return on investment, which varies significantly depending on the stakeholder and application [10]. Furthermore, while large OEMs and airlines have the IT infrastructure to support Digital Twin development, smaller companies across the supply chain often do not, which further limits the potential for industry-wide collaboration [10].

Even if there is a collaboration platform for the exchange of digital data for a Digital Twin in the future, there is still the question of the ownership of the twin and the data it contains, which accumulates over the course of the life cycle phases through the various stakeholders. Stakeholders may include OEMs, suppliers of systems such as engines, landing gear or cabin equipment, airlines, owners, operators or MRO companies, all of whom provide information and data for the overall system. The issue of data ownership is therefore a central problem with Digital Twins. It is crucial to clearly define who has control over the data that is collected, processed and stored in a Digital Twin. This includes rights to access, modify, share and monetize the data as well as responsibility for its accuracy and security.

IT security is a crucial aspect in the safety of a Digital Twin, especially when human beings are involved. Since there has to be an exchange of data and information between the physical and the Digital Twin, there is a gateway for intruders and the databases have to be protected against any kind of cyber-attacks, ransomware, or data theft [25]. Bae et al. [26] sees an active research of integrating AI and blockchain within Digital Twins promising a secure, reliable, and traceable data exchange.

To avoid potential conflicts, Abounaja [29] advises clear contractual agreements that regulate the ownership rights and terms of use of the Digital Twins. This primarily refers to the ownership of the data and information generated by different stakeholders and on which the Digital Twin is dependent. In addition to a clear contractual regulation on the ownership claims to the data within the Digital Twin, Illman et al. [30] also sees an ethical aspect in the use of Digital Twins, especially in the discovery of unexpected information and a possible obligation to notify the persons concerned. Kabashkin et al. [14] sees the ethical aspect in a different way. As Digital Twins “becomes more autonomous and play a greater role in decision-making processes", questions of accountability and responsibility emerge when errors or failures occur. Therefore a regulatory framework has to be established, that ensures that Digital Twin technology is implemented in a manner that is ethical, transparent, and fully compliant with relevant laws.

Naderi et al. [31] describes that Digital Twins integrate data from different sources, which has already been mentioned as a problem. This diversity of sources can lead to conflicts in the question of ownership rights, especially when it comes to accessing, modifying, sharing or monetizing the data. To overcome the challenge of ownership of collected data, Naderi et al. [31] and Kabashkin et al. [14] proposes the use of blockchain technology and non-fungible tokens (NFTs), which offer the possibility of establishing unique ownership rights to data via digital certificates. NFTs offer the advantage of clearly assigning data ownership, ensuring the integrity and authenticity of data and thus facilitating the exchange of knowledge between stakeholders. Additionally, blockchain technology can provide a secure, immutable record of maintenance history, ensuring all relevant data remain accessible even when ownership changes.

3 Tracking cabin modifications using 3D scanning

While 3D scan data and point cloud processing methods have been widely studied in domains such as building surveying and autonomous driving, their application to document aircraft and aircraft cabin in the context of Digital Twins has received limited attention. This work applies these methods to a new domain, demonstrating how 3D scan data can be used to track cabin modifications and generate geometric updates for a Digital Twin, without relying on data from other stakeholders. The contribution is therefore primarily application-oriented, showing the feasibility of this approach for a specific and practically relevant use case in aviation.

As long as data and information cannot be exchanged between stakeholders due to ownership issues or a lack of suitable interfaces, it is possible to collect data by yourself and use it to serve your own Digital Twin. Next, a case will be considered in which geometric changes have been made to an aircraft cabin, such as through a retro-fit. In this case, it may happen that a stakeholder has the rights to the modeling data for the conversion, such as 3D CAD data but, does not share it to the airline or other stakeholders. One way to generate 3-dimensional geometric actual data is to use suitable 3D scanning methods. Moenck et al. [27] points out that the generation of data and information for retro-fit and modifications to an aircraft is a frequently repeated work step. 3D scanners offer the advantage of capturing the physical environment in its actual state. This section will focus on the use of 3D scan data to update the actual geometric data in the context of Digital Twins.

3.1 Application of 3D scanning for geometric data acquisition

3D scanners generate a replica of the captured objects in a point cloud or a surface mesh, which describes the physical interface between the work-piece and its environment. These are essential for creating realistic virtual models and makes it possible to accurately capture the physical properties and behavior of a system and make it easier to understand them. The 3D models integrated in Digital Twins enable an early and efficient assessment of the impact of design decisions on the quality and function of new developments and modifications, without costly and time-consuming physical mock-ups [32]. In addition to installation space analyses, geometric models also help the applications of Digital Twins described in Sect. 2.3, such as the virtual training of flight attendants.

For Digital Twins to be effective, the data and information they contain must mirror the current state of the physical counterpart. To achieve this, latest status and operating data of the systems is recorded using suitable sensors, such as acceleration or vibration sensors. Optical measurement technology with 3D scanners is suitable for recording current geometric data. This method makes it possible to create a virtual model that reflects the actual geometry of the system, including possible deviations from CAD data due to manufacturing inaccuracies or wear. This involves continuously recording the systems, including changes and modifications, and integrating them into the virtual model within the Digital Twin [33].

3.2 Analysis of modifications within the life cycle of a research aircraft

Research aircraft are subject to frequent conversions and modifications due to the diverse nature of their field campaigns. This characteristic makes them ideal for collecting various datasets at short intervals. In the DLR project DigECAT,[4] these changes are regularly captured and digitized using 3D scanners on the DLR research aircraft ISTAR. The procedure for recording the actual geometry of the cabin and the aircraft exterior, as well as the post-processing steps, is described in [34].

Figure 3 illustrates the modifications of the ISTAR over the course of 2021 and 2022. Figure 3a depicts the aircraft's delivery state, showing an empty cabin that contains only the seats. In May 2022, the flight test engineer (FVI) workstation was captured and integrated into the overall cabin model (Fig. 3b). Subsequently, the basic measuring station was recorded in its installed position in November 2022. This configuration (Fig. 3c) represents the general flight condition, as these components are permanently installed in the cabin. Depending on the specific measurement campaign, additional research equipment is added, for example, Fig. 3 displays a camera frame for an IPCT[5] measurement, along with equipment for surface pressure measurement on the fuselage and wings.

These datasets document the modifications to the ISTAR's cabin over a two-year period. All this data is consolidated into a comprehensive virtual geometric model of the aircraft, reflecting its shape at any point in time. The scan data used in this work was captured using an ATOS Compact Scan, a structured light scanner with a manufacturer-specified measurement accuracy of up to 0.02 mm. The resulting point cloud of the ISTAR cabin consists of approximately 12.9 million points with a total file size of 880 MB in the STL-format, which gives an indication of the data volume involved in processing a single cabin scan

[4] Digital Twin for Engine, Components and Aircraft Technologies.

[5] Image Pattern Correlation Technique.

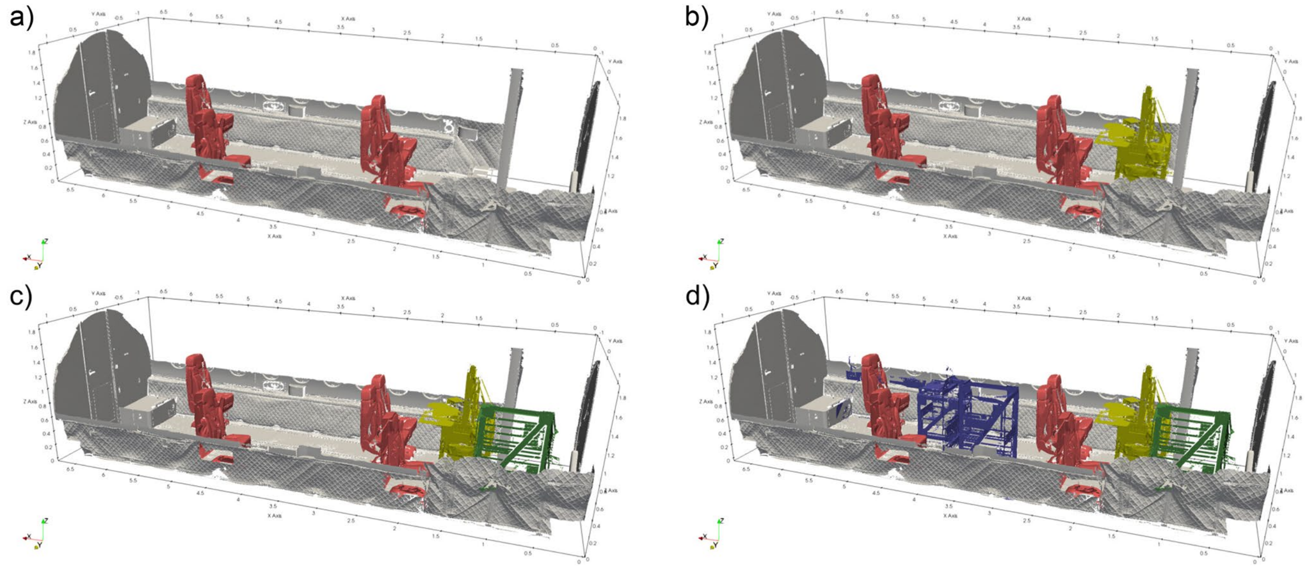

Fig. 3 Modifications in the cabin of the DLR research aircraft ISTAR March 2021 to November 2022, **a** delivery status March 2021; **b** installation of the FVI station in May 2022; **c** modification by basic measurement system in November 2022; **d** integration of camera rack and measurement setup in November 2022

of the ISTAR research aircraft, based on a Dassault Falcon 2000LX. A systematic quantitative validation of the change detection results, including accuracy analysis under varying environmental conditions and computational performance measurements, is beyond the scope of this work and is identified as a necessary next step before the approach can be applied in an operational setting.

While the cabins of passenger aircraft are not refurbished as frequently as those of research aircraft, they also undergo changes at recurring intervals. For instance, cabin components are typically replaced every 5–7 years and may exhibit significant wear and tear due to constant use [4]. Similar to research aircraft, these modifications can be tracked over time and visualized within the geometric model of the aircraft for its respective Digital Twin.

3.3 Workflow to process 3D point clouds

In order to record and visualize the individual components or the modifications and changes in the cabins after a retrofit, the 3D data sets must be prepared using suitable methods. A comparison method between the images from two different points in time is suitable for identifying the modified components. As the recording systems and settings can differ from scan to scan, which can result in a different point distribution and density in space, pre-processing of the data sets is necessary. In addition, there are two further challenges when using point clouds or surface meshes in space. Scan-related artifacts can arise due to non-diffuse reflection properties or noise caused by air particles which can lead to false change detection and therefore also require pre-processing of the data. Occlusions or inaccessible areas lead to incomplete point cloud data and make it difficult to reliably detect changes. In order to identify modifications in this case, deep learning methods are proposed to fill in the areas that cannot be detected [35]. For the case considered in this contribution, however, initially only the detection of the change is required, such as a change in seat pitch, so that scanner-related artifacts must be filtered out, but hidden areas are not taken into account.

Kharroubi et al. [35] proposes the removal of unwanted measurement points for the pre-processing of the point clouds. These can be caused by moving parts, reflections or measurement noise. Manual processing of the point clouds or algorithms such as statistical outline removal or noise filters, which remove outliers and measurement points that are further away from other points, are suitable for this purpose. Filters are also used to separate out irrelevant areas, such as ground points. For this purpose, Kharroubi et al. [35] mentions, among other things, segmentation-based filters that classify point clouds into defined classes. In order to be able to compare the images of two or more states, the point clouds must be superimposed, which is done in the registration step. This can be done by transferring them to a common coordinate system, such as the global aircraft coordinate system in this case is the origin oriented at the nose tip. The 3D data is then rasterized in order to obtain a uniform distribution of measurement points in all states and to make the states more comparable [35].

The point-based comparison method is the most widely used, whereby the object-based comparison method, in which changes can be determined at object level, is suitable

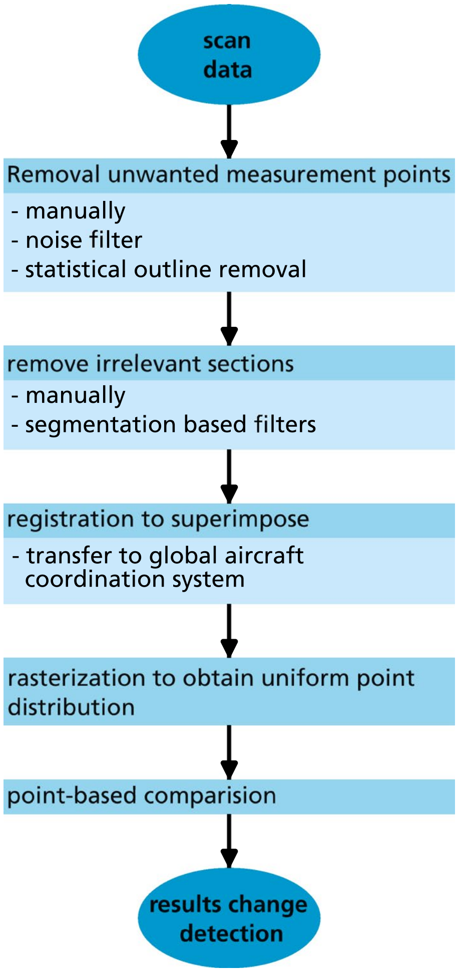

Fig. 4 Workflow describing the steps from raw scan data sets to change detection

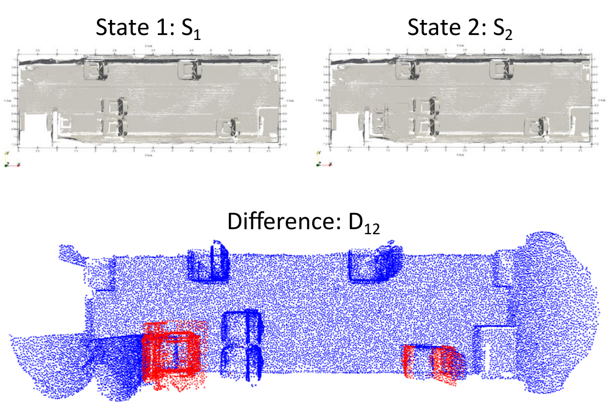

Fig. 5 Identification of the changed cabin components using the example of the FVI station and a moved seat in the ISTAR

for detecting changes in the aircraft cabin. This includes clusters of homogeneous points, such as rows of seats [35]. In Fig. 4 is the above described process, from the raw scan data to the change detection, displayed. Figure 5 shows the workflow applied to two datasets generated from the research aircraft ISTAR. The detected difference D_{12} results from the conditions S_1 and S_2 according to

$$S_1 \setminus S_2 = D_{12} \tag{1}$$

The flight test engineer's workstation was installed in state S_2 and the rear seat was moved forward, as can be seen in Fig. 5 by the modified components highlighted in red. This step is determined by calculating the distance between the point clouds of the two states data sets.

3.4 Adapting level of fidelity for different digital twin applications

The geometric information extracted from the point cloud data should be incorporated into the Digital Twin to update its geometric data. The different levels of accuracy, as described above, make it possible to adapt the models derived from the scans to specific applications within the Digital Twin. The high-resolution geometric data, captured by 3D scanners, provides a detailed representation of the physical environment in triangulated surface meshes or point clouds. They describe the outer, visible layer of the components, but cannot capture internal or hidden areas. In addition to high-resolution models, they can also include models of any level of detail. Figure 6 shows the different levels of detail using the ISTAR seat as an example, and Table 3 shows the parameters of the two seat models.

The components represented by surface meshes are too detailed for many applications, such as space analysis or crash simulations, unnecessarily reducing performance and consuming a large amount of resources to obtain results. Alternatively, simplified bounding boxes, as shown in Fig. 7b, are sufficient for installation space analyses or LOPA representation. The information provided to the masses and the position of the centers of gravity can also be of great importance for certain simulations, such as crash test simulation (Fig. 7c). This representation can be expanded to include other cabin components, such as workstations or measuring equipment. However, full integration with additional data and information from the Digital Twin, such as simulation models, operational sensor data, or maintenance records, requires defined interfaces that have not yet been established.

4 Discussion

This work shows that there has been a lot of development focused on the creation and design of Digital Twins within and outside of the aviation industry. The analysis of current

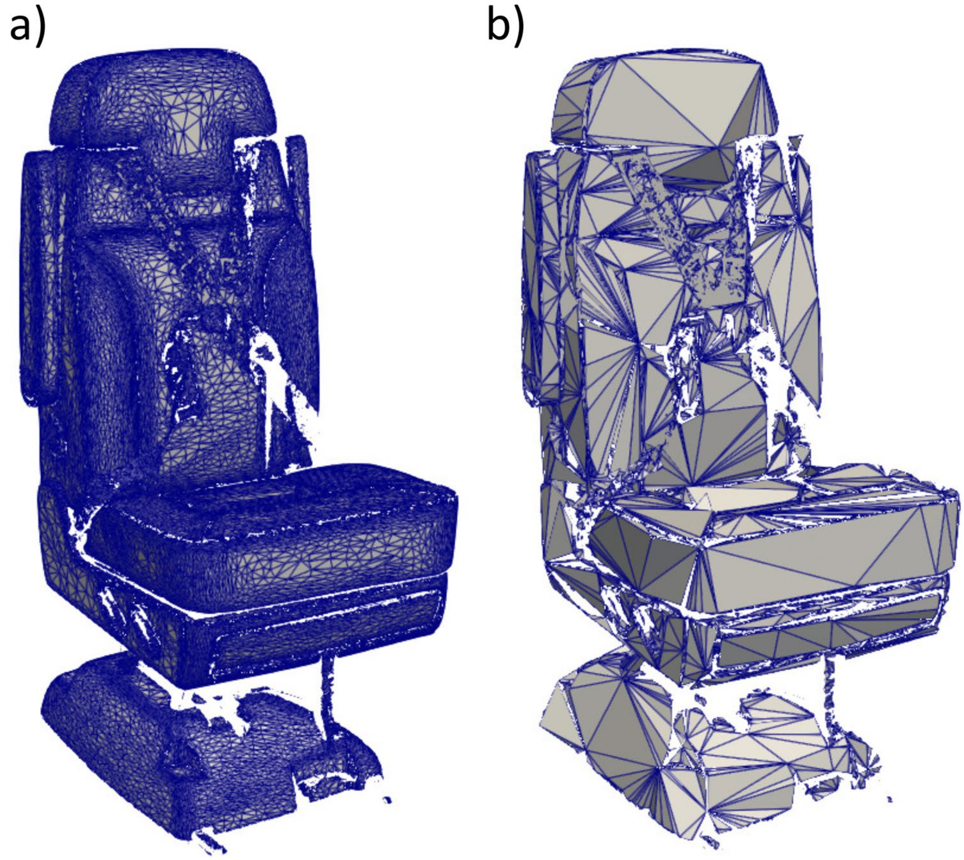

Fig. 6 Changed level of detail of the surface meshes using the example of a seat in the ISTAR

Table 3 Parameters of the ISTAR seats in the two levels of detail shown

	No. of points	No. of points	File size.stl [KB]
Low resolution	11,914	9615	469.00
High resolution	80,025	92,640	4632.08

Digital Twins reveals a fragmented landscape with parallel implementations by competing companies, such as OEMs, airlines, and MRO providers, that is working against the goal one Digital Twin per system. A critical observation is that the term Digital Twin itself lacks a consistent definition within the industry, ranging from simple panoramic visualization tools to subsystem-specific models and full aircraft-level representations. This inconsistency is not merely a terminology problem. These differences are not merely a terminological issue, they also affect the practical application of Digital Twins. Since the applications are based on different assumptions, data interoperability is not straightforward.

It is shown, that the actual goal of creating a Digital Twin for an aircraft cannot be guaranteed. The list of application examples in Sect. 2.3 shows that many different stakeholders collect data and add it to their Digital Twins systems, but that there is no exchange between the twins. This means that not all information is up to date in all instances. A further problem is the absence of data ownership regulation. Without a common framework, the different stakeholders have little interest to share data with each other. Right now, contractual agreements are needed, but they are not a scalable solution across the entire industry.

3D scanning offers the opportunity to address one specific part of this problem. It enables individual stakeholders to capture and update spatial data, which provides a wealth of information once the data sets have been processed. This work can be done without depending on information from other parties. By identifying the individual components within the data sets, information of the current cabin layouts can be generated and integrated into the Digital Twins of the respective stakeholder.

However, this approach does not provide a solution for the underlying problem of fragmentation. Each stakeholder still maintains a separate twin. Data and information generated through 3D scanning will update only one Digital Twin instance, but ensures that analyses and simulations are based on the current data.

There are limitations to this approach that need to be acknowledged. To generate 3D scan data you need to have access to the system of interest, in this case the aircraft. Not every stakeholder might have this access after a retro-fit. Furthermore, data acquisition requires dedicated equipment and personnel, and the scanning process itself takes

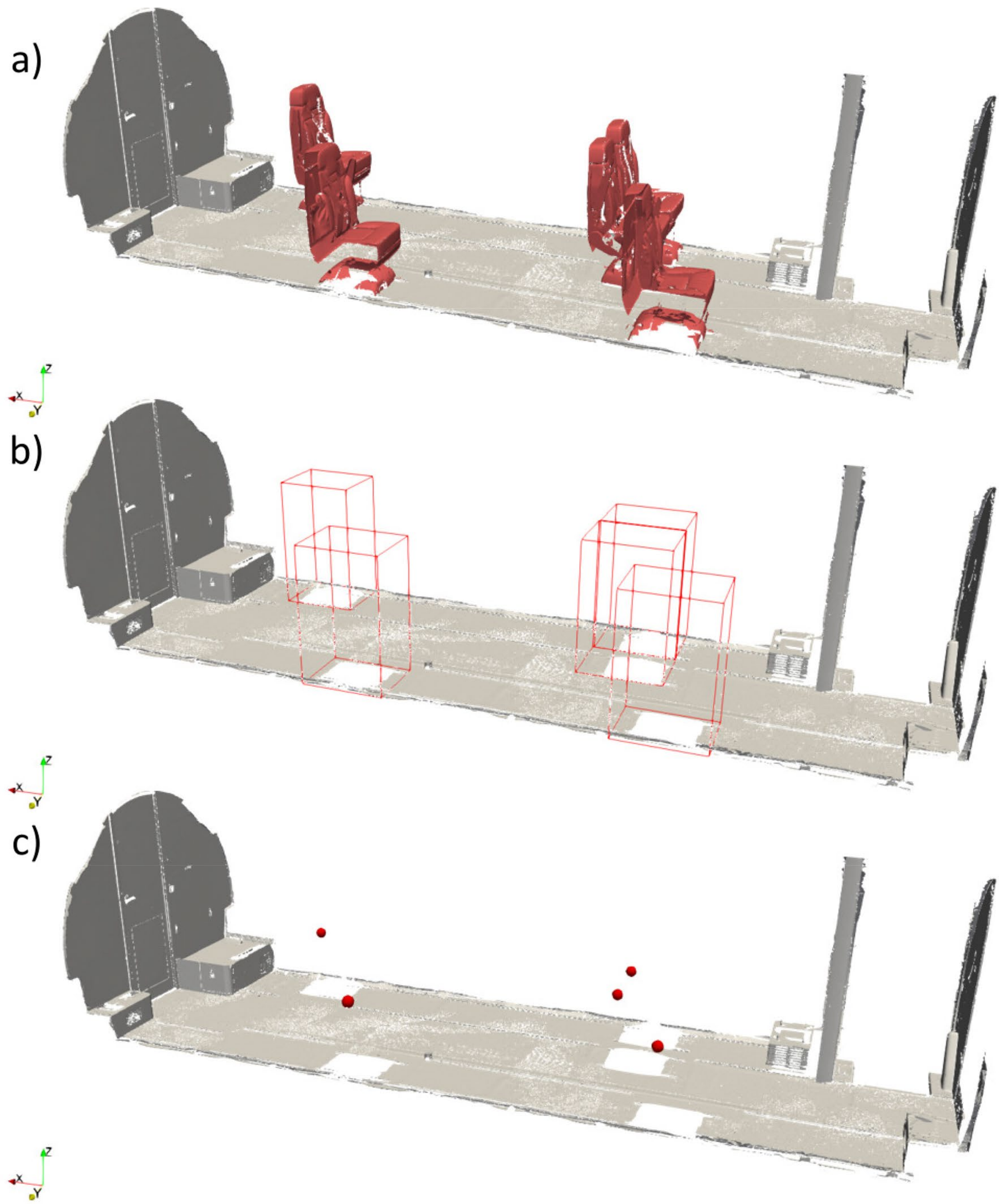

Fig. 7 Representation of the different fidelity levels using the example of the seats in the ISTAR cabin

time, which means that the aircraft is not available for other operations during this period. Once the data is captured, processing large point cloud data sets requires significant computational resources, which adds to the overall effort. In addition, the quality of scan data depends on environmental conditions and the presence of occlusions, which can affect the consistency of results in practice. Further, only the changes have been detected so far. Automated object detection is still needed to extract structured information of the components from the point clouds.

These limitations, such as time and computational resources, become significant when scaling the application to large fleets. Whether this effort is justified depends on the frequency of cabin modifications and the benefits of continuously updating the Digital Twin.

To move closer to the goal of a unified Digital Twin, a common interface for a standardized data-exchange format to communicate data between stakeholders is needed. This would allow modifications captured by one party to be shared with others in a structured way. This is beyond the scope of this work, but represents important directions for future research.

5 Conclusion and outlook

The transition to climate-neutral and a more sustainable aircraft is driving the adaption of Digital Twin technology with in the aviation industry as a key enabler for increasing the aircraft efficiency, optimize maintenance, and accelerate development cycles.

At present, various stakeholders in the aviation industry, such as OEMs, airlines and maintenance companies, are developing Digital Twin applications that run in parallel and conflict with the actual goal of providing one Digital Twin for the overall system. This work identifies and discusses the central challenges currently associated with Digital Twins in the aviation industry, including fragmented stakeholder implementations, missing standardization, and unresolved questions of data ownership across the aircraft life-cycle.

As a practical contribution, this work demonstrates that 3D scan data offers a viable approach for independently capturing 3D information about aircraft cabins, without reliance on third-party data sources. This makes it possible to digitize the modifications and changes and generate information that reflects the placement and positioning of the components in the cabin. Using the DLR research aircraft ISTAR as a case study, it is shown that 3D point cloud data can be used for this applications.

Building on these findings, future work will focus on developing a method for automated object detection within point cloud data, with the goal of extracting structured component information and making it consistently available for Digital Twin integration.

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Declarations

Conflict of interest Björn Nagel, co-author of this paper, is also an editor of this journal, but was not involved in the review process. All other authors have no conflict of interest to declare that are relevant to the content of this article.

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