DIGITAL TWIN FOR RESEARCH AIRCRAFT

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Abstract

The DigTwin project, launched at the German Aerospace Center (DLR) in 2018, is the first to bundle the developments on the topic of digital twins in aviation. This project is continued by the follow-up project Digital Twins for Engine Component Aircraft Technologies (DigECAT, 2022-2025). In addition to the development of digital twins as research objects for aircraft, components and engines, an important building block is the development of digital twins as a tool for DLR research aircraft. This digital twin will be used as a service to enlarge the availability of research data within the organization. The DLR operates a large research fleet of 12 aircraft with different on-board measurement systems in the areas of aircraft systems, aerodynamics, structure and environment. The developments are modular and scalable and will be extended to other systems, e.g. UAVs, of which DLR is operating a large and diverse fleet.
This paper introduces the project DigECAT and shows the motivation for implementing digital twins for research aircraft. This includes contributions to scientific and various technology roadmaps. Subsequently, the scope and complexity of data acquisition by research aircraft is discussed before addressing data processing. After that it will give a short introduction into the architecture and software features developed, before the different applications are described.

ADS-B *Automatic Dependent Surveillance- Broadcast*
API *Application Programming Interface*
ATRA *Advanced Technology Research Aircraft*
CAD *computer-aided design*
CAMO *Continuing Airworthiness Management Organisation*
DBSCAN *Density-Based Spatial Clustering of Applications with Noise*
DigECAT *DLR Project Digital Twin for Engines, Components and Aircraft Technologies*
DigTwin *DLR Project Digital Twin*
DLR *Deutsches Zentrum für Luft- und Raumfahrt e.V.*
ECMWF *European Centre for Medium-Range Weather Forecasts*
FAIR *Findability, Accessibility, Interoperability, Reusability*
FX *Flight Experiments*
GUI *graphical user interface*
HGF *Helmholtz-Gemeinschaft*
IP *Intellectual Property*
ISTAR *In-flight Systems & Technology Airborne Research*
IT *Information Technology*
METAR *METeorological Aviation Routine Weather Report*
MWP *Main Work Package*
OCR *Optical Character Recognition*
REST Representational State Transfer
SMS Safety Management System
twinstash *Digital Twin Storage and Application Service Hub*
UAV *Urban Aerial Vehicle*
VPH *Virtual Product House*

1. INTRODUCTION

The DigECAT project is planned as the successor to the DigTwin [1] project. Over a period of four years, the two milestones: “Prototype of a digital twin of an aircraft component / aircraft system demonstrated under operating conditions” in 2023 and “Prototype of the digital twin for ISTAR is available” in 2025 are being addressed. Methods, procedures, standards and tools for the use and development of digital twins at DLR will be developed in Main Work Package (MWP) 1. Particular attention is paid to

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the further development of the data management and access architectures shepard [2] and twinstash [3] developed in DigTwin. Among other things, the integration of in-depth provenance and metadata will take place here. In MWP 2, the processes that were developed in cooperation with the VPH will be expanded and the entire life cycle of a component will be simulated in a digital twin. For this purpose, methods in both production and operation should be developed and implemented. Particular attention is paid to the feedback from operations to the design, where the connection to the physical link to the research aircraft ISTAR will also take place at the end of the project period. In MWP 3, a digital comparison process between design and real geometries will be created. For this purpose, two development activities are being conducted in parallel. One activity is developing end-to-end processes required for evaluating geometries, the other activity focuses on develop different technologies for digitizing real world geometries. This should increase the informative value with regard to the use of technology for the identification of suitable inspection procedures in the repair process. The activities are intended to develop a digital twin at the component level. However, the overall process is also an essential component for the engine concept of the digital twin of the ISTAR. In MWP 4, the digital twins for research aircraft will be further developed. Particular attention is paid to the ISTAR's digital twin. The aircraft will be connected to the twinstash architecture developed in DigTwin. The existing applications of the digital twin will be advanced and new applications developed as needed. The focus of the MWP and the associated Milestone is at an ISTAR system level, but it, of course, provides interfaces and data required for MWP 2 and MWP 3.

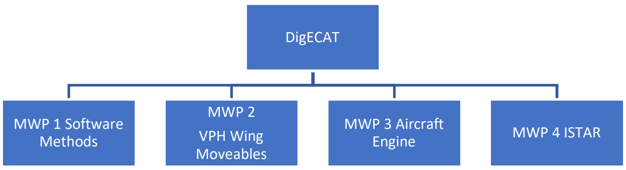

Figure 1: Workbreakdown structure DigECAT

The following institutes and facilities are involved in the project:

- Flight Experiments
- Institute of Aerolasticity
- Institute of Aerodynamics and Flow Technology
- Institute of Propulsion Technology
- Institute of Structures and Design
- Institute of Composite Structures and Adaptive Systems
- Institute of Flight Systems
- Institute of Maintenance, Repair and Overhaul
- Institute for AI Safety and Security
- Institute for Software Technology
- Institute of Test and Simulation for Gas Turbines
- Institute of System Architectures in Aeronautics
- Institute of Software Methods for Product Virtualization

The above-mentioned milestones are part of a larger scope defined by HGF, in addition to these the project also has its own objectives. The main objectives are:

1. Develop and provide standards, methods, tools for digital twins at DLR

2. Represent the digital twin of an aircraft component for a life cycle

3. Integration of real geometries into a digital design and analysis process

4. Provision of research data with the help of digital twins and creation of analysis methods for scientists

5. In the field of artificial intelligence, tools, research and methods at DLR should be strengthened and promoted.

The digital twin for research aircraft is aiming at goal 4. To reach this goal, the following results should be reached. At first all data from different data sources should be stored in the central platform twinstash. The platform should have a search function for flight test data, to increase the findability of the research data. For first analysis and a "feeling" for the different data, various visualizations of flight test data must be developed. Also, a partially automated data transfer process from research aircraft to data storage should be developed. A "Single Source of Truth" for flight test data should be established at DLR.

In HAP 4 the focus is on the development of a digital twin for the ISTAR aircraft. Nevertheless, the platform and technologies introduced in the project DigECAT can be transformed and used for all DLR research aircraft.

The MWP 4 consist of three sub work packages. The first work package integrates the different data sources for the research aircraft. This includes the maintenance, CAMO, ADS-B, Basic Measurement Equipment, Nose Boom, CAD, and 3D Scan Data (ref to Figure 5). The second work package will further develop the functions developed in the project DigTwin. The last project aims on new applications, for analysis, data handling or health and safety functions of the research aircraft.

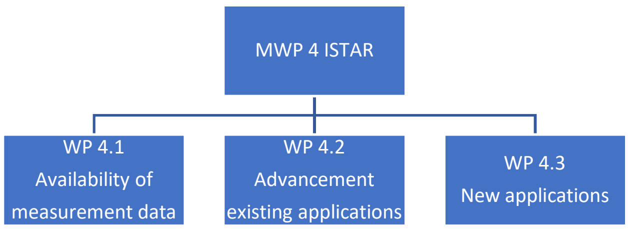

Figure 2: Work break down MWP 4

2. ROADMAP TOWARDS DIGITAL TWINS

In this chapter the overall roadmap of the project together with the political framework is presented. In the second part the specific research aircraft with IT data sources are described.

2.1. Roadmap

In 2016 the Helmholtz Centres adopted a position paper about making information resources more usable. [4] Within this paper, the position in the direction to open science and open access to research, knowledge and data. One of the steps, to strengthen the digital science is to store the research data within suitable infrastructures. To contribute to this the project is following the FAIR (Findability, Accessibility, Interoperability, Reusability) principles.

When the German government was formed in 2021, two passages were included in the coalition agreement that have a direct impact on our research. Firstly, a paragraph on digital twins was added: *“We want to use the potential of digitization for more sustainability. Through the promotion of digital twins (e.g. working on a virtual model of an analog product), we help to reduce consumption of resources.”* [5]

The DigTwin and DigECAT project will contribute to this global goal by researching methods for the use of digital twins over the whole life cycle of an asset. Especially in work package two, where we have a close link to the virtual product house (VPH) project which develops methods for the digital design, testing and certification of aircraft components [6]. Therefore, the DLR digital twin will help to reduce the resource consumption for test and certification on one side. Additionally, by enabling modern predictive maintenance concepts it will contribute to more sustainable operations. Also, with the data over the whole life cycle a more detailed analysis of the economic impact of an asset can be performed and the knowledge gained can be included in new designs.

The second relevant paragraph in the agreement is about the unused potential of research data: “*We want to use the unused potential that lies in numerous research data more effectively for innovative use ideas. We also want access to research data for public and private research comprehensively improve, simplify and manage a research data law research clauses. We want to establish Open Access as a common standard. We sit down for a more science-friendly copyright law. The National Research Data Infrastructure we want to further develop and promote a European research data space. Data sharing of fully anonymized and non-personal data for research in we want to enable the public interest”* [5]

The activities of main work package four make a particular contribution to the open data aspect. As a basis for systematic subsequent use at DLR, but also with research partners, high-quality provision of research aircraft data is necessary. This includes the preparation of the data, the provision of analysis tools, databases, linking to external data sources, but also the semantic description of the existing data. In addition to the technical aspects, the legal points must also be considered, since some test flights examine technologies that need to be protected for IP or other reasons.

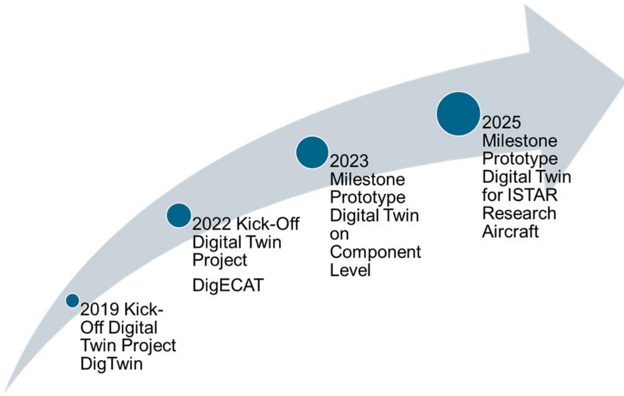

Figure 3: Roadmap Digital Twin

2.2. Research Aircraft

The DLR facility Flight Experiments (FX) operates the largest fleet of civil research airplanes and helicopters in Europe. It provides support to internal and external customers during planning, execution and post processing of scientific research missions focusing on flight research and airborne science. These research missions either use the aircraft as a carrier platform for scientific equipment or as a research object in aeronautical research.

The newest member – a Dassault Falcon 2000LX – has been operating under the name 'In-flight Systems and Technologies Airborne Research' (ISTAR) since 31 January 2020.

Figure 4: ISTAR (Credit: Jörg Graupner (CC-BY-3.0))

With ISTAR, DLR has an airborne test platform for the study of innovative technologies, simulation of new aircraft and continuing to facilitate increasing digitalization in the aeronautics sector. This research aircraft is essential for the development of new, efficient and environmentally friendly aircraft, engines and pilot assistance systems. ISTAR will drive the evolution of technologies that enable climate-neutral aviation.

When fully upgraded, ISTAR will be able to the test flight characteristics of new aircraft designs – whether real or virtual, crewed or uncrewed – under real operating conditions. Each year, the experimental aircraft fleet produces large sums of data to support research in aviation, space and atmospheric research. In the current state of data management, it is not possible to provide FAIR data. The biggest problem is the decentralized filing of measured data and metadata. Furthermore, the metadata is not constantly linked to its associated datasets, which makes it impossible to find, access and reuse the data beyond the context of the project in which it was created. A tool for metadata management and enrichment was clearly missing. The data are of great interest for research work in a large number of different academic fields, but scientists are often not aware that they exist.

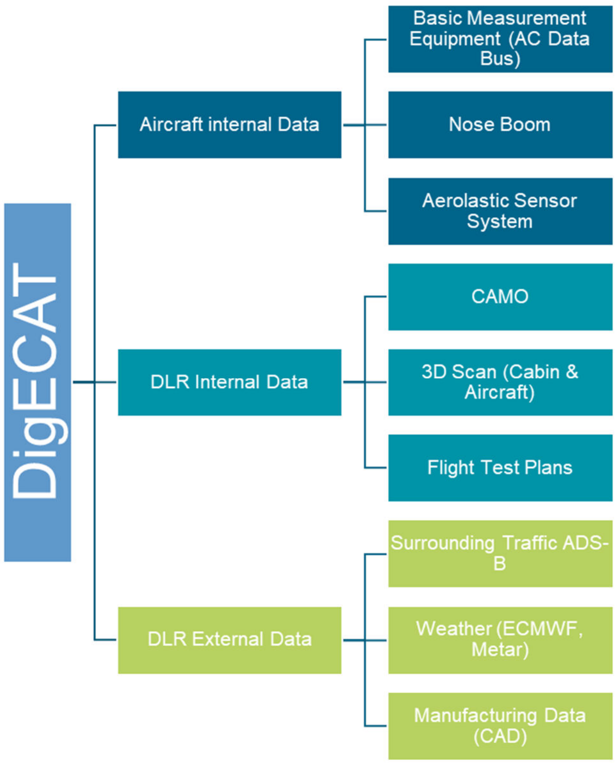

Figure 5: DigECAT Data Sources

For the research aircraft different data sources are possible. Basically, the data can be divided into three categories ref to Figure 5). On the one hand there are the aircraft-internal or integrated measuring systems. They contain a basic measuring system, which records approx. 3000 aircraft parameters from the aircraft data buses with different frequencies. In addition, the ISTAR can be equipped with a nose boom, which records additional environmental and current values with great accuracy. There is also an aeroelastic measuring system that records sensors attached to various structural elements. Furthermore, DLR internal data is stored in the system. This includes the documentation for the flights and maintenance, but also the additional digital recording of the geometries through 3D scans [7]. The final category is the external data sources that can be used to enrich or reconcile the collected data. The ADS-B, weather, but also data from the manufacturer should be included as examples.

Reusable data will have many positive effects in the different DLR research fields. Scientists will be able to search for data in their specific fields, making research work more efficient. Scientists will not need to plan new flight tests for every new project, if there are enough data to work with. The process to get research data also becomes much faster, which leads to a faster research in general. Research funds could be used in a more sustainable manner and interoperability between various research directions would be promoted. In order to support synergies between the different academic fields, it should be possible to store analyses of the existing data in the system and make them usable for the whole scientific community.

The goal of the projects “DigTwin” and “DigECAT” is the development of a prototype of a digital twin for the ISTAR but led to a system which can be used for our whole aircraft fleet to support the findability, availability, interoperability and reusability of a huge amount of flight test data.

3. TWINSTASH

The basis for developing and operating digital twins is a properly designed software system or even ecosystem of multiple components where digital twins with all their data and respective functionality can be hosted.
Within the DigTwin project a stable prototype of a data management system with particular focus on the ability to include and provide corresponding functionalities on the data was initialized. The so-called *digital twin storage and application service hub,* in short *twinstash*, is now being developed by a small team of the DLR Institute of Software Methods for Product Virtualization within the DigECAT project.
It supports the upload, download and search for all forms of flight data, including very specific sensor data from additionally built-in measuring systems along with their respective meta data. All data and functionality can be accessed programmatically via python and is therefore easily usable in fully automated workflows. Additionally, twinstash offers a browser-based graphical user interface which allows to navigate through the data by project, time, or aircraft. Beyond that it provides rich possibilities to display flight trajectories in 2D as well as 3D and provides comparative, interactive timeline plots for arbitrary parameter selections.
In the current stage we build components for and towards a digital twin. A “general” digital twin, however, which provides simulations, predictions or real-time processing and decision making is quite some time in the future. In the following, we summarize the architecture of twinstash based on its current version 1.21. Further details on design, architecture, functionality and particularly on available features of the twinstash system can be found in a dedicated in-depth review [3].

3.1. Architecture

The architecture of twinstash, depicted in Figure 6, follows the pattern of a web service. We utilize a *backend* which is composed of different software systems doing the main work like authentication, file serving, and data handling, and offer several light *frontends* which provide users the option to programmatically or graphically interact with the backend. Frontends and backend run on different machines and are communicating via a *REST API*[1].

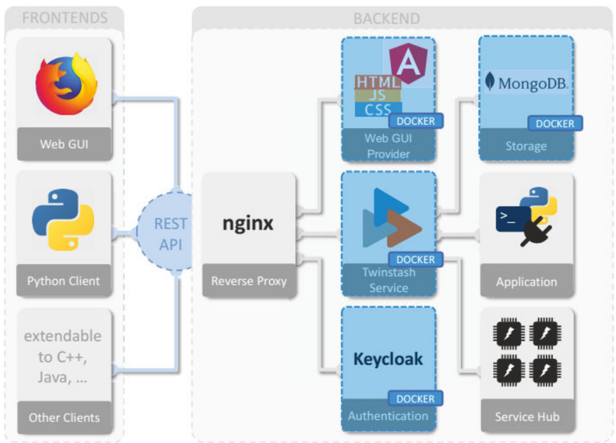

Figure 6: Web-service architecture of twinstash with frontends (left) and backend (right).

A REST API allows computer programs to communicate via http requests sent through the internet. Our REST API provides the usual methods to upload, download, manipulate, and erase data. The endpoint `search` offers extensive search capabilities for data stored in twinstash. A variety of search examples are demonstrated in [3]. The REST API further provides all files which are necessary for rendering the graphical user interface in a web browser, and some additional endpoints required for authentication.

3.2. Features

Currently, we provide two frontends for twinstash, a *web GUI* and a *python client*. The web GUI runs in any modern web browser. The user browses to the DLR-internally available web page https://stash.dlr.de, logs in with its DLR credentials, and is then provided with browsing, search, and visualization capabilities (Figure 7). The web GUI provides different views on the content such as a project, flight and series (actual data) view but also an aircraft overview or calendar heatmap for intuitive and quick use. All these features are described in more detail in **[3]**.

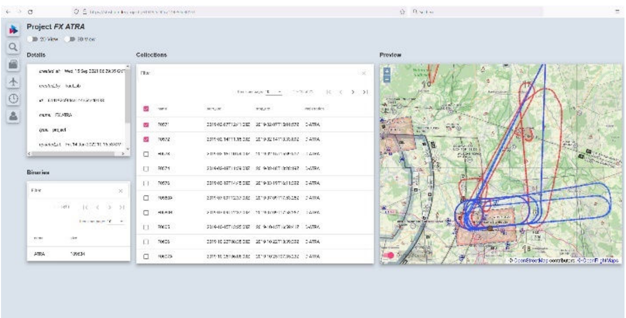

Figure 7: twinstash project view with flight list and flight trajectories on a 2D map.

From a list of flights within the project view, a user can select a flight to open the detailed flight view shown in Figure 8. Like the project view, it lists its meta data and attached files besides the actual parameter list. This parameter list can be filtered by name. One or more selected parameter can be displayed in an interactive time series plot right on the same page.

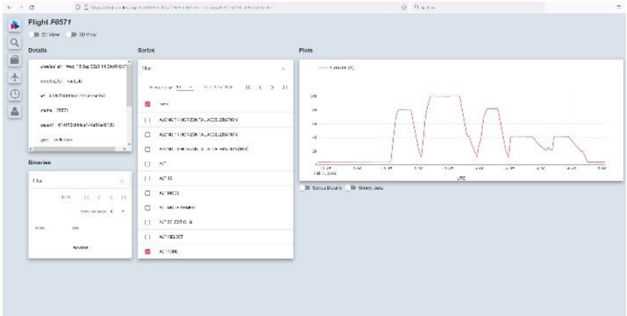

Figure 8: twinstash flight view with list of recorded parameters and time-series plot.

The python client is the most straight-forward way for users to interact with the system and completely encapsulates the twinstash REST API. The following section will show some applications which use the python client as a basis to interact with twinstash.

4. APPLICATIONS

With the large amount of research aircraft data comes together in the digital twin, in this section we describe some of the applications that have been implemented so far or are currently in development. The scope of the applications ranges from data visualization, monitoring and augmentation to large scale data analytics.

4.1. Data Upload

Before data is uploaded it is important for it to be uncorrupted and correct. Currently, the aircraft generated data gets fed through several proprietary routines that convert it to a more readable format. This process is lengthy as several of its steps are not automated, furthermore, the hundreds of sensor values are not checked for presence of sensor data nor its “correctness”. This means that a faulty sensor often gets detected weeks after the experiment, leading to time delay and additional costs if the parameter is needed to evaluate the experiment results. It might also make the data unusable for other applications, so finding and correcting errors increases the reusability of data. To solve these issues, we develop an automated multilayered sensor data health monitoring flow consisting of three layers. These layers check data in increasingly more strict ways and make sure the data that is further processed is free of errors and correct. The presence of sensor data is checked first to ensure that all sensors deliver an output. Plausibility is checked second, asserting that the sensors return the expected data type, and their value lies in the expected range. Followed by the third layer which runs deeper checks such as physical relations between measured parameters and a neural network algorithm as a final warning measure to detect unforeseeable anomalies.

In order to also avoid user error, two graphical user interfaces (GUIs) allow the user to enrich the data to be uploaded and edited. With the project GUI one can upload project data and with the flight data upload GUI one can

[1] Representational state transfer - Wikipedia

upload flight specific data, i.e. the flight measurement data and its related metadata. These interfaces are developed to minimize any failures within the process of uploading the data packages to the twinstash system and ease the **data** uploading process for the user. Combo boxes, checkboxes, radio buttons and lists with predefined content ensure the consistency of the uploaded data and prevent any typing errors introduced by the user. In the project GUI the user provides the name of the planned project, the planned period of time for the project and contact information of responsible project manager by means of predefined templates. In the flight data upload GUI, the responsible flight test instrumentation engineer fills the GUI with all the metadata of the flight, such as the link to its related project, flight date and times, flown manoeuvres and other characteristics. These metainformations are essential to ensure the findability and ultimately the reusability of the flight data.

Flight data monitoring is an essential part of the Safety Management System (SMS). The Safety Management which requires surveillance of safety critical data and subsequent analysis for the purposes of risk assessment, identification of adverse trends, the evaluation of safety performance and ultimately mitigation of hazards in flight operation. **[8]** Unlike Flight Data Recorder obtained data, FDM provides insights in presently existing risks and hazards (proactive identification) and even emerging adverse trends and risks before they result in an accident (redictive identification). The FDM process will be designed as an additional module to the already existing twinstash. A program that analyses flight data for exceedances of defined limits and thresholds, which reflect the different FDM Indicators, automatically begins to process as soon as a new set of data, enters twinstash, e.g. after the conduction of a flight experiment. The results of this analysis will then be summarized as an anonymous, confidential report, either as a post flight report, or as a statistical report, accordance with already existing safety management procedures.

4.2. Data Augmentation

Once the flight internal data from the sensors and the shop floor can be found in the Digital Twin, this data is augmented to ease its usage.

The sensor data is augmented with ‘phase of flight’ information, following the taxonomy in ICAO ADREP. A rule-based phase of flight identification algorithm considers several inputs to perform the classification for each time stamp. This is described in more detail in [8]. The flight phase classification can later be used to compare the time series data from same flight phases regarding certain events of interests.

The DLR is not only in possession of the flight data of its aircraft, but has also access to the documents originating from its maintenance procedures. The D-ATRA research aircraft maintenance documents are available to the DLR provided as scanned PDF files. As the extraction of information from a scanned document can be take considerable effort we allow for a more efficient search through these documents by enriching them with basic metadata obtained from their content. This allows to select fewer documents of interest rather than the complete set and perform the costly interpretation and information extraction on fewer files. The metadata that is added contains the type of document (deferred item, work performance sheet, job card etc.), the keywords found in the document (number of flight cycles, date, aircraft etc.) as well as the main text in the document.
The algorithm uses Tesseract [9] to perform Optical Character Recognition (OCR) and to find bounding boxes around the words. These bounding boxes allow for creating a distance function between words that considers the distance between their closest edges. With this distance function words are clustered together to identify blocks of words that are likely connected. The clustering was performed using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) [10] algorithm as it is not bound by knowledge of the number of clusters and the bounding boxes are not always accurately placed around the words. From these blocks of text, the largest is identified as the main text, this is applicable to maintenance documents as they are characterised by many fields and tables with sparse information, however the largest text often regards the maintenance that was performed from which the document originated. Finally, the document is searched for values (e.g. numeric or date values) that fit the mask for specific keywords.

4.3. Combination with External Data Sources

While the aircraft data of the research aircraft is of uttermost importance to the DLR, there are also some external sources (ref to. Figure 5) that provide useful information regarding the performed flights. The data that has been connected to the flights in the Digital Twin are weather data from the ECMWF database and air traffic data from OpenSky network.

The weather data is used to validate and identify differences between the aircraft’s environmental sensors and the world-wide weather information. Along its flight path, the aircraft’s sensors can provide a better resolution of ambient condition measurements. This can create better insight into the accuracy of data provided by weather data sources which have lower resolution, such as the ECMWF data base or METAR data.

The OpenSky network [11] provides (ADS-B) and Mode S based air traffic data for research. It allows to obtain trajectory data from specific aircraft and regions in different points in time, including live information. Traffic information from the OpenSky network was used to analyse the proximity of the research aircraft to nearby traffic during their flights. For the proximity report, the OpenSky network is firstly parsed for the trajectory of the research aircraft itself at an interval of 30 seconds. For each position found, the nearby traffic within a predefined range of 5 nautical miles horizontally and 2000 feet vertically is determined. The trajectories of all aircraft that entered this range are analysed during the time they were in the range and a report is created where the closest proximity, average proximity and the time in range is listed for each aircraft indexed by the aircraft’s international ICAO code.

The nearby traffic can also be seen in the simulated flight replay that has been developed. This flight replay, for the purpose of Flight Data Visualisation, is an interface to handle the pre-processed flight data and allow for a real-time rendering of a given flight. This render, done on a commercial flight simulator, is also fed with historical weather of the respective flight, date and time. Ensuring the correct cloud coverage and wind speeds are used during the visualisation. Through the usage of multiple instances of the flight replay – interface, it is also possible to render multiple aircraft at the same time. Thus, making it possible to display traffic and other aircraft involved in the flight test. All trajectories, of the rendered aircraft, can be plotted during the rendering process and shown on top of a map, together with the according airspace boundaries. During rendering, the user can manipulate the views to change to different positions inside the aircraft as well as to outside views. This allows for a straightforward approach in gathering of a situational overview for arbitrary points in time, during recorded flights.

5. OUTLOOK AND CONCLUSION

Each year, the experimental aircraft fleet produces large sums of data to support research in aviation, space and atmospheric research. The data are of great interest for research work in a large number of different academic fields, but scientists are often not even aware that they exist. As the metadata is not constantly linked to its associated datasets, the effort to find, access and reuse the data beyond the context of the project in which it was created is challenging.

To overcome these problems the prototype of the digital twin storage and application hub (twinstash) was created to enable the data driven research within the dlr. Therefore, the research data are collected and stored according the FAIR principles. The prototype also enables the researcher to get first data insides by implemented visualization and analysis tools. Additional interfaces for external tools can be used.

For the future developments several works are necessary. At first the semantic and ontology description for the included data need to be developed. This will enhance the search function, unit transformation and the understanding of the data. A wide variety of data from different sources in the aircraft come together in the measuring system and are stored there and in twinstash. Many of these parameters describe similar or even identical sensor values. The reason for this is the redundant avionics and sensor architecture in the aircraft. In addition, many parameters are available both in unprocessed and in computed or fused form. For a user with only average knowledge of the system, it is therefore very difficult to decide which of the parameters is the correct one for his calculation. For this purpose, a measurement data structure is to be defined and integrated in twinstash. All common parameters will be assigned a standardized name via a mapping in order to avoid difficulties and errors when interpreting the data. The aim is to make it recognizable at first glance for a user with little knowledge of the system which parameter he should work with, as well as for the user with a high level of knowledge of the system to receive all the information. In particular, the physical dependencies between different measured values should be described with the ontologies, since many measured values are directly connected to one another via the physics of the aircraft or the flight. In order to increase the usability of the flight test data, it is planned to adhere to existing standards as best as possible.

The time data of the acceleration sensors of the ISTAR are jet stored in twinstash. In future they should be systematically evaluated and augmented with the flight and loading condition of the aircraft. With the help of software for vibration monitoring in flight tests, the natural vibrations should be systematically identified as a function of the flight condition. This provides the aeroelastic behavior in almost all points of the flight envelope in twinstash to be able to validate e.g. numerical models for the aeroelastic behavior. By combining these analyses with 3D models of the aircraft, for example geometry models or finite element models, and using spatial interpolation methods, it is possible to calculate the deformations of points on a wing structure or to calculate internal loads on components. This link between the structure describing data and the measurements of acceleration in flight will lead to new insights in the field of aircraft design and predictive maintenance.

In the next steps it is important to gradually increase the number of users so that their feedback can be used to improve the system. Also, an open documentation with a DLR wiki needs to be implemented to increase the usability.

Additionally, an open developer platform as a pool for all the possible applications running over the REST API of twinstash will be created. The basic idea was that many small calculations (e.g. center of gravity of an aircraft over the flight duration) are made again and again by different scientists. With an open developer platform, we offer scientists the possibility to make their applications available to others. Since we cannot ensure that all published applications are complete and provide correct results, the developing scientist should provide his source code and a description which can then be used by other scientists at their own risk and can be continuously improved. This will result in a better linking of DLR scientists of similar research fields to one another creating a positive competition and supporting the exchange of new ideas.

Another important point will be the transformation of the results from the field of research aircraft to the operation of commercially operated aircraft.

Acknowledgement

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