Linking Digital Twins to Use Time Series for Predictive Maintenance at Component Level

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ABSTRACT

In complex systems, the life cycle of components is often detached from the life cycles of the overlying systems. For example, individual systems or components are removed from the vehicle for maintenance and sent for overhaul and replaced with components that have already been overhauled. This also increases the complexity for the digital twins of these systems since the data is often processed and stored in the overlying systems or at the overall system level. An example could be the landing gear for an aircraft, which is removed from aircraft A after its lifetime or usage limits have expired and is replaced by an already overhauled landing gear. After maintenance, the landing gear is installed on Aircraft B. (Figure 1) In addition to changing the system affiliation, the owner, operator, or another stakeholder role can also change. This greatly increases the complexity of mapping the digital twin. Since there can be competitive situations between the various stakeholders, not all parameters should be available for every point in the life cycle of the higher-level asset. A concept is therefore required that ensures that only the relevant data is provided for the period of affiliation.

1.0 INTRODUCTION

Especially in the case of very complex systems with long service lives, individual elements are often separated from the life cycle and have their own life cycle with their own maintenance measures and changing affiliations in higher-level systems. In order to do justice to this, the system must be considered on the one hand and possible concepts for the solution on the other. Therefore, the problem is explained further in the first subchapter, and relevant publications on possible solutions are considered in the second subchapter. The third subchapter explains a typical use case for predictive maintenance.

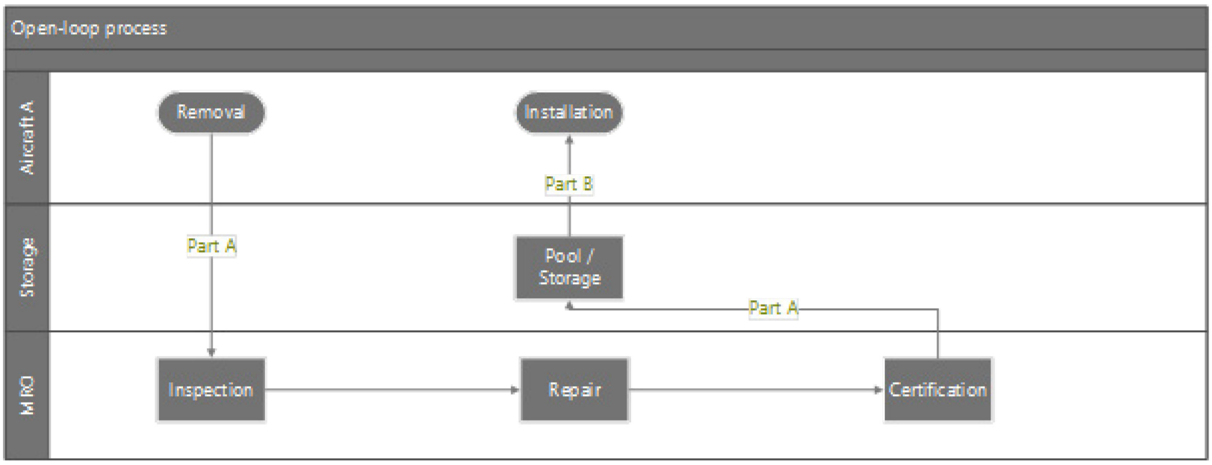

Figure 1: Open-loop process: After the removal of part A, the object is replaced by another part B [5].

1.1 Problem Statement

To enable modern maintenance concepts such as predictive maintenance, prescriptive maintenance or health indexes, the data flow must be guaranteed over the entire life cycle. These modern concepts not only have an influence on the direct effect of lower maintenance costs by utilizing the entire Remaining Useful Life Time, but also on inventory management and the ideal resource utilization of spare parts. In particular, by integrating resources, prescriptive maintenance can be used to achieve higher overall availability. In current systems in aviation, information about resources is available within companies. Across company boundaries, such information is only available to a limited extent. There are initial spare parts platforms in which a company can search for the assets it needs.

Another problem is the availability of lifecycle data. Various data are needed to develop prognostic algorithms or health indices. This includes from the component manufacturer design data and limitations, from the system integrator different parameters regarding the installation position, from the operator the data during operation and from the maintenance company the corresponding repairs, maintenance, and certifications.

For such a system to work meaningfully, the stakeholder in physical possession of the asset must have access to the relevant data in order to have the most efficient system possible. At the same time, the equipment manufacturer and the integrator need a feedback loop of the data to be able to perform data-based product improvement.

A particular problem is certainly also the fact that many components do not have their own computers, but the computing power and data acquisition is done on the next higher level, e.g., the aircraft, ship or vehicle.

The final challenge is the current lack of standardization regarding data exchange for digital twins. There are already several standards such as (ARINC, AAS, data links). However, stronger descriptions of the connections are needed for the exchange. As an example, the description of the available data and their context descriptions.

1.2 Essential Reading

This section includes the state of the art and research for the two different fields aircraft maintenance and digital twin data. Since aviation maintenance is an evolved system, direct conversion to modern Digital Twin

Systems is not straightforward. At the end of this chapter, various applications in the context of aircraft maintenance from research are presented.

1.2.1 Aircraft Maintenance / Systems

Aircraft are very complex overall systems that are designed in a multidisciplinary manner. Aircraft can be divided into different subcategories. An example is the subdivision into ATA chapters, this subdivision is subdivided into the system affiliation such as electrical, hydraulic or engine [1]. At the same time, however, multiple systems may be involved according to ATA chapters to provide services. An example could be a rudder function. The engine supplies power to the hydraulic pump, which is used to move a control surface, while at the same time several computer systems such as flight control computer or autopilot are involved to calculate the control pulses. The data collection and processing are very often done in the avionics systems of the aircraft. The only exceptions to this are mainly the engines, which have their own computers on the engine (FADEC).

This complexity is often reflected in aircraft maintenance planning. These are basically divided into structural, zonal and system tasks, which results from the procedure from the MSG 3 analysis [2]. The tasks themselves are then defined down to component level. The maintenance plans then only contain the installation and removal and no longer the repair and maintenance that takes place in workshops [3]. The criticality of the individual system components is determined by their system affiliation, the impact of the failure, the probability of failure and the redundancy [4]. In particular, system membership and system redundancy can have a significant influence on task frequency, while the probability of failure results from component design and usage. For example, a component may be installed in several places in the aircraft and have different maintenance requirements.

In principle, the responsibility for aircraft maintenance lies with the operators. However, several other stakeholders are needed to implement maintenance in order to maintain or establish airworthiness at various levels. All of these stakeholders require data and information, which today is handed over in very manual processes. In maintenance, there is a similar market segmentation as in manufacturing. For example, there is MRO at the aircraft level, at the system level, and at the component level [5]. For components in particular, there is often also the component manufacturer as the maintenance company. However, there are several digital platforms from the major stakeholders in the market. The main focus of these platforms is on the granularity of the aircraft. The systems also only work as long as the asset is in a controlled environment [6].

To ensure high availability and keep maintenance times low at airplane level, a so-called open-loop process has become established. In this process, the component is separated from the actual asset for overhaul and replaced by a serviceable component from the warehouse. This also reduces the total number of components required. In contrast, in the closed-loop process, the components are removed, overhauled, and then reinstalled [5].

1.2.2 Digital Twin / Data

The basic definition of digital twins goes back to a definition by Grieves et al. He defined the connection between a physical and a virtual asset with a two-way data information exchange [7]. Today's definitions go further and have gone into more detail.

The DLR defined the digital twin as follows:

> *The Digital Twin is a uniquely identifiable digital representation of a physical or logical object for one or more purposes. It is irrelevant whether this object will only exist in the future, actually exists or no longer exists. The digital twin links information and data stored in the digital thread in order to be able to represent the characteristics, status and behaviour of an object with regard to different aspects. In addition, the Digital Twin has access to the application layer and thus enables*

interoperability between applications such as models, simulations, and predictions in order to functionally describe and predict the object. The Digital Twin can be hierarchically composed of several Digital Twins and reference other Digital Twins. As long as the Digital Twin represents a physically existing object, the current state of the physical object is synchronized into the Digital Twin in a timely manner [6].

This definition includes the main characteristics that were also identified, for example, by van der Falk et al. in a literature analysis [8]. These include identification, connection between asset and digital twin, and real-time capability. An initial definition of a Digital Twin Web goes back to Autiosalo et al. who linked the connection of the individual Digital Twin documents with a Digital twin registry to ensure the findability of the data [9]. The concept was further developed by Meyer et al. to derive and integrate the requirements from the aviation sector [5]. Haße et al. analyzed the design principles for shared digital twins. In doing so, they defined the four basic design goals of Sharing Resources, Transparency, Openness, and Scalability. Through structured interviews, they were able to derive fifteen Key Requirements based on a use case, which were then used to develop eight design principles. (Data link, purpose, interface, synchronization, data input, data acquisition, interoperability, and data security) [10]. Privat describes in his research the use of graph models for system of system digital twin. These graph-based digital twins reflect the connection of the individual digital twins (components) to an overall system (aircraft). Many descriptions are needed in this approach, which include the configuration and context information to describe the connections between the individual elements [11].

Developed by the Air Transport Association (ATA) The ATA SPEC 2500 standard introduces an industry standard for exchange in electronic formats standardized for aircraft records. It is intended for operators buying or selling aircraft, lessors and lessees on lease return, or aircraft or engine manufacturers on initial delivery. It contains XML structures for a limited scope of data such as AD status, aircraft status, service bulletins. It is not intended for time series data or predictive maintenance [12]. Another standard is in the Industry 4. the ECLASS standard. ECLASS enables product master data to be exchanged digitally across company boundaries. It is constantly being developed further but is currently mainly used for master data of production machines and their components [13].

1.2.3 Applications

Xiong et al. did a literature review on different application fields in Digital Twin for Aviation. He identified the following fields for Digital Twins: Design, Assembly, Manufacturing and Operation/ Maintenance. Since this paper is mainly about maintenance, only this field is of interest. Here, the link was made to Integrated Vehicle Health Management (IVHM) on the one hand, and to Condition Based Maintenance on the other [14].

A very important part is to meet the requirements of air law, which includes, for example, the tracking of all relevant components [5]. This also includes being able to trace the location, installation site and air-legal status at any time [15]. Currently, this task is performed in Europe by the EASA Part-M organization.

Another possibility is the calculation of a health index on aircraft or component level. In this case, the calculation at aircraft level is made up of the partial calculations at component level and their system context. The health index represents the current condition in relation to the total service life and functional performance [16]. The health index can also be as an input value for the calculation of the remaining useful life (RUL) to enable higher planning methods such as predictive and prescriptive maintenance [17].

Another important use case is visualization, especially in the field of virtual or augmented reality there are many possibilities to make damages visible for maintenance personnel. At the same time, the interpretability of the data can be increased by such applications [18].

1.3 Example System

To keep the complexity of the digital twin as low as possible, a relatively simple system is used as an example system. Therefore, an airplane tire is used as an example system. There are basically two different wear behaviors. On the one hand pressure loss from the tires due to leakage, on the other hand mechanical wear due to friction/landing impacts. There may be other wear mechanisms due to the different impacts and the combination of them. Dieses Papier greift nur den Reifendruck auf, da dieser schon Umfangreich betrachtet wurde. Meissner et al. describes in their publications [19], [20], [17], [21] the condition behavior and maintenance planning based on the tire pressure. It should be noted that the on-board condition monitoring systems have a different goal than a forecasting system for tire pressure refilling. While the on-board condition monitoring system needs absolute pressures to make statements about over- or underinflation, the prognosis system needs a temperature compensated pressure. Therefore, the conversion of the pressure must take place at one point in the system. However, it is much more important that the data receiver is able to interpret the data correctly. For this purpose, the META data must be stored accordingly.

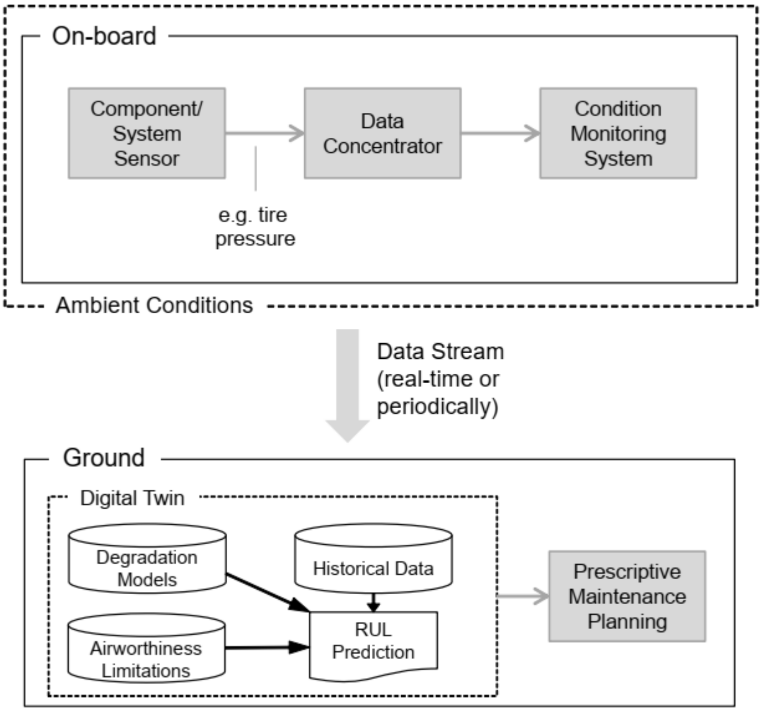

Figure 2: Proposed system layout [17].

2.0 PROPOSED CONCEPT

In this chapter, the basic concept for the digital twin registry is presented. Then, in a second part, the example use case will be discussed.

2.1 Digital Twin Registry Concept

The proposed concept is based on the publication [5]. Individual elements are deepened here for linking the data from the aircraft to the component. First, the concept shown below is described. Then, the specifics, of the coupling of the data are discussed.

Basically, the concept represents the digital thread as an element of the digital twin. It is important that the registry is maintained by a body recognized by all stakeholders. There may well be a difference here between military and civilian solutions. It depends very much on the system boundaries. The system boundary is also important in terms of whether joint spare parts management takes place at alliance level, or whether a country acts independently of other nations. In the civil sector, with the high level of networking among global stakeholders, the registry only makes sense at the level of the global organization, such as IATA or ICAO.

In this concept, the manufacturer of a component creates a corresponding entry in the DT Registry. This then refers to the stored data on his server. Each time one of the stakeholders creates a data record for this asset, it creates a corresponding entry in the registry. The registry thus contains a list of all data endpoints. Access to the data endpoints must be controlled via access rights. These can be predefined by the system but can also include contractually regulated data transfers. System-dependent would be, for example, that the person who installs the component has access to the airworthiness certification, or the aircraft operator has the collection of all certificates.

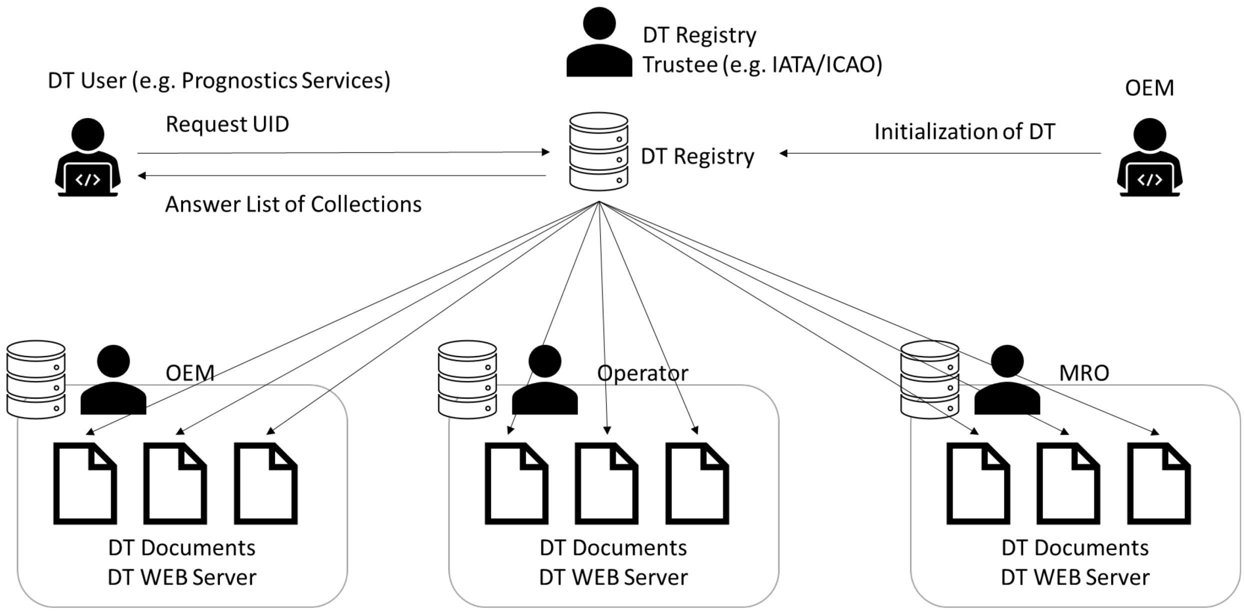

Figure 3: Digital twin concept [5].

One of the particular difficulties for the assignment of data to the digital twin takes place during operation. The data in production can be very clearly assigned to the actual component. Examples could be production data of production machines, but also the META data of the component (such as part number, serial number, date of manufacture, weight...) or also certificates (e.g., EASA Form One) Data in an MRO workshop can also be assigned to the actual component. The activities take place directly on the component. Data could be performed maintenance measures, test results or certificates. In operation, this assignment is so difficult because the data is created and recorded at the vehicle level. This means that data for a subsystem or a component is collected and stored on the overall system.

2.2 Digital Twin Use Case

For a digital twin for aircraft tires, an initial data set would be generated by the manufacturer, which would include Part No., Serial No., Date of Manufacture, Technical Documentation, Certificates, and others. Maintenance would contain data such as date of repair, location, company, tasks performed, modifications, certificates and others.

From Operations, without consideration of new maintenance concepts, installation and removal would be documented in the Digital Twin with attributes of date, location, company, position (e.g., left landing gear or position 1) and reason for removal.

For the integration of predictive, prescriptive maintenance or the Health Index concept of Kamtsiuris et al. additional parameters are needed. This includes mainly the temperature compensated tire pressure. However, additional parameters may be needed if pressure losses depend on different events. This could be for example excessive thermal or mechanical stresses depending on different temperature sensors or accelerometers. Also, it would be important for the digital twin of the tire to know that the pressure is temperature compensated. Also, the description of the mounting position has to be extended by identifiers to replace the free text description that is common today. This can avoid errors in the parameter assignment.

3.0 DATA LINKING

Part of a possible solution can be the distributed digital twin architecture, which is used here as the basis for linking the digital twins. It provides the digital thread. The digital thread of the aircraft or component is a collection of unique identifiers (UID) of the individual subsystems and components combined with the associated meta data and the system parameters belonging to the aircraft.

In order to enable the retrieval of time series, various requirements must be met. First of all, the installation and removal messages must be digitally recorded in the digital twin of the component but also in the next higher asset. In addition to the date and time for the limitations of the time series, these must also contain the UID of the component and the UID of the asset in which the component was installed or from which it was removed. An example record for the installation might look like this:

```
UUID Component:        de710a84-46bb-47a0-a563-06eb6266155f

UUID Data Set:         c6829bcf-8053-4b76-8052-4eac8681b3b9

Part Number:           PN1234

Serial Number:         S123

Name:                  Tire

Date:                  24.06.2020 18:35

UUID Parent:           e120dcb8-64f9-4b04-ac2f-184d4d7d012c

Position:              left Landing Gear

Document:              EASA Form One.pdf
```

Another point is the relevant parameters for the component. Modern aircraft process (possibly store or transmit) several thousand parameters. However, the individual components only require a small number of these or data in aggregated form. From the complete data set, conclusions can be drawn about the airline's business model or the performance of the pilots, which is why there are legitimate interests in limiting access. On the other hand, aggregated values for further processing can or must be calculated from a large number of parameters. An example could be the tire pressure indicating system, for which the (temperature compensated) pressure is required. The calculation of the pressure required for the prognosis can either be carried out directly in the data processing asset (aircraft) or on the ground in post-processing. The post-processing can take place with different stakeholders either in the DT of the aircraft or in the DT of the tire.

Accordingly, it must be specified for each component which parameters are required. However, this can evolve or change over the life cycle or with different applications. In addition to the parameters themselves, the resolution of the time series is also required. In the case of aggregated values, other descriptions such as min. and max. values could also be important. This description is necessary for each individual component that is to be provided with the corresponding functionalities. A parameter list could look like this:

```
UUID Component:       de710a84-46bb-47a0-a563-06eb6266155f

Part Name:            Tire

Part Number:          PN1234

Serial Number:        S123

Name:                 Asset 1

Parameter:            temperature compensated pressure

                           total tire pressure

                           tire temperature

                                 brake temperature

                           Total air temperature

Resolution:           20ms
```

This comes to the next problem the standardization. The pressure for example is not a unique name as we have temperature compensated and total pressure. Therefore, a high standardization for the parameter are needed and should also include semantic identifier.

The interfaces in the aircraft are defined by the system integrator during development. This usually includes mechanics, power, hydraulics, data interfaces. In addition, for digital twin concepts to work, they would need to include the interfaces of the digital twin at the component level.

For the tire example, the individual parameters would require persistent unique identifiers. At the same time, there must also be unique identifiers for the data source or installation position.

The installation position ID has the lower requirements for the digital twin conversion. The only important thing here is that the conversion is consistent in an aircraft pattern. Existing numbering systems such as ATA or the IDs used by the manufacturers (Airbus FIN, Boeing EquipmentID) could be applied. The installation ID is assigned to the component with each installation. Example:

```
Position_ID:          32200101 (reflects left LG, left tire)
```

The parameter ID is different. This must be unique and transferable across aircraft types. Especially for components that are used on different patterns. Therefore, standardization is needed. It should be recognizable that it is a parameter ID, and the parameters should be divided into groups in order to quickly identify the correct parameters in the design that are assigned to the digital twin. The parameters are defined once by the component manufacturer in the initialization. Another possibility would be that other stakeholders use individual parameters later for their predictors and store them in their own configuration file. Example:

```
Parameter:          P000111 temperature compensated pressure

                    P000112 total tire pressure

                    P000211 tire temperature

                    P000212 brake temperature

                    P000213 Total air temperature
```

It should also be defined for each parameter ID how often they occur during a mission, what the unit is and what uncertainty is assigned to them. For data bus systems, such information is usually defined in the associated standards. The last aspect is the data protection after removal of the component from the higher asset. For the owner of the component no data of the higher asset should be accessible after removal of the component.

4.0 CONCLUSION

One of the main problems for digital twins on component level is the linkage with data from other digital twins. Only by linking with the parameters from the aircraft can predictive, prescriptive and health index concepts be enabled at the component level. An essential point is the link between the components and the aircraft. This should be done by digital on and off messages. In order to implement this parent-child relationship well, unique position identifiers must be available at aircraft type level. In order to then successfully assign parameters to a component over a life cycle, the parameters must be equipped with persistent one-to-one identifiers. Only in this way can they be linked to the associated component. The individual data sets then also require individual identifiers to identify them. The META data for each parameter must also be known in order to make the correct selection in design and operation. In order to enforce these standardization requirements, it is essential that this takes place at the highest possible level to ensure interoperability between the individual assets. Points not yet sufficiently considered for such digital twin concepts are access rights, IP protection, ontologies, and data markets.

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