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RESEARCH ARTICLE

Certification Compliant Performance Analysis and Requirements Management of an Electrically Powered General Aviation Aircraft

Elektrikle Çalışan Bir Genel Havacılık Uçağının Sertifikasyona Uygun Performans Analizi ve Gereksinim Yönetimi

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Abstract

This article presents an implementation of a requirements validation toolchain for the certification-compliant performance analysis of an electrically powered general aviation aircraft. As part of the dtec.bw project ELAPSED, a novel approach for an electric propulsion system for an aircraft of the EASA certification specification class CS-22 is developed. Predefined requirements for the aircraft must be met by the design in order to comply with the CS-22 certification rules, such as a maximum take-off distance of 500 meters. Other requirements defined by the manufacturer or customer can also be easily added. A toolchain providing bidirectional traceability from the requirements to the test results has been established to validate the feasibility of the aircraft and system requirements and their compliance with the certification standards. This toolchain consists of Polarion PLM for requirements management and MATLAB/Simulink for mission evaluation using a non-linear 6-DoF simulation model for the respective aircraft. Two in-house tools called SimPol and Tico provide connectivity and round-tripping between Polarion and Simulink. The application of this toolchain is presented in this article using a test run with 3 requirements.

Keywords: Requirements, Certification, Polarion, Simulation, Performance Analysis

Öz

Bu makale, elektrikle çalışan bir genel havacılık uçağının sertifikasyona uygun performans analizi için bir gereksinim doğrulama araç zincirinin uygulanmasını sunmaktadır. ELAPSED dtec.bw projesinin bir parçası olarak, EASA sertifikasyon spesifikasyon sınıfı CS-22 olan bir hava aracı için elektrikli tahrik sistemine yönelik yeni bir yaklaşım geliştirilmiştir. CS-22 sertifikasyon kurallarına uymak için, maksimum 500 metrelik kalkış mesafesi gibi uçak için önceden tanımlanmış gereklilikler tasarım tarafından karşılanmalıdır. Üretici veya müşteri tarafından tanımlanan diğer gereksinimler de kolayca eklenebilir. Uçak ve sistem gereksinimlerinin uygulanabilirliğini ve sertifikasyon standartlarına uygunluğunu doğrulamak için gereksinimlerden test sonuçlarına çift yönlü izlenebilirlik sağlayan bir araç zinciri oluşturulmuştur. Bu araç zinciri, gereksinim yönetimi için Polarion PLM ve ilgili uçak için doğrusal olmayan 6-DoF simülasyon modeli kullanarak görev değerlendirmesi için MATLAB/Simulink'ten oluşmaktadır. SimPol ve Tico adlı iki şirket içi araç Polarion ve Simulink arasında bağlantı ve gidiş geliş sağlamaktadır. Bu araç zincirinin uygulaması, bu makalede 3 gereksinimli bir test çalıştırması kullanılarak sunulmuştur.

Anahtar Kelimeler: Gereksinimler, Sertifikasyon, Polarion, Simülasyon, Performans Analizi

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1. INTRODUCTION

The dtec.bw project ELAPSED is concerned with the development of an innovative electric drive chain comprising a multi-stage battery technology and an improved electric motor. This drive train is to be integrated into a powered glider that is currently being developed by an aircraft manufacturer. The electric glider with a take-off mass of 820 kg and a maximum continuous power of 80 kW is aiming for EASA CS-22 certification [1]. To achieve this goal, the development of the aircraft, including the powertrain, must be in accordance with the EASA certification specification and standard. Therefore, several additional standards must be met to ensure sufficient and appropriate requirements definition and derivation, traceability, requirements testing, validation and verification.

The following chapters present the associated standards, the toolchain for requirements management including the implemented workflow and the selected tools. Furthermore, the traceability concept and an exemplary execution for some requirements of the requirements verification and validation workflow are presented. From the results of this research, requirements for several key components such as the battery or the engine are derived, which increases the importance of this process. In addition, these subsystems can use the same toolchain and workflow to ensure their own certification-compliant development.

2. PROJECT STRUCTURE AND WORKFLOW

In order to be able to carry out tests, the simulation framework with all relevant models and functions must be part of this research and available for the test toolchain. For this reason, the MATLAB project structure is shown in Figure 1. Most of the project parts are implemented in MATLAB/Simulink, but all projects are stored in the DevOps tool GitLab.

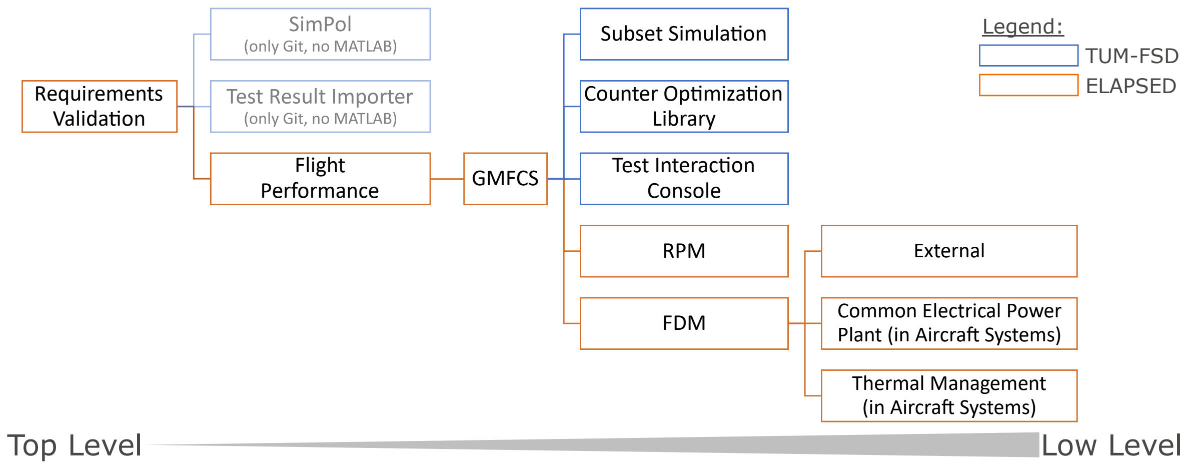

Figure 1. MATLAB project structure.

This research combines work of two institutes of two different universities – the Institute of Flight System Dynamics at TU Munich [2] and the chair of the authors of this article. Tools such as SimPol [3], Test Result Importer [4] or Test Interaction Console Tico [5] from TU Munich are combined with the Flight Performance implementation of UniBw ELAPSED which includes e.g. a Reactive Pilot Model (RPM) and a Flight Dynamics Model (FDM). Top-level project in this structure is, of course, the Requirements Validation repository. The Flight Performance project is only directly linked to the God-Mode Flight Control System (GMFCS), but also contains its own functionalities such as trimming or linearizing the simulation model. The GMFCS itself can execute missions automatically and in parallel manner. In that way, a wide range of functionalities is also available for requirements validation at top-level.

Table 1. Associated norms and standards.

Standard	Title	Use
CS-22 [1]	Certification Specifications, Acceptable Means of Compliance and Guidance Material for Sailplanes and Powered Sailplanes	Requirements Definition and Derivation
SC E-19 EHPS [6]	Special Condition for Certification of Electric and/or Hybrid Propulsion Systems	
ARP 4754 [7]	Certification Considerations for Highly-Integrated or Complex Aircraft Systems	Requirements Validation, Traceability, …
ARP 4761 [8]	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment	

As mentioned, the electric-powered glider developed in the project aims for a certification according to CS-22. Therefore, other standards such as SC E-19 EHPS [6], ARP 4754 [7] and ARP 4761 [8] are also applicable and associated. Certification specification 22 [1] and special condition SC E-19 EHPS [6] for electric and/or hybrid propulsion systems are mostly used for definition and derivation of requirements. ARP standards focus more on the process of requirements validation including traceability and completeness of requirements. Table 1 shows the standards applicable to the requirements discussed in this article. In order to achieve a complete certification, the list keeps on getting extended.

Figure 2 shows the toolchain for requirements management. In short, requirements mostly derived from CS-22 are stored in work items in the requirement management tool Polarion. SimPol links these work items to unit tests defined in MATLAB/Simulink. The test cases are executed via the Test Interaction Console Tico. This workflow ensures integrity, traceability, transparency and consistency.

The certification specification CS-22 [1] is the source of most of the requirements to be fulfilled for obtaining a successful certification. On top, some requirements do not originate from the CS-22, but are customer-, manufacturer- or self-defined such as a minimum achieved distance traveled or number of completed Touch and Gos.

Polarion ALM [9] is an industrial application lifecycle management tool by Siemens AG including requirements, test, quality, and risk management. Advantage of this tool is the traceability of the whole development process ensuring a completeness of the information about every step. Another opportunity is the variation of settings such as user roles or work item types. Along with this, the collaboration among teams in the project and between projects is easily possible. This allows e.g. an easy configuration exchange with TUM-FSD [2] according to [4] and who also developed the tool SimPol.

SimPol [3] is developed by TUM-FSD and allows uni- or bidirectional linking of work items in Polarion and test cases in MATLAB/Simulink. To receive necessary information of the work items and being able to upload the test results later, a bidirectional link via surrogate linking method and surrogate work items is required. All settings such as the related project, Polarion server address, target file or the mentioned linking method need to be adjusted in the allocation file.

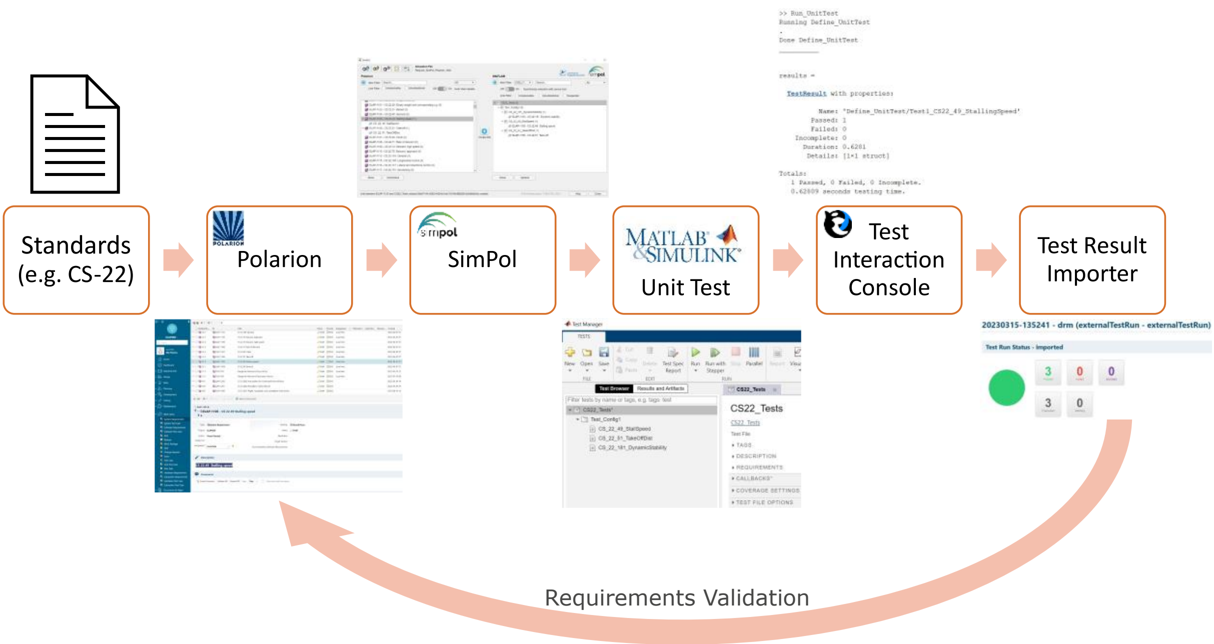

Figure 2. Requirements management toolchain and workflow.

There is a variety of ways defining the test cases: MATLAB vs. Simulink Unit Test, script- vs. class-based. Within these options (e.g. class-based MATLAB Unit Test), there are still multiple ways of implementing test cases and storing all relevant executions and data. In this approach, all test cases are defined in a single Simulink Test file. The Simulink Test Manager allows an intuitive creation of several testsuites and testcases with a range of options, e.g. callbacks or custom criteria for test verification.

The Test Interaction Console Tico [5] merges and simplifies the test execution of the Simulink Requirements Management Interface of MathWorks in a way, that the commands reduce themselves to 1 single line '*tico polarion test*' or *'tico test'* for executing the related test cases.

The generated test results by Tico must be fed back into Polarion to close the loop and verify if the tested cases fulfill the connected requirements. Tico can output an XML-file and push it via *'tico push'*. On Polarion side, the Test Result Importer by TUM-FSD [2] is the indispensable counterpart. The Importer can deal with the provided information of the tests and work items such as the work item revision, an execution date or the evaluation result in the XML-file. Every performed test run results can then be visualized as shown later in chapter 4 and requirements – or better their work items – marked as passed or failed.

After implementing all requirements into the Polarion and defining and linking the test cases in the MATLAB/Simulink Unit Test, the test execution is fully automized. Running the test run means running one single script which sets the *'tico path'* to the path where the test cases are stored, calling *'tico test'* or *'tico polarion test'* for conducting the specified tests and generating an XML-file with all results for importing into Polarion via *'tico polarion push'*.

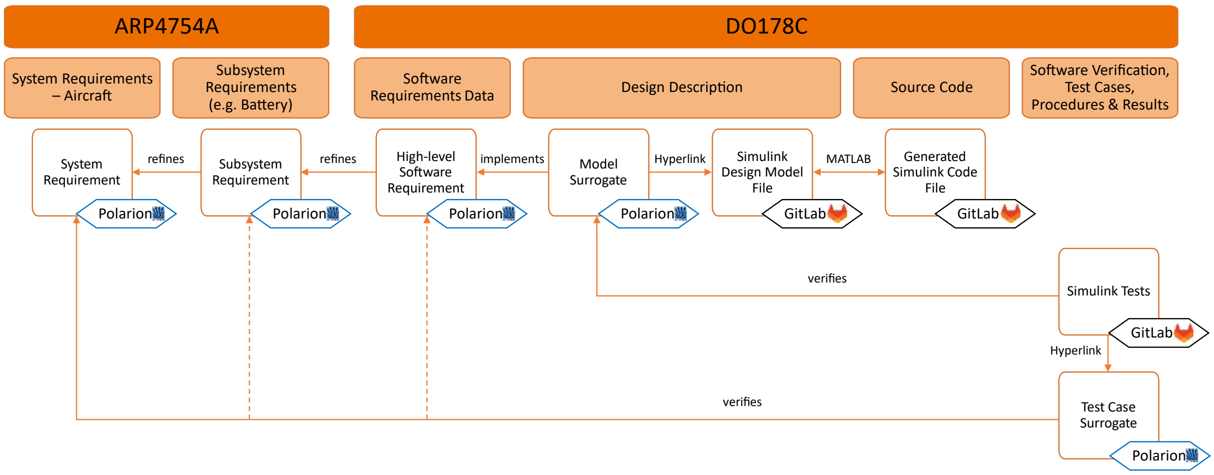

Figure 3. Traceability concept.

As mentioned, traceability of requirements must be given according to ARP 4754 [7]. Due to that, a traceability concept between the test cases in Simulink Test and the requirement work items in Polarion is developed and is shown in Figure 3. In this concept, the ARP 4754 is the top-level standard to be followed on aircraft level (here called system level) including all components, e.g. battery or motor (here called subsystems). Going more into detail, it can be split up into software and hardware components.

Software relies on DO 178C [10] and e.g. electronic hardware to DO 254 [11]. For the sake of simplicity and clarity, Figure 3 focuses on the traceability from aircraft level to software. On top, the applying standards are illustrated. Below that, the system is divided into system and subsystem for ARP 4745 and into software requirements data, design description, source code and software verification, test cases, procedures and results. Each of these captions contains at least 1 item which is defined in Simulink and stored in GitLab or in Polarion. The Simulink test file creates as mentioned a hyperlink connection to a test case surrogate work item in Polarion via SimPol. This surrogate work item is automatically generated by SimPol after linking a requirement work item. Depending on the requirement, linking and verification can be implemented to the system, subsystem or software level.

Due to the specified test run setup in chapter 3 of this article, the line to aircraft level is solid and not dotted. The link types *'verifies'*, *'refines'* and *'implements'* are defined in the Polarion project settings. It can also be seen that these test cases run on the Simulink code file. This file is generated by MATLAB Embedded Coder out of a Simulink Design Model, which is linked via hyperlink to the model surrogate in Polarion to ensure traceability.

3. TEST RUN SETUP

Exemplarily, this article presents the results of 3 requirements of CS-22: CS22.49 Stalling Speed, CS22.51 Take-Off Distance, CS22.181 Dynamic Stability. These 3 requirements are chosen to demonstrate the variability of the system. For simulating the stall speed, a 6-DoF aircraft model is trimmed as described in [12] for the related speeds of 80 km/h and below, so in general the flight envelope is generated. For calculating the short period damping, a suiting aforementioned trimmed state needs to get linearized, and the state-space model extracted. As third functionality, for the take-off distance, there is a dynamic simulation model as described in [13] and [14] necessary to generate accurate results.

The toolchain of this articles research can handle all types of tests. As there is no value for the damping of the short period in the CS-22, but mentioned "heavily damped" [1, p. 28], the value is defined by MIL-F-8785C [15]. For this approach and to be on the safe side for all categories of flight phases, a minimum short period damping of 0.35 and maximum of 1.35 is used as verification criteria, according to [15, 3.2.2.1]. An optimal damping would of course be $\sqrt{2}/2$. These criteria are also shown in Table 3.

Table 2. Executed tests – IDs.

Requirement Name	Requirement Work Item	Surrogate Test Case Work Item
CS22.49 Stalling Speed	ELAP-1105	ELAP-2859
CS22.51 Take-Off Distance	ELAP-1106	ELAP-2860
CS22.181 Dynamic Stability	ELAP-1133	ELAP-2879

The considered requirements in Table 2 are implemented in Polarion via work items with unique IDs. As mentioned in chapter 2, these requirements work items again are verified by individual surrogate work items which rely to a certain test case. For example, the requirement for a maximum allowed take-off distance is represented via the work item ELAP-1106. The test case with the ID ELAP-2860 verifies the requirement work item if the test results pass the test verification criteria. This fulfills the traceability concept in Figure 3, but due to the requirement on aircraft level, the lower levels, e.g. subsystem requirements are not necessary, and the verification can be managed directly between the test case surrogate and the system requirement.

4. TEST RUN RESULTS

Execution of the test setup in chapter 3 generates various outputs supporting easy documentation, visualization, and automation:

- MATLAB base workspace: variable with test results
  - Simulink Test Manager
  - Exportable test run results and artifacts including all logged signals
  - Plots of simulation output, if required
  - error report, e.g. if a test fails verification
- Tico: XML-file to view results and upload to Polarion
- Polarion: test run status of imported results (see Figure 5)

Some of these output objects are shown in this chapter. The exemplarily test run execution of 3 associated requirements of CS-22 specified in chapter 3 gives a test compliance of 100% by verifying 3 of 3 test cases as shown in Table 3.

Table 3. Executed tests – results.

Requirement Name	Verification Criteria	Resulting Value	Test Compliance
CS22.49 Stalling Speed	$\leq 80\ km/h$	$79.2\ km/h$	✓ Passed
CS22.51 Take-Off Distance	$\leq 500\ m$	$401\ m$	✓ Passed
CS22.181 Dynamic Stability	$0.35 \leq \zeta_D \geq 1.3$	0.97	✓ Passed

According to Table 3, the stall speed of 80 km/h is not exceeded with 79.2 km/h. Maybe there would even be a smaller stall speed possible, but was not tested, because the requirement is already fulfilled. The allowed take-off distance of 500 m is also not exceeded at an automated full power start even at the runway height of Innsbruck Airport in Austria which is nearly 60 m higher than Munich (Germany). Figure 4 shows this dynamic simulation of the automated take-off by displaying the height over ground and the corresponding absolute kinematic velocity of the aircraft over the traveled distance since initializing the model on the runway of LOWI (Austria, Innsbruck Airport). The data such as position and speed are logged during the simulation for each time step allowing postprocessing. Out of the position data, for example the travelled distance from the initial position to the actual location in each time step can be easily calculated and among others used for the take-off distance computation.

The left dotted line in red color shows, that the reactive pilot model is behaving properly due to introducing the lift-off directly after reaching the target velocity of around 31 m/s on the slightly inclined runway. The desired climb angle is reached sufficiently fast after the rotation phase. The right dotted line in red color with the circle at the top end depicts the point of reaching 15 m above ground, leading to the take-off distance needed. In this case – which is reproduceable – 401 m is the distance traveled from initial position to reaching the defined height of 15 m. The take-off distance is calculated automatically at test execution specified in the test definition for this requirement. This leads to verifying the requirement.

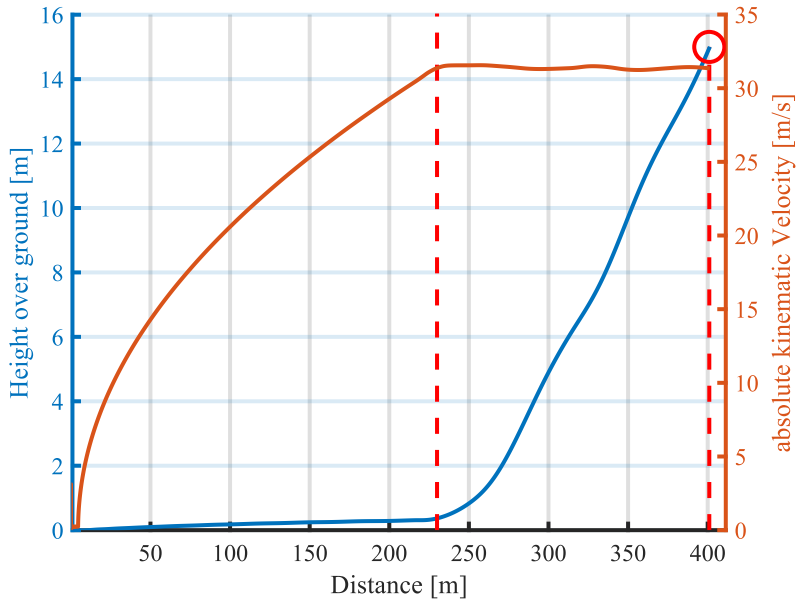

Figure 4. Dynamic simulation results – take-off distance.

The damping of the short period as an eigenmotion is not as well and easily visualized as the dynamic simulation of the take-off distance. In the simulation, the 6-DoF model of the aircraft including data of all subsystems such as weight and balance, powertrain and aerodynamics getting trimmed and then linearized. The steady-states space model (SS-model) can be cut into the parts of the longitudinal and the lateral movement. These can again be divided and simplified into the SS-models of specific eigendynamics. For the short period, the states of the pitch rate q and the angle of attack α are mostly relevant as shown in Equation (1). Z and M represent the dimensional state and input derivatives and η the elevator deflection [16]

$$\begin{bmatrix}\dot{\alpha}\\ \dot{q}\end{bmatrix} = \begin{bmatrix}Z_\alpha & Z_q + 1\\ M_\alpha & M_q\end{bmatrix}\begin{bmatrix}\alpha\\ q\end{bmatrix} + \begin{bmatrix}Z_\eta\\ M_\eta\end{bmatrix}\cdot\eta \tag{1}$$

Out of this part-model, the eigenvalues, and thus the relative damping ζ of this eigenmotion can be easily calculated out of the absolute damping σ and the natural frequency ω as defined in Equation (2). The damping of the short period is with a value of 0.97 a bit higher than the optimal value of $\sqrt{2}/2$, but still well within the limits of the verification criteria of 0.35 and 1.3. Summed up, all 3 tests are resulting in a compliance to and validation of the 3 aircraft requirements.

$$\zeta = \frac{\sigma}{\omega} \tag{2}$$

Once the test run results have been automatically imported into Polarion, a status overview can be viewed in Polarion. This test run status is shown exemplarily in Figure 5. As the pie chart in the upper part of Figure 5 illustrates clearly, all 3 executed test cases passed the verification criteria. The surrogate work items and their status – passed, failed or blocked – can be seen in the lower part of the mentioned figure. Accordance to the traceability concept in Figure 3, the test results in Simulink are imported automatically into Polarion to set the status of the test case surrogate work items. These in turn, verify the requirement work item, which is in this case relying to CS-22 and aircraft level.

Figure 5. Status of imported test run in Polarion.

5. CONCLUSION AND OUTLOOK

As this article's title indicates, an approach for certification compliant performance analysis and requirements management of an electrically powered general aviation aircraft is discussed. Therefore, the applicable standards for a certification according to EASA CS-22 as well as the project structure including all relevant subprojects to fulfill requirements testing and validation are introduced. The main requirements management tool for this research is Siemens Polarion. The toolchain and workflow that was developed under this premises start with the standards, such as certification specification CS- 22, and derive them into requirement work items in Polarion. These are linked via SimPol with a MATLAB/Simulink unit test. The tests are executed by the

Test Interaction Console Tico and the results imported back into Polarion via a Test Result Importer. A traceability concept has been developed in accordance with the standards, such as ARP 4754. An exemplary test run setup of the mentioned toolchain was carried out and verified, that all 3 tests were linked to Polarion, passed the verification and were imported into the Polarion. This provides an effective, traceable, comprehensive, and to certification requirements compliant way of requirements management, validation and verification.

The research forming the basis of this article is not yet fully completed. There are several ways to extend and improve its current state. All considered requirements stored in Polarion need to be implemented in test cases to ensure completeness. Especially subsystem requirements are not yet thoroughly enforced. Additionally, the usage of a continuous integration server for guarding a version in GitLab for which every test must be passed would be valuable. At present, a CI-Server is already set up but is only used for integrating the projects, not the test results.

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REFERENCES

[1] *CS-22 Amendment 3: Certification Specifications, Acceptable Means of Compliance and Guidance Material for Sailplanes and Powered Sailplanes,* European Aviation Safety Agency. [Online]. Available: https://www.easa.europa.eu/en/downloads/131414/en

[2] TUM, *TUM-FSD: Technische Universität München -Institute of Flight System Dynamics.* [Online]. Available: https://www.fsd.ed.tum.de/

[3] M. T. Hochstrasser, "Modular model-based development of safety-critical flight control software," Dissertation, Fakultät für Luftfahrt, Raumfahrt und Geodäsie, Technische Universität München, München, 2020.

[4] K. Schmiechen, S. Zafar, K. Dmitriev, C. Krammer, M. Maly, and F. Holzapfel, "A Requirements Management Template in Polarion for Model-Based Development of Airborne Systems," in *Software Engineering 2021 Satellite Events, Lecture Notes in Informatics (LNI)*, Bonn, 2021.

[5] F. Schwaiger, K. Schmiechen, and F. Prof. Dr.-Ing. Holzapfel, "Tico – a Toolbox to Author and Execute Large Parametrizable Test Suites in MATLAB," in *AIAA SCITECH 2023 Forum*, National Harbor, MD, 2023.

[6] *SC E-19 EHPS: Special Condition 19 - Electric / Hybrid Propulsion System,* European Aviation Safety Agency, Apr. 2021.

[7] *ARP 4754: Certification Considerations for Highly-Integrated or Complex Aircraft Systems,* SAE International.
[8] *ARP 4761: Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment,* SAE International.
[9] Siemens AG, *Polarion ALM - Application Lifecycle Management.* [Online]. Available: https://polarion.plm.automation.siemens.com/products/polarion-alm (accessed: Mar. 15 2023).
[10] *DO-178C: Software Considerations in Airborne Systems and Equipment Certification,* Radio Technical Commission for Aeronautics.
[11] *DO-254: Design Assurance Guidance for Airborne Electronic Hardware,* Radio Technical Commission for Aeronautics.
[12] L. Hein and S. Myschik, "Simulation of an Electric Powered Aircraft for Flight & Mission Performance Evaluation," in *AIAA AVIATION 2022 Forum*, Chicago, IL & Virtual, 2022.
[13] L. Hein, D. Surmann, N. Sauert, and S. Myschik, "Simulationsumgebung zur Ermittlung der Missionsleistungen eines elektrisch angetriebenen Luftfahrzeugs," in *DLRK 2022: Deutscher Luft- und Raumfahrtkongress 2022*, Dresden, 2022.
[14] L. Hein, P. Panchal, D. Surmann, and S. Myschik, "Performance Analysis of an electrically powered General Aviation Aircraft using parallelized automated Mission Simulations," in *AIAA AVIATION 2023 Forum*, San Diego, CA, 2023.
[15] *MIL-F-8785C: Flying Qualities of Piloted Airplanes*, Nov. 1980.
[16] M. V. Cook, *Flight Dynamics Principles: A Linear Systems Approach to Aircraft Stability and Control,* 2nd ed. Oxford, England: Butterworth-Heinemann, 2007.
[17] dtec.bw, *Electric Aircraft Propulsion – die Zukunft der Flugzeugantriebe.* [Online]. Available: https://dtecbw.de/home/forschung/unibw-m/projekt-elapsed (accessed: Nov. 8 2022).

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