

A MULTIDIMENSIONAL FRAMEWORK FOR DEMONSTRATION AND V&V CAPABILITIES FOR NEXT-GENERATION FLIGHT CONTROL SYSTEMS

Oliver Bertram[1], Holger Schumann[1], Robert Kowalski[1], Alexander Bagdahn[1]

[1]German Aerospace Center (DLR), Institute of Flight Systems, Braunschweig, Germany

Abstract

The development of next-generation flight control systems requires early and realistic demonstration, verification and validation (V&V) at multiple system levels, as increasing system complexity requires the integration of physical components, control functions and environmental influences. Specialized demonstrators and test platforms offer such capabilities by combining real hardware with model-based simulations in representative environments.

However, existing approaches describe these environments from isolated perspectives, such as system level, physical and virtual representation, or specific investigation objectives. This fragmentation limits their systematic comparison, coordinated use and targeted planning, especially for configurations that require the integration of multiple subsystems under realistic conditions.

In this paper, a multidimensional framework for the structured characterization of demonstration and V&V capabilities is presented and applied to a set of representative test and demonstration platforms. The framework structures these capabilities along the dimensions of system level, ranging from component to system, system representation, ranging from physical to virtual, and V&V focus, ranging from functional behavior and physical effects to system integration and fault scenarios. It enables a consistent characterization of the considered capabilities, supports their comparison and reveals structural gaps in their coverage.

The results show that demonstration and V&V cannot only be interpreted as a sequence of test activities, but rather as the problem of achieving sufficient coverage within a multidimensional capability space. Based on this perspective, the framework is understood as a structured set of dimensions and categories that provides a common description space for characterizing, comparing and identifying gaps in demonstration and V&V capabilities. It supports the systematic characterization, combination and planning of such capabilities and their realization through complementary test and demonstration environments, while providing a structured basis for organizing and linking corresponding activities within systems engineering processes.

Keywords: Flight Control Systems, V&V Framework, Demonstration Platforms, Systems Engineering

1. Introduction

1.1 *Motivation and V&V Challenges for Future Flight Control Systems*

Climate-friendly flying is a key driver for new aircraft concepts aimed at higher energy efficiency and reduced emissions. A key approach is the use of high aspect ratio wings, low drag profiles and lower structural weight to improve aerodynamic performance [1], [2]. These concepts lead to more flexible wing structures with increased loads, stronger deformations and an earlier occurrence of aeroelastic effects such as flutter. To actively control these effects, additional flight control functions with high dynamics and bandwidth are required (e.g. Gust Load Alleviation, Active Flutter Suppression) [3]. At the same time, the more flexible structure itself in turn influences control and stability. Due to the aeroelastic coupling between structure, actuators and control, the design of flight control systems (FCS) with multifunctional control surfaces is increasingly becoming an integral part of the early wing

design and requires a close interlocking of system design, integration and verification and validation (V&V) [4].

The contributions of the supplier industry are gaining importance in the design of these future flight control systems at an early stage, as central system functions such as actuation, power distribution and avionics must be implemented largely through new technologies or specialized subsystems. Driven by the trend towards More Electric Aircraft and the partial introduction of power-by-wire in the primary flight control of the A380 and A350, the integration of electric control surface actuators in new flight control architectures is becoming increasingly important [3]. However, electric actuators can also lead to interactions with other systems such as the on-board electrical power system. In the context of highly dynamic flight control functions, for example, high design-relevant load peaks can occur. Furthermore, environmental influences and faults increase the design requirements and lead to non-linear or difficult-to-predict dynamic system behavior over time. Future flight control systems will also require increasingly powerful, networked computer systems and integrated avionics architectures, resulting in additional dependencies between flight control, system architecture and software. Overall, highly coupled, multidisciplinary systems are emerging whose pronounced, non-linear interactions can no longer be described in isolation at component level. These developments significantly increase the system complexity of future flight control systems and shift the focus from the component level to the system level and to the integrated consideration and V&V of coupled systems.

To master this complexity, model-based approaches such as Model Based Systems Engineering (MBSE) [5], [6] and simulation models are used for system analysis, virtual testing, early design validation or the development of control functions [7], [8]. Although these enable efficient development and analysis, they cannot fully predict critical system interactions and emergent behavior. In practice, it is often the case that relevant system behavior only becomes visible when real components, control functions and operating conditions are integrated together. In particular, critical interactions only arise in the interaction of all systems and remain hidden in isolated model and component tests. The central break thus occurs during the transition from isolated component and subsystem verification and validation to an integrated overall system view, which makes it difficult to consistently evaluate and compare test and V&V results across different environments. As a result, system-critical effects are often only recognized at a late stage of development.

Traditional test and V&V approaches for flight control systems follow a separate consideration of component, subsystem and overall system levels in isolated development and test environments. On the one hand, the state of the art includes component and subsystem-based test benches with a high test depth, but without comprehensive mapping of system interactions. On the other hand, there are highly integrated system test benches (so-called Iron Birds), which enable realistic system integration, integration testing and selected V&V activities, as well as the identification of critical interactions. However, these system test benches are typically strongly tied to specific aircraft programs, resource-intensive and often monolithic in design. As they are also only available in late development phases, i.e. at a time when essential system decisions are largely fixed or already frozen (design freeze), they can only be adapted to new system architectures and technologies of flight control systems to a limited extent or with considerable effort. This means that the middle area between component-related validation and later overall system integration remains insufficiently addressed.

This results in a methodological gap between the early, isolated verification and validation of individual components, technologies and subsystems on the one hand and the later, fully integrated testing in a representative overall system context on the other. In particular, there is a lack of suitable test, integration and demonstration environments in the critical technology readiness level (TRL). In the context of this TRL model, the area between TRL 4 and TRL 6 is often referred to as the Valley of Death, in which numerous technologies do not successfully make the transition to application [9], [10]. TRL 4 generally refers to validation in a laboratory environment, TRL 5 to validation in a relevant environment, and TRL 6 to demonstration in a relevant environment. As a result, system-critical interactions cannot be recognized early enough, which leads to increased development risks and later adaptation costs in technology maturation. At the same time, existing integration environments only partially support the early and flexible evaluation of innovative supplier systems in a representative aircraft context, particularly when new technologies must be assessed before a complete aircraft-level integration facility is available. This gap particularly affects early and iterative technology and system integration under realistic conditions. There is therefore a clear need for modular and flexible test and demonstration environments that enable early technology and system integration under

representative conditions. The aims are to identify critical system interactions at an early stage, support reliable architecture decisions and reduce integration risks at a later stage.

1.2 *Need for an Integrated Demonstration and V&V Framework*

Beyond these technical and integration-related challenges, existing test, demonstration and V&V environments are typically viewed from different and largely isolated perspectives, for example with regard to system level, system representation, technology maturity or test strategy. In this paper, demonstration refers to the integrated showing of a technology, function or system capability under relevant and representative, but not necessarily certification-complete, conditions. As a result, there is a lack of consistent and integrated characterization of demonstration and V&V capabilities and their systematic comparability, combination and planning across different test and demonstration environments, as schematically illustrated in Figure 1.

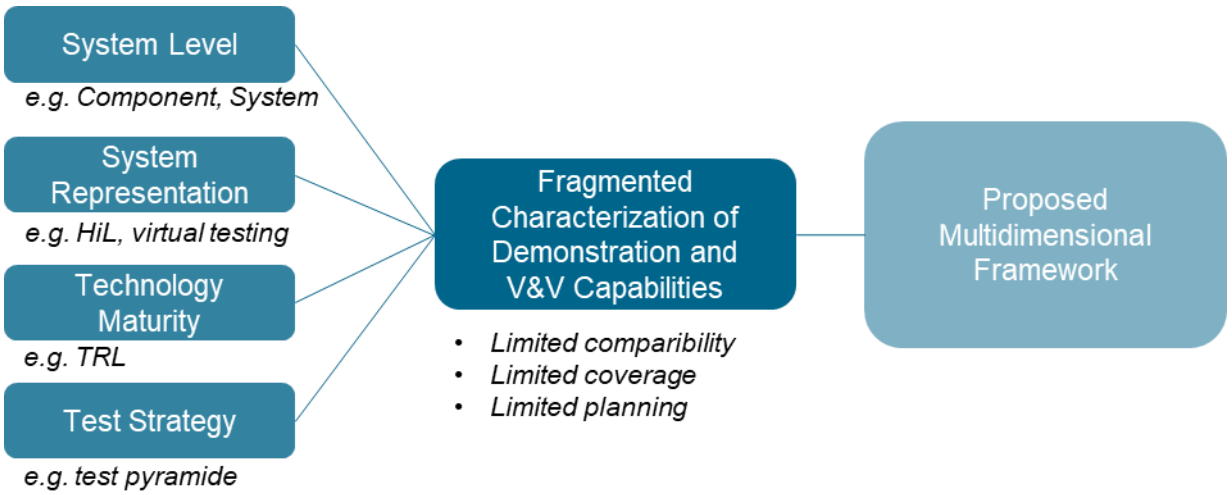


Figure 1 - Fragmented characterization approaches for demonstration and V&V capabilities. Existing concepts address different aspects such as system level, system representation, technology maturity and test strategy from isolated perspectives, limiting the consistent characterization, comparison and planning of demonstration and V&V capabilities. (Copyright DLR)

There is therefore a need for an integrated framework that consistently brings together different perspectives on demonstration and V&V capabilities, thereby enabling a structured description, comparison and combination of such capabilities. This paper addresses this gap by analyzing and structuring existing test and demonstration environments for future flight control systems and introduces a multidimensional framework that integrates different perspectives on demonstration and V&V capabilities within a common multidimensional description space. The framework supports the consistent classification, analysis and systematic planning of such capabilities, particularly to support the transition across the Valley of Death between isolated technology V&V and integrated system demonstration and V&V under representative conditions.

Section 2 provides an overview of test and demonstration environments from literature, research and industry, describes selected representative platforms and analyzes them comparatively. The resulting observations form the basis for the integrated framework introduced in Section 3, which enables a systematic characterization of demonstration and V&V capabilities within a multidimensional description space. Section 4 discusses the positioning of existing platforms within this framework as well as the resulting implications for future test and demonstration environments. Finally, Section 5 concludes the paper by summarizing the main findings and outlining the relevance of the proposed framework for future demonstration and V&V capabilities.

2. Test and Demonstration Platforms for Flight Control Systems

2.1 *State of the Art*

Providing assurance for safety-critical functions of future flight control systems (FCS) is becoming increasingly challenging as system complexity and integration requirements continue to grow. This development is driven in particular by new system architectures in which flight control, actuation, power supply, software, communication networks and condition monitoring are increasingly interconnected [3], [5], [6], [11], [12]. The transition toward More Electric and All Electric Aircraft

introduces additional dependencies related to power electronics, energy distribution, thermal behavior and fault management. As a result, the number of potentially safety-critical interactions between functions, subsystems and technologies increases significantly. Consequently, integration, verification and validation (V&V) approaches are required that explicitly address the behavior and interactions of integrated overall systems.

Accordingly, different verification methods are used depending on the development phase. While analysis and simulation methods support early development phases, test and demonstration environments are typically used in later phases to provide reliable evidence of integrated system behavior under representative conditions. Effective V&V therefore requires the coordinated use of complementary approaches.

A heterogeneous integration, test and V&V landscape has been established to overcome these challenges. This ranges from component-level technology and actuator test benches [13] to specialized subsystem test benches [14] and hardware-in-the-loop environments with real-time simulation [15] through to complete system integration benches [16], [17]. Depending on the level of integration, these platforms address individual hardware, coupled functions, real-time behavior or overall system interactions. This illustrates that effective V&V is typically not performed by a single test bench, but by several complementary platforms.

For many years, the state of the art in the field of system-level integration and V&V was largely characterized by classic systems integration test rigs (so-called Iron Birds) [17]. These platforms integrate real hardware components such as actuators, electrical systems, hydraulics, avionics and control functions in a representative ground-based environment. They are used in particular to reduce technical risks before flight tests, make integration problems visible at an early stage and verify system functions under controlled conditions. A significant added value of classic Iron Birds lies in their ability to identify unexpected interactions and integration problems that often remain hidden in isolated component tests or purely virtual environments [17].

At the same time, the literature shows that complete Iron Birds are typically associated with high investment, operating and modification costs, are often strongly tailored to a specific aircraft program and can only be reconfigured to a limited extent [16], [17], [18]. As a result, they are only suitable to a limited extent for the rapid, iterative and cross-program testing of new technologies in an early design phase. In addition, they come up against methodological or economic limits for certain issues, such as highly dynamic aeroelastic effects, local actuator dynamics or variable load and environmental conditions.

Against this background, virtual and hybrid test and V&V platforms have become increasingly important, ranging from pure real-time simulation to hardware-in-the-loop configurations [11], [15]. Such platforms combine realism with greater flexibility and enable fault injection, architecture comparisons and system studies with less risk. In addition, more recent developments show a clear shift towards modular and reconfigurable test and demonstration platforms. These modular Iron Bird concepts make it possible to replace individual partial test benches or subsystems without having to rebuild complete integration environments. Real actuators, load simulation, flight mechanics models and cockpit environments can be flexibly combined to form integration platforms [14], [19].

Furthermore, industrial test strategies increasingly aim to shift integration verification activities toward earlier development phases while systematically combining virtual and physical test environments [20]. This is intended to identify risks earlier, support early V&V of development decisions and reduce the extent of subsequent flight testing. To increase the relevance of early evidence for downstream certification and release processes, test and demonstration environments should increasingly address not only functional integration aspects but also relevant environmental and operational conditions, depending on the intended use of the generated evidence. Standards such as DO-160 define corresponding requirements regarding temperature, altitude, vibration and electromagnetic influences [21]. As a result, demonstration platforms are evolving from isolated integration test benches toward comprehensive test and V&V environments addressing functionality, robustness and operational behavior.

On this basis, the most advanced stage of development currently combines physical demonstration platforms with digital twins and virtual flight test environments to support the concept of virtual certification [18]. Validated Iron Bird data can be used to build virtual flight test environments with higher model fidelity. This allows tuning, pre-validation and, in some cases, certification-related activities to be carried out more efficiently. The digital twin therefore does not appear to be a

replacement for physical demonstration platforms, but rather a data-driven functional extension of such platforms to support virtual verification activities.

Overall, the literature shows a broad but heterogeneous landscape of component-oriented, subsystem-oriented, hybrid and complete integration platforms. Differences exist in particular with regard to the degree of integration, form of representation and deployment phase. To concretize this general platform landscape, selected DLR test and demonstration platforms are considered in the following section.

2.2 *Representative Platforms*

The platforms presented in Figure 2 were developed in different project and development contexts and today represent essential test, demonstration and V&V capabilities for future flight control systems at DLR. They represent test and demonstration environments across different integration levels, ranging from component- and subsystem-level test benches to system-level integration platforms.

The platform selection includes an electromechanical actuator test bench (section 2.2.1), a demonstration platform at the subsystem level (section 2.2.2) and a modular system integration test rig (section 2.2.3). These platforms cover different test, demonstration and V&V tasks, from component qualification, functional integration and aeroelastic investigations to early system-level V&V of system architectures and their interactions.

Taken as a whole, the considered platforms exemplify different test, demonstration and V&V capabilities across several integration levels. Together with the previously discussed state of the art, they form the basis for the subsequent comparative analysis and for the derivation of the integrated framework introduced in Section 3.



Figure 2 - Representative test and demonstration platforms considered in this work. From left to right: CONCERTO electromechanical actuation test bench, WISDOM subsystem-level demonstration platform, and NewFlAir system integration test rig. The platforms represent complementary test and demonstration environments across different system levels and integration scopes. (Copyright DLR)

2.2.1 Electromechanical Actuation Test Bench (CONCERTO)

As part of the European Clean Aviation project CONCERTO, a modular test bench for the parallel-redundant actuation of an aileron using electromechanical actuators is being operated and further developed [8], [22]. The environment serves as a component- and subsystem-level test and V&V platform for the verification, selected validation and qualification-oriented testing of electromechanical and safety-critical actuator systems, as well as their integration into real-time-capable control and hardware-in-the-loop environments. The focus is on the complete functional chain, ranging from setpoint generation and state and fault management to actuation, sensing and load application. This allows both the behavior of individual components and the interaction of multiple hardware and software elements within the actuator system to be investigated.

Technically, the environment combines real hardware with model-based software components. Integrated elements include actuators, sensors, load simulation, power electronics and real-time and control hardware. The control, state and safety logic is implemented using model-based approaches and executed within a real-time-capable hardware-in-the-loop environment. This allows both physical system interactions and control- and software-related effects to be investigated within an integrated test environment.

The test bench can be used to carry out various test, verification and selected validation activities. These include tracking and trajectory orientation tests, investigations of dynamic behavior and analyses of position, speed and torque paths. Fault injection tests, communication error analyses,

investigations of state transitions and safe-state verifications are also possible. In addition, the interaction between actuator, load simulation and test bench mechanics can be examined under representative load and operating conditions. By connecting a climate chamber, defined environmental conditions such as temperature, humidity and pressure can also be set in order to investigate environment-dependent influences on actuator behavior and performance as well as qualification-related verifications.

The platform has a modular and reconfigurable structure. Individual hardware components, signal paths, load interfaces or software functions can be adapted and expanded without significantly changing the basic architecture. This allows the environment to be used for project-specific development tasks as well as recurring integration and verification activities. The primary application area of the environment is at component and subsystem level. However, due to its real-time and integration interfaces, it can also be used as part of higher-level hardware-in-the-loop or system test environments.

2.2.2 Subsystem-Level Demonstration Platform (WISDOM-Rig)

As part of the nationally funded aviation research project WISDOM, a test rig for future multifunctional flight control systems is being developed and built [23]. The platform serves as a subsystem-level test, demonstration and V&V environment for investigating system interactions between selected components of future flight control systems. The focus is on the integration of relevant components of a flight control system in a representative and hybrid test environment. Central elements such as wing control surfaces, actuators, flight control computers, sensors as well as data and power supply buses including associated control functions are considered. As a reference architecture, the WISDOM project is investigating a triple-split aileron concept in the context of active load reduction and flutter suppression. The test rig thus addresses in particular the integration and investigation of coupled subsystems in their interaction, without providing a complete representation of an overall system.

Technically, the platform combines real hardware with model-based simulation components in a hardware-in-the-loop architecture. This enables hybrid testing in which flight mechanics, structural and aeroelastic models are coupled with real components in real time. Aircraft behavior and environmental conditions are predominantly represented virtually and serve as a simulation-based context for investigating real subsystem components. Real actuators, control surfaces and control components are integrated into the simulation loop. Air loads, structural reactions and gust influences calculated by the simulation can be transferred to real components, while measurement and state variables from the test bench are fed back into the simulation. This allows both physical effects and system interactions to be investigated within a coupled hybrid test and demonstration environment.

The platform can be used to perform various demonstration, integration, test and V&V activities. These include investigations of active load reduction functions, flutter suppression, the interaction of multiple actuators and control surfaces, as well as the V&V of control strategies under aeroelastic conditions. In addition, bus communication, interface behavior and systemic interactions between subsystems can be investigated. This includes both static and dynamic investigations as well as targeted analyses of fault scenarios.

The test rig has a modular design and enables the flexible integration of different control surface and system configurations. Individual components, actuator principles, control functions or simulation models can be adapted and exchanged without significantly changing the basic platform structure. This makes the environment particularly suitable for iterative integration and V&V activities involving coupled subsystem interactions within flight control systems.

The focus is on the investigation of system interactions within a hybrid and predominantly simulation-based system context, in particular on the integration of actuators, flight control computers and communication systems. Structural components are primarily taken into account only insofar as they are required for representing relevant load and system couplings. The primary area of application is at the subsystem level with reference to critical flight control components.

2.2.3 System Integration Test Rig (NewFlAir)

As part of the nationally funded aviation research project NewFlAir, a modular hardware-in-the-loop test rig for the integration, verification and selected validation of innovative fly-by-wire flight control systems is being developed and built. Following the terminology of SAE AIR5992, the platform can be understood as a modular system integration test rig and Iron-Bird-like integration facility, while not

implying full aircraft-level representativeness or certification conformity. The platform serves as a test and demonstration environment at the subsystem and system level. The aim is the early investigation and evaluation of flight control system architectures through the system-wide coupling of real and virtual components, particularly with regard to integration behavior, fault scenarios and architectural interactions.

The focus is on the integration of central elements of a fly-by-wire flight control system in a modular and reconfigurable test environment. The test field is designed for integrating hydraulic and electric flight control actuators and can optionally be coupled with flight control computers. At the subsystem level, the test rig enables the investigation of individual control surface actuation systems under load, including targeted fault injection. At the system level, the interaction of flight control laws with physically or virtually represented control surfaces is investigated. The optional coupling with a pilot-in-the-loop engineering flight simulator also enables an end-to-end view from pilot input to control surface actuation. The test rig explicitly addresses integration, verification and selected validation of coupled system functions, including architectural, communication and fault management aspects.

Technically, the platform is based on a hybrid hardware-in-the-loop architecture. Real components such as actuators, cockpit systems and flight control computers are coupled with model-based simulation components in a system-wide hardware-in-the-loop environment. Flight mechanics, load and system models are integrated in real time with the real test rig components. External development and simulation environments can be connected via standardized interfaces. This allows both integration behavior and complex interactions between real and virtual system components to be investigated within a coupled overall architecture.

The platform can be used to perform various demonstration, integration, test, V&V and pre-validation activities. These include static and dynamic investigations under load, the analysis of fault scenarios and the evaluation of system reactions to degraded operating modes. In addition, the platform enables the investigation of bus communication, interface behavior and system-wide interactions between coupled subsystems across different integration levels.

The test rig has a modular structure and is designed for scalability. Several test stations can be operated in parallel and expanded with additional actuators or control surfaces. Different actuator principles, system architectures and communication interfaces can be flexibly integrated. The focus is on the reconfigurable investigation of system-wide integration aspects and architectural interactions. As a result, the platform supports different development phases from early concept investigations to system-level integration and pre-validation tasks. The primary area of application targets the critical transition from technology maturation toward integrated system demonstration, with the possibility of extension toward higher integration levels through additional hardware and system coupling.

2.3 *Comparative Analysis*

Based on the previously discussed state of the art and the exemplary test and demonstration platforms, a comparative analysis is carried out below to identify key structural characteristics of test, demonstration and V&V environments. The aim is to systematically evaluate their classification, comparability and suitability for the integration and V&V of future flight control systems and to provide a basis for the design of future test and demonstration platforms.

The considered platforms address different integration levels within flight control systems. They range from test rigs focused on individual components or specific functional chains to subsystem-level environments and integration platforms investigating the interaction of multiple subsystems. This reveals the considered system level as a central distinguishing characteristic of test, demonstration and V&V environments. As the system level increases, the complexity of the investigated interactions and the associated requirements for integration and system understanding also increase.

Closely linked to this is the representation of the system context. While component-based test benches mainly rely on physical setups, higher-level platforms increasingly combine real hardware with model-based real-time simulations. At higher integration levels, the overall aircraft is often represented virtually as part of the system context. This results in another distinguishing characteristic, defined by the respective system representation within the test and demonstration environment. Such representations enable the investigation of system interactions under controlled and variable boundary conditions.

A third distinguishing feature results from the addressed V&V focus. The platforms are used for

different purposes, ranging from the functional analysis of individual components and physical effects to the investigation of system integration, interface behavior and complex interactions. Operating states and fault scenarios can be considered at different integration levels, with the scope of the investigated interdependencies increasing as system integration grows.

The analysis shows that the considered platforms can be systematically described, classified and compared based on these characteristics. Differences between the platforms become visible along common structural characteristics and enable a consistent comparison of different platform configurations. The identified structural characteristics also form the basis for the framework introduced in the following section, which enables a structured description and classification of demonstration and V&V capabilities provided by individual platforms.

The preceding analysis and the comparative overview in Table 1 show that the platforms under consideration can be systematically characterized along common structural characteristics such as system level, system representation and V&V focus. Although the platforms differ considerably in terms of their integration level, system context and investigation objectives, these characteristics enable a consistent description and comparability of their realized demonstration and V&V capabilities. Demonstration and V&V capabilities are therefore interpreted as the result of specific combinations of system level, system representation and V&V focus within a given platform configuration. This illustrates that different platform configurations provide different demonstration and V&V capabilities and thus address different aspects of the integration and V&V of future flight control systems. The identified structural characteristics therefore form the basis for the framework for the structured description and classification of demonstration and V&V capabilities presented in the following section.

Platform	System Level	System Representation	V&V Focus	Realized Demonstration and V&V Capabilities
CONCERTO	Component / Subsystem	Hybrid	Functional behavior, physical effects	Investigation of actuator behavior and environmental effects under realistic loading conditions
WISDOM	Subsystem	Hybrid	Physical effects, system integration	Investigation of aeroelastic interactions and subsystem coordination in a simulated aircraft context
NewFlAir	Subsystem / System	Hybrid	System integration, fault scenarios	Investigation of integrated system behavior and failure scenarios in coupled architectures

Table 1 - Comparative overview of representative test and demonstration platforms showing their positioning across system level, system representation, and V&V focus, as well as the demonstration and V&V capabilities they realize

As a result, relevant aspects of the integration and V&V of future flight control systems cannot be fully covered by individual platforms. Different platforms each realize specific demonstration and V&V capabilities and address different aspects of system interactions. An isolated consideration of individual environments is therefore only of limited value. This means that the investigation of complex coupled systems requires the coordinated use of several test and demonstration platforms.

Particularly in the transition between lower and higher integration levels, it becomes apparent that the representation of system interactions becomes increasingly challenging as complexity increases. In this area, both component-based test rigs and fully integrated platforms reach their respective limits, as relevant issues can neither be investigated in isolation nor under fully realistic conditions alone. This applies in particular to the medium technology maturity range, in which technologies are already integrated but cannot yet be evaluated in a fully representative system context.

Against this background, there is a need for an overarching framework that brings together the identified characteristics and enables consistent classification and comparability of different test and demonstration environments. This framework is formalized in the following section as an integrated framework.

3. A Multidimensional Framework for Demonstration and V&V Capabilities

3.1 *Framework Definition*

The distinguishing features identified in section 2.3 are transferred in the following into an integrated framework for describing test and demonstration platforms for flight control systems. The aim is to describe, compare and systematically classify demonstration and V&V capabilities along uniform criteria, independently of specific technical implementations. The previously identified characteristics have not yet been brought together in a consistent framework, which means that a uniform description and comparability across different platform types is only possible to a limited extent.

A demonstration and V&V capability is defined as the ability to investigate specific aspects of system behavior under defined conditions within a test and demonstration environment. Within the proposed framework, demonstration and V&V capabilities result from specific combinations of the considered dimensions and their respective characteristics. Such capabilities are independent of specific technical implementations and can be realized through different test and demonstration environments. Different platforms can realize identical or overlapping capabilities, while individual platforms typically cover several capabilities simultaneously.

The framework introduced in the following brings these characteristics together in a structured and generally applicable form and integrates them into a multidimensional description space. This enables a consistent characterization, classification and comparability of demonstration and V&V capabilities.

The framework is defined by three basic dimensions that describe the system level under consideration, the type of system representation and the objective of the investigations carried out. The dimensions are largely independent of each other and address different aspects of demonstration and V&V capabilities. The framework does not integrate any existing process, test or maturity models itself, but focuses on the structured description of such capabilities independently of specific development processes or technology maturity levels. The three dimensions and their respective focal points are summarized in Table 2.

Dimension	Description	Representative Characteristics
System Level	Describes the level of the system under investigation within the overall architecture	Component, subsystem, system
System Representation	Describes how the system and its context are realized within the test and demonstration environment	Physical, hybrid, virtual
V&V Focus	Describes the primary investigation focus and addressed demonstration, verification or validation aspects	Functional behavior, physical effects, system integration, fault scenarios

Table 2 - Overview of the dimensions defining demonstration and V&V capabilities within the proposed framework

The first dimension describes the system level at which investigations are carried out. It is specified by the considered system under test, which represents the actively examined part of the overall system within the test and demonstration environment. The system level thus specifies the classification of this part within the overall architecture. This dimension ranges from the component level, at which individual hardware elements or specific functional chains are examined, to the subsystem level, at which several functionally coupled components are examined in an integrated manner, through to the system level, at which the behavior of integrated flight control systems is examined.

The second dimension describes the system representation and thus the way in which the considered system and its relevant context are realized within a test and demonstration environment. It includes both the system under test and the associated system context, i.e. the parts of the overall system relevant to the system behavior that are not part of the actively investigated system, such as aircraft dynamics, aerodynamic loads or environmental conditions. A distinction is made between three basic types. In physical configurations, the relevant system components are mainly realized by real hardware components. In virtual configurations, the representation is mainly carried out using models and simulations. Hybrid configurations combine real hardware with model-based real-time simulations

within a common test and demonstration environment.

The third dimension describes the v&V focus and thus the focus of the investigations carried out within a test and demonstration environment. It determines which types of questions and V&V activities are addressed with a platform and which aspects of system behavior are emphasized. The dimension encompasses different characteristics, ranging from the investigation of functional behavior and physical effects to the consideration of system integration and fault scenarios. The V&V focus therefore does not describe the development phase or the degree of maturity of a technology, but rather the primary purpose of a capability in terms of knowledge, verification and investigation.

Together, the three dimensions form the basis for a structured description of demonstration and V&V capabilities. Concrete capabilities result from specific combinations of system level, system representation and V&V focus within a test and demonstration environment. On this basis, an integrated description space is introduced in the following section.

3.2 *Framework Representation and Platform Mapping*

The dimensions defined in section 3.1 are combined below to form an integrated framework. They can be combined independently of each other and form a structured description system in which demonstration and V&V capabilities can be described independently of specific platforms. Together, they define a multidimensional description space in which such capabilities are described as combinations of characteristics along the three dimensions, while concrete platforms represent these capabilities in the form of real implementations.

The description space does not represent a temporal or procedural sequence of development or V&V steps and does not replace process or maturity models. Instead, it describes demonstration and V&V capabilities based on their structural properties independently of specific development processes or technology maturity levels.

The capabilities realized by platforms can be clearly classified within this description space based on their characteristics. The description is independent of concrete technical implementations, specific system architectures or project-related boundary conditions and enables a consistent and comparable characterization of different demonstration and V&V capabilities.

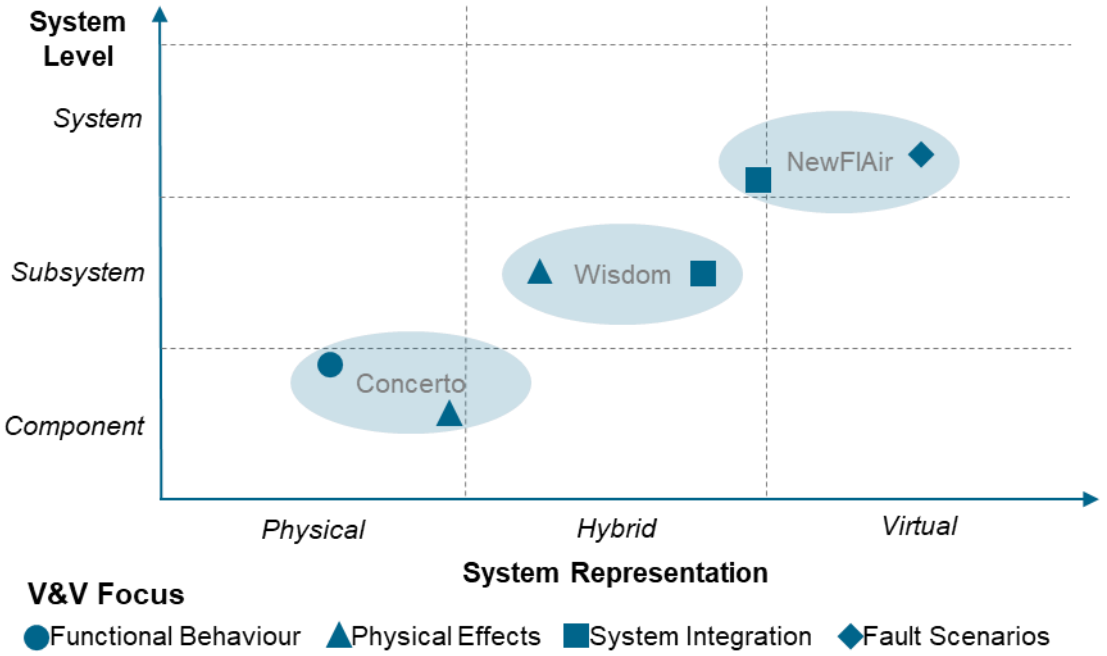


Figure 3 - Two-dimensional representation of the proposed multidimensional framework showing the positioning of representative test and demonstration platforms within the capability space. Platforms are depicted as bounded regions reflecting the range of validation capabilities across system levels and system representations. Marker types indicate the dominant V&V focus. (Copyright DLR)

Figure 3 shows a schematic representation of the resulting multidimensional description space based on the dimensions summarized in Table 2. System Level and System Representation are visualized as axes, while V&V Focus is represented as an additional dimension through marker shapes.

The representation takes into account that platforms address several demonstration and V&V

capabilities or investigation objectives and can have a limited range of characteristics, which are represented in condensed form. To illustrate the approach, the selected platforms are positioned as concrete realizations of such capabilities within the description space. The exemplary classification shows the application of the framework for the consistent characterization of different capabilities realized by platforms. Building on this, the following section analyzes the resulting distribution patterns, identifies structural gaps and derives implications for the design of future test and demonstration environments.

4. Discussion

4.1 *Interpretation and Structural Gaps*

Based on the classification of the three test and demonstration environments presented in section 3.2, there is a specific distribution in the description space along the dimensions of system level, system representation and V&V focus. This distribution is not uniform, but shows a focus on the component and subsystem level with less coverage of system-level integration areas. It is a result of the analysis and is not determined by the framework itself, which only describes the structure of the description space.

A differentiated view along the System Level dimension shows that the platforms under consideration extend across several system levels, from component-level studies (CONCERTO) to subsystem considerations (WISDOM) and system-level integration environments (NewFlAir). In the case of NewFlAir, the optional coupling with cockpit-based engineering flight simulation facilities, such as the DLR Air Vehicle Simulator AVES, can further extend the integration scope toward pilot-in-the-loop assessment of integrated flight control functions [24]. As the system level increases, so does the number of interfaces considered, which also significantly increases the complexity of the interactions examined within the respective platforms.

An examination of the System Representation dimension shows that all platforms under consideration pursue hybrid approaches in which real hardware components are combined with model-based simulations. The specific characteristics of these hybrid approaches differ between the platforms, particularly with regard to the proportion of physical components and the extent of virtual system components, such as the physical emphasis of CONCERTO, the hybrid balance in WISDOM and the stronger virtualization in NewFlAir.

An examination of the V&V Focus dimension shows clear differences in the addressed investigation objectives between the considered platforms. CONCERTO primarily focuses on functional behavior and physical effects. WISDOM focuses on physical effects and system integration. NewFlAir further shifts the focus toward system integration and fault scenarios within coupled flight control system architectures.

The combination of the three dimensions clearly shows that the platforms address different investigation aspects and objectives. This distribution indicates that the platforms provide complementary demonstration and V&V capabilities. None of the considered platforms covers the entire description space, meaning that a comprehensive investigation of flight control systems requires the combined use of several platforms.

Test and demonstration platforms should therefore not be regarded as isolated individual solutions, but rather as elements of a broader capability space in which specific combinations of system level, system representation and validation objective are realized. This perspective forms the basis for the identification of structural gaps in the description space.

On this basis, areas become visible within the description space in which certain combinations of characteristics are still insufficiently covered. These gaps occur particularly in areas where intermediate system levels, hybrid system representations and cross-system investigation objectives must be addressed simultaneously. Such constellations require the simultaneous consideration of several coupled subsystems and realistic system contexts, which significantly increases both the integration effort and the demands on the system representation.

These structural gaps correspond to known challenges in the medium technology maturity range, especially between TRL 4 and TRL 6. In this range, technologies are typically already integrated, but not yet demonstrated or validated in a fully representative system context. Technology Readiness Level is therefore not treated as an intrinsic dimension of the proposed capability space, but rather as an external indicator of technology maturity.

Existing platforms are either geared toward component-related investigations with a high level of physical detail or address higher integration levels, where model-based components are increasingly used to represent the system context. As a result, continuous coverage of the intermediate combinations of system level, system representation and investigation objectives within the description space remains limited.

These gaps result from the uneven distribution of existing platforms within the description space and the lack of systematic linking of their respective demonstration and V&V capabilities. This observation highlights the need to systematically combine and further develop such capabilities in a targeted manner.

4.2 *Implications for Future Test and Demonstration Environments*

This observation has implications for the design of future test and demonstration environments. It becomes clear that such environments should not be viewed in isolation, but rather as components of an integrated capability landscape. This implies that test and demonstration environments do not only occupy individual discrete positions within the description space, but typically cover multiple combinations along the considered dimensions.

This extended perspective is illustrated in Figure 4, where test and demonstration environments are depicted as locally bounded regions within the description space, each covering multiple combinations of system level, system representation and V&V focus. The dashed outline represents the overall capability space defined by the framework, while individual platforms address only specific subsets of the possible demonstration and V&V capabilities. In contrast to Figure 3, this representation emphasizes the ability of individual platforms to simultaneously cover multiple characteristics within the description space. Comprehensive coverage of the capability space can therefore generally only be achieved through the targeted combination of several platforms.

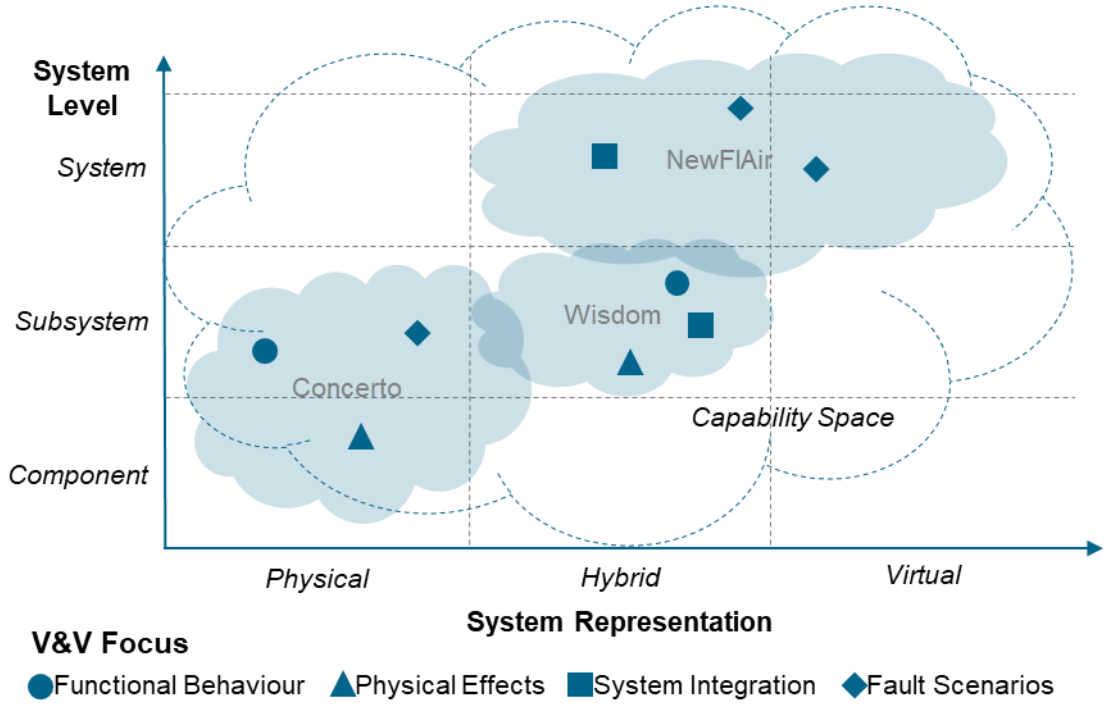


Figure 4 - Conceptual use of the multidimensional framework for identifying coverage gaps and planning complementary demonstration, verification and validation capabilities. In contrast to Figure 3, which positions existing platforms, this figure highlights insufficiently covered regions of the capability space and illustrates how additional or combined environments can address them. (Copyright DLR)

This results in fundamental requirements for the design of future test and demonstration environments, particularly with regard to modularity, hybridity and scalability. These properties also determine which areas of the capability space can be addressed by test and demonstration environments and to what extent different demonstration and V&V capabilities can be covered.

A central characteristic is modularity, which enables different system components to be flexibly combined, exchanged and reused for different investigation objectives. Closely related to this is hybridity, resulting from the combination of physical and virtual system representations. By coupling

real hardware with model-based simulations, both real system interactions and different system configurations can be investigated. In addition, scalability is of central importance for adapting test and demonstration environments to different system levels and integration stages. This enables a gradual expansion of the investigation scope and system integration across different development phases. Another key aspect is the stronger focus on coupled subsystems and their interactions rather than isolated individual components. This is particularly relevant for future flight control systems, which are increasingly characterized by close coupling and complex interactions between functions, actuators, power supply and communication systems.

Overall, these aspects illustrate that the design of future test and demonstration environments requires an integrated, flexible and system-oriented approach.

4.3 *Relation to Existing Approaches*

The introduction of the proposed framework also raises the question of how the approach can be categorized in relation to existing concepts and classification approaches in systems engineering and V&V. Existing concepts and classification approaches typically address different aspects of demonstration and V&V capabilities from isolated perspectives. Process models describe the temporal sequence of development, verification and validation activities, maturity models such as TRL characterize the achieved development status of technologies, while classifications such as Hardware- or Software-in-the-Loop address the type of physical-virtual system representation. Test strategies such as the test pyramid describe the distribution of tests across different levels of abstraction and integration.

These approaches each address specific aspects of demonstration and V&V capabilities, but do not place them within a common structural context. The proposed framework therefore does not replace these models, but complements them with an integrated view of such capabilities along the dimensions of system level, system representation and investigation focus. This enables a consistent description, comparability and coordination of demonstration and V&V capabilities across different test and demonstration environments.

This perspective is also evident in industrial V&V processes, in which requirements are systematically assigned to different test and demonstration environments and V&V results are consolidated across complementary test means, for example via physical test benches, real-time simulators, flight tests and virtual test environments [25]. V&V no longer takes place within isolated individual platforms, but results from the coordinated interaction of heterogeneous test and demonstration environments. Industrial approaches to virtual testing also highlight the importance of traceability, configuration management, workflow integration and the consistent management of V&V artifacts across distributed V&V activities [25]. This emphasizes that future test and demonstration environments should not only provide isolated technical capabilities, but also support their systematic coordination and integration within comprehensive V&V ecosystems and systems engineering processes.

These perspectives are largely independent of each other, as they address different and unrelated descriptive dimensions, and therefore do not allow a consistent description of test and demonstration environments as integrated overall systems. In particular, there is no structured link between system level, system representation and investigation objective, which means that systematic planning, classification and combination of demonstration and V&V capabilities is only possible to a limited extent.

The framework proposed in this paper addresses this gap by merging these perspectives into a common multidimensional description space. In contrast to existing approaches, it enables a consistent linking of these dimensions and thus an integrated description of test and demonstration environments as combinable systems. It supplements existing approaches with an integrative view of such environments and enables their consistent classification, comparability and targeted combination along central dimensions. In addition, the framework can support the structured planning and assignment of V&V activities by explicitly describing demonstration and V&V capabilities and systematically assigning them to different platform configurations.

The framework can therefore support decision-making in the planning and coordination of V&V activities by enabling a more systematic allocation of investigation objectives, demonstration and V&V capabilities and platform configurations. In this context, modular and scalable test and demonstration environments, as well as the reuse of test articles and distributed test infrastructures, may contribute to a more efficient allocation of V&V effort, cost and infrastructure resources across different

development and technology maturation activities.

In conjunction with the design principles derived above, this creates a basis not only for describing test and demonstration environments, but also for systematically designing and further developing them as combinable elements of an integrated capability space. In addition, test and demonstration environments can be interpreted as supporting systems in systems engineering, which can be used to specifically address requirements at different system levels, provide evidence in a structured manner and plan and assign V&V activities in a traceable manner.

5. Conclusion

This work addresses the lack of a consistent and integrated description of test and demonstration environments for flight control systems. Existing concepts and classification approaches typically consider demonstration and V&V capabilities from isolated perspectives and therefore do not support the systematic combination and planning of such capabilities.

To overcome this limitation, a multidimensional framework was introduced that integrates the dimensions of system level, system representation and V&V focus into a common description space. This enables a consistent characterization and comparability of heterogeneous test and demonstration platforms, whose respective characteristics can be explicitly described within a uniform structure.

The analysis shows that the exemplary demonstration and V&V capabilities are unevenly distributed within this space, resulting in structural gaps, especially in configurations that require the integration of multiple subsystems under realistic conditions. In particular, combinations involving intermediate system levels, hybrid system representations and system-wide investigation objectives remain only partially covered by existing platforms.

Against this background, demonstration and V&V cannot be understood as a sequence of isolated test activities, but as a problem of sufficiently covering a multidimensional capability space. The proposed framework provides a basis for structuring this space and supporting the targeted combination, expansion and planning of test and demonstration environments.

In this context, test and demonstration environments can be interpreted as supporting systems in systems engineering, which can be used to allocate requirements in a structured manner, provide V&V evidence in a traceable manner and make V&V strategies more transparent and scalable. The proposed framework makes it possible to describe test and demonstration environments as complementary realizations of demonstration and V&V capabilities within a common multidimensional capability space, to classify them systematically and to combine them in a targeted manner.

Future work can focus on the application of the framework in larger capability ecosystems as well as on its integration into model-based systems engineering processes.

Acknowledgements

This research has been performed in the frame of the CONCERTO project (Construction Of Novel CERTification methOds and means of compliance for disruptive technologies), which is funded by the European Community's Clean Aviation Joint Undertaking programme, under Grant Agreement No 101101999. The project started on January 1, 2023.

Disclaimer: Co-Funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

The exemplary demonstration and validation platforms presented in this work were also developed within the projects WISDOM ("Wing Integrated Systems Demonstration On Mechatronic Rig", German national aeronautics research program LuFo VI-2, funding reference 20Y2105) and Next Generation Fly by Wire for Regional Aircraft (NewFlAir, German national aeronautics research program LuFo VII-1, funding reference 20M2429B). The authors would like to thank all sponsors and project partners, without whom this work would not have been possible.

Contact Author Email Address

Oliver.Bertram@dlr.de

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

[1] Lübbe S M, Schäfer M and Bertram O. Mass and power estimations in preliminary flight control system design. Proc 34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024), Florence, Italy, 2024.

[2] Wöhler S, Häßy J and Kriewall V. Establishing the DLR-F25 as a research baseline aircraft for the short-medium range market in 2035. Proc 34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024), Florence, Italy, 2024.

[3] Lübbe S and Bertram O. Safety critical design of flight control system architectures - potential safety aspects for a triple split aileron for the project WISDOM. Proc Deutscher Luft- und Raumfahrtkongress 2023, Stuttgart, Deutschland, 2023. https://doi.org/10.25967/610292

[4] Eberle A, Stefes B and Reckzeh D. Clean aviation ultra-performance wing (UP-Wing). P *Proc AIAA SCITECH 2024 Forum*, 2024-2109, Orlando, Florida, January 2024. https://doi.org/10.2514/6.2024-2109

[5] Lübbe S M, Schäfer M and Bertram O. Coupling of model-based systems engineering and safety analysis in conceptual aircraft system design. Proc 33rd Congress of the International Council of the Aeronautical Sciences (ICAS 2022), Stockholm, Sweden, Vol. 2, pp 1484-1495, 2022.

[6] Voth V and Bertram O. Aircraft system design: A model-based and collaborative approach. Proc 34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024), Florence, Italy, 2024.

[7] Hollmann R W, Schäfer A, Bertram O and Rädel M. Virtual testing of multifunctional moveable actuation systems. CEAS Aeronautical Journal, Vol. 13, pp 979-988, 2022. https://doi.org/10.1007/s13272-022-00602-5

[8] Kowalski R. Drehgeberlose Regelung elektromechanischer Flugsteuerungsaktuatoren. Dissertation, Technische Universität Braunschweig, DLR-Forschungsbericht DLR-FB-2024-2, 2024. doi: 10.57676/hcb3-9c65

[9] DiMario M and Hodges A. Systems engineering management in research and development valley of death. INSIGHT, Vol. 26, pp 8-14, 2023. https://doi.org/10.1002/inst.12451

[10] Ruth S. An approach to bridging the gap between the attainment of research objectives and system application. INSIGHT, Vol. 26, pp 33-38, 2023. https://doi.org/10.1002/inst.12454

[11] Bertolino A C, Maré J-C, Akitani S, De Martin A and Jacazio G. Development of real-time models of electromechanical actuators for a hybrid iron bird of a regional aircraft. Actuators, Vol. 14, No. 172, 2025. https://doi.org/10.3390/act14040172

[12] Röben T, Stumpf E, Weber G and Grom T. An innovative all-active hybrid actuation system demonstrator. Proc AIAA Modeling and Simulation Technologies Conference, 2017.

[13] Erofeev E, Khaletsky L, Skryrabin A, Steblinkin A. Advanced test rigs for development and certification of flight control actuation systems. Proc 8th International Conference on Recent Advances in Aerospace Actuation Systems and Components, Toulouse, France, pp 109-116, 2018.

[14] Blasi M et al. Modeling and control of a modular iron bird. Aerospace, Vol. 8, No. 39, 2021. https://doi.org/10.3390/aerospace8020039

[15] Denti E, Di Rito G and Galatolo R. Real-time hardware-in-the-loop simulation of fly-by-wire flight control systems. 25th International Congress of the Aeronautical Sciences (ICAS 2006), Hamburg Germany, September 2006.

[16] Li D, Lin M and Tian L. Design of iron bird for a regional jet aircraft. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 234, No. 3, pp 681-688, 2020. https://doi.org/10.1177/0954410019879822

[17] SAE International. Descriptions of systems integration test rigs (iron birds) for aerospace applications. SAE Standard AIR5992, 2009. Reaffirmed April 2023. https://doi.org/10.4271/AIR5992

[18] Aydemir E, Zengin U, Pinon Fischer O J, Durak U and Hartmann S. From iron birds to digital twins with engineering simulators: Toward virtual certification. AIAA Journal of Aerospace Information Systems, 2025. https://doi.org/10.2514/1.I011569

[19] Spangenberg H and Vechtel D. Failure detection, identification and reconfiguration: Applications for a

modular iron bird. Proc AIAA Modeling and Simulation Technologies Conference and Exhibit, Hilton Head, SC, USA, 2007. https://doi.org/10.2514/6.2007-6466

[20] Geiwiz P and Cerbelaud Y. Integrated testing of flight control systems on various test means during development and certification. Proc Deutscher Luft- und Raumfahrtkongress 2011, Bremen, Germany, 2011.

[21] RTCA, Inc. DO-160G: Environmental conditions and test procedures for airborne equipment. Radio Technical Commission for Aeronautics, Washington, DC, USA, 2010.

[22] Kowalski R, Möller F, Gallun P and Bierig A. Test facility for electro-mechanical actuation systems. Proc 7th International Workshop on Aircraft System Technologies, Hamburg, Germany, pp 133-142, 2019. ISBN 978-3-8440-6470-4.

[23] Schumann H, Lübbe S M, Klimmek T and Quero D. Prüfstand für multifunktionale Flugsteuerungssysteme zur Lastminderung und Flatterunterdrückung bei Verkehrsflugzeugen. Proc Deutscher Luft- und Raumfahrtkongress 2023, Stuttgart, Deutschland, 2023. https://doi.org/10.25967/610255

[24] Duda H, Gerlach T, Advani S, Potter M. Design of the DLR AVES Research Flight Simulator. AIAA MST 2013, Boston, USA. https://doi.org/10.2514/6.2013-4737

[25] Ulmer T, Virtuelles Testen für Hochauftriebssysteme, Proc Deutscher Luft- und Raumfahrtkongress 2011, Bremen, Germany, 2011.