

Interdisciplinary human-in-the-loop simulation framework for evaluation of actuation system concepts

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Abstract

This paper presents the initial work of an international collaboration with the aim of connecting distributed test rigs for evaluation of new flight control actuation system technologies. The involved partners are companies, universities, and institutions from Sweden and Brazil. Three test rigs with different capabilities and scopes are available through the partners involvement in the project, that includes an industrial robot-based flight simulator, a test rig for digital hydraulic actuators, and a full-scale Iron Bird for energy management and flight control actuation system testing. Connecting the test rigs facilitates a larger test scope and the evaluation of several technologies than using only one test rig. A model-based approach is adopted surrounding a virtual flight simulator used for model integration to allow testing both actuator performance and HMI aspects. The test case is a fictive fighter aircraft. The virtual flight simulator includes the aircraft behaviour, aerodynamics, propulsion, and flight control system. The virtual flight simulator is implemented in the physical one, and two flight missions are defined and flown by trained pilots. The generated data set is used by the actuator test rigs for performance evaluation. In the final part the actuator models are validated using the test data and integrated in the physical flight simulator for evaluating the impact of the actuator characteristics on aircraft performance and handling. The paper outlines the framework and method and illustrates the first part of the distributed testing by integrating pilot generated flight data for actuator performance evaluation and comparison.

Keywords: Human-in-the-loop simulation, actuation system, iron bird, flight simulator, digital hydraulics

1 Introduction

This paper describes the development and use of an interdisciplinary human-in-the-loop simulation framework for evaluating actuation system concepts in a distributed manner in an international context. The work is part of a long-term collaboration between Swedish and Brazilian universities, institutes, and companies, where the main actors are the Flumes laboratory at Linköping University (LiU) and Saab AB in Sweden, and the Laboratory of Hydraulic and Pneumatic Systems (LASHIP) at Federal University of Santa Catarina (UFSC) and the Competence Center in Manufacturing (CCM) at Instituto Tecnológico de Aeronáutica (ITA) in Brazil. The main purpose is to create a framework for investigating flight control system concepts by sharing physical resources, test rigs, through a model-based

interface. With each test rig having a different purpose, the combination enables investigations from a broader perspective than what is achievable with only one test rig.

UFSC has been studying the use of so-called digital hydraulic actuators for flight control, which offer a significantly more energy-efficient solution compared to traditional hydraulic actuators. The actuator under test consists of a multi-chamber cylinder combined with several hydraulic sources and on/off valves. The test rig is a specialized tool for investigating the actuator's performance.

A full-scale integration test rig, Iron Bird, has been developed at LiU, which includes actuation, hydraulic and electric power supply, air load emulation, and electric load emulation. A flight simulator allows to simulate complete missions and

provides actuation commands and realistic aerodynamic hinge moments. The Iron Bird is a means to evaluate the actuators' performance under realistic conditions in an integrated environment.

CCM-ITA has developed a flight simulator based on an industrial robot, called SIVOR [1]. This is a unique solution with seven degrees of freedom (7DoF) that provides a wider working envelope than traditional Stewart platform-based simulators [2]. This expanded range is particularly useful for evaluating flight-critical situations and performing manoeuvres that are not typical in conventional simulators [3]. The simulator features a standard cockpit, enabling human-in-the-loop simulations and the evaluation of human factors and flight control systems.

Robotic-based flight simulators have gained increasing attention in recent years due to their extended workspace and design flexibility. The German Aerospace Center (DLR), for instance, developed a 7DoF simulator using an industrial robotic arm mounted on a linear track [4], while the Max Planck Institute (MPI) introduced an 8DoF platform that combines a robotic arm with a motion base [5]. These systems demonstrate the potential of robotic platforms to support more immersive and dynamic simulation scenarios.

An additional advantage lies in the use of off-the-shelf industrial robots, which can significantly reduce development costs compared to custom-built motion platforms [4], [1]. However, the adoption of robotic platforms also presents challenges, such as the need to address payload limitations and implement robust collision avoidance mechanisms [6], [2]. Despite these issues, the versatility and adaptability of robotic simulators make them especially valuable for research applications, where reconfigurability and modularity often take precedence over certification requirements.

A set of test cases are presented that demonstrates how the implementation of the framework contributes to the actuation system analyses. The foundation of this work is the development of a set of models that can be integrated into each test rig, ensuring that all test cases are defined based on a consistent set of requirements and assumptions. Building on previous research, the test cases are designed to expand understanding of the systems from new perspectives. On one hand, this involves evaluating actuator performance under the influence of pilot inputs, providing a more representative reference framework than previously possible. On the other hand, the simulator's response analysis serves as a basis for future investigations into the effects of actuators on pilot workload and handling qualities.

2 Test Rig Description

This work includes the use of three different test rigs, all with different capabilities and purposes. An overview of each test rig is presented in this section.

2.1 SIVOR and the Cave

The SIVOR is a full flight simulator platform featuring a Phenom cockpit mounted on a KUKA KR TITAN robotic arm positioned on a 10-meter rail. This configuration provides the system with seven degrees of freedom (7DoF), enabling a larger workspace and, consequently, a greater potential for motion fidelity. Originally intended to meet the requirements of a Level D simulator, the highest certification standard defined by ICAO for pilot training [7], SIVOR has since been adapted to accommodate a broader range of research applications. For instance, the cockpit can be configured with either a yoke or a sidestick as the primary control interface, enhancing the simulator's versatility for studies [6].

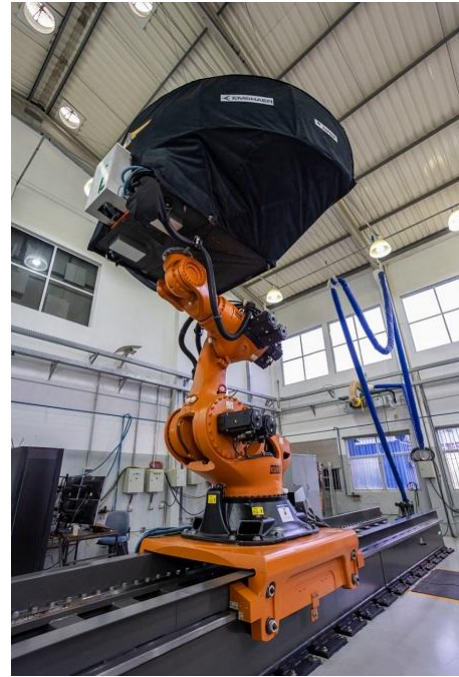


Figure 1: SIVOR flight simulator based on the KUKA robotic arm.

In addition to SIVOR, the test rig includes the Cave Simulator shown in Figure 2, a static simulation platform equipped with three display screens for pilot visualization, along with standard flight controls, including pedals, throttle, and joystick. Although it lacks motion capabilities, the platform designed for Human-Machine Interface (HMI) analysis [8] supports pilot-in-the-loop simulations and serves as a valuable tool for preliminary testing. This makes it particularly useful for validating scenarios and ensuring pilot safety prior to transitioning to full-motion simulations with SIVOR.



Figure 2: Cave: a static flight simulation platform.

2.2 Digital hydraulic test bench at LASHIP

In the last decade, digital hydraulics was one of the main research topics at LASHIP. A test bench was, therefore, incrementally composed at the group.

This equipment employs a multi-chamber cylinder connected to a manifold block of two-way cartridge valves, as seen in the left part of Figure 3. These are chosen for their small response time and, although being proportional, are mainly operated as digital (on/off) valves. Additionally, the bench includes a conventional hydraulic power unit and digital power unit with a pressurized reservoir simulation system. Also, a load simulation system is coupled to the rod of the multi-chamber cylinder, allowing the experiments to be performed with constant or variable counter force.

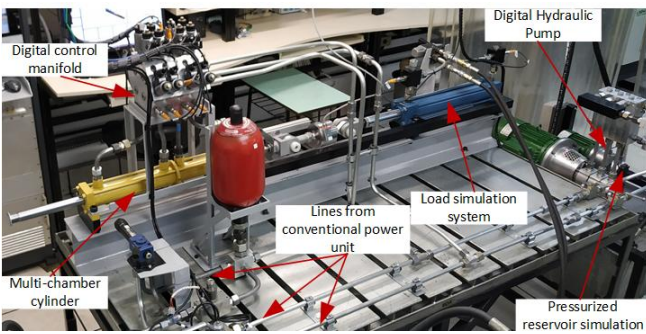


Figure 3: The digital hydraulic test bench at LASHIP.

The valve block has the ability to connect any of its four input lines to any of the chambers of the cylinder and, together with the other systems, is capable of performing as any of the digital solutions developed in LASHIP – DHA [9], [10]; DEHA [11], [12]; and VSDEHA [13], [14].

In the Digital Hydraulic Actuator (DHA), proposed by Belan [9], [10], three different pressure levels can be independently allocated for each of the actuator chambers. For such, the test

bench is operated as shown in Figure 4. This delivers 81 different force levels that are selected by a cost function to best approximate the needed output. The pressure lines are achieved by the conventional hydraulic power unit available.

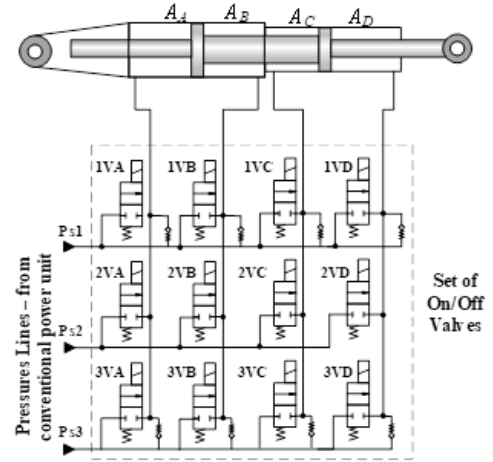


Figure 4: DHA hydraulic circuit.

For implementing the Digital Electro-Hydrostatic Actuator (DEHA), Proposed by Nostrani [11], [12], the manifold block is only utilized to define the direction of the flow to the cylinder, as seen in Figure 5. The main development of this solution is the Digital Hydraulic Pump (DHP), shown in the lower part of the figure. This technology employs on/off valves to allow the flow of each pump unit to be diverted directly to the reservoir or to be combined and sent to the system. This creates 43 different velocity levels in which only the pump units utilized at the moment impose a load on the electric motor.

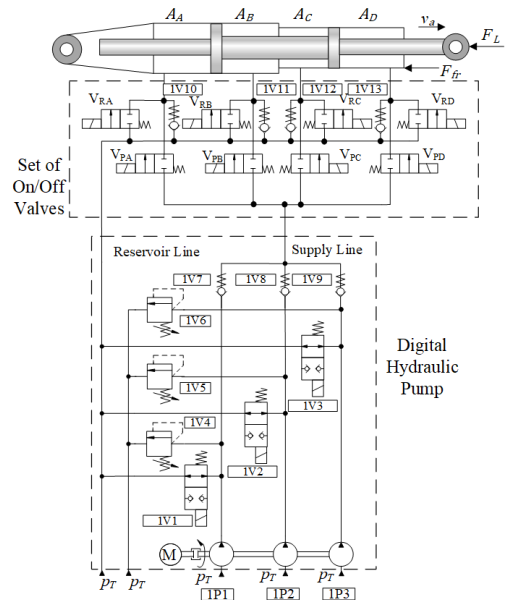


Figure 5: DEHA hydraulic circuit.

When employing the Variable Speed Digital Electro-Hydraulic Actuator (VSDEHA), proposed by Silva [13], [14], the DHP is employed as in DEHA, but with variable electric motor speed. This generates several different continuous

velocity curves in which the system can be operated and the controller, utilizing the pump unit efficiency maps, chooses the best combination of pump units and speed to match the needed output with the greatest efficiency. The valve block is applied, as before, to define the direction of flow but also employs a third line of valves that, operating with throttle control, act as a brake in assistive load conditions, as depicted in Figure 6.

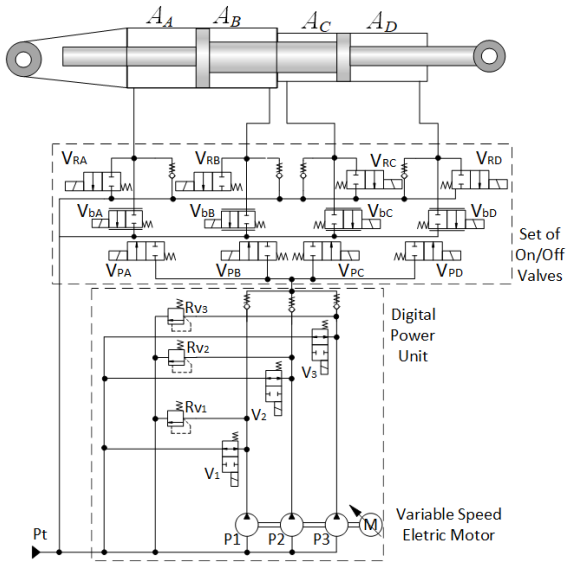


Figure 6: VSDEHA hydraulic circuit.

2.3 Iron Bird

The Iron Bird is a full-scale research test bed for energy management and flight control systems, shown in Figure 7, developed in collaboration between Linköping University and Saab AB. It provides a platform for technology demonstrations, experimental research, and data collection, in an integrated environment where complete missions can be simulated.



Figure 7: The image shows the full-scale Iron Bird at the Flumes Lab.

The Iron Bird has five control surfaces where the outer horizontal surfaces are equipped with electromechanical actuators and the other ones with servohydraulic actuators. A

hydraulic air load simulation system simulates the aerodynamic hinge moments during flight by applying a counter force. The reference to this force is estimated from a flight mechanics and aerodynamic model running in real-time in conjunction with the hardware. An illustration of the setup is shown in Figure 8, which shows how the electromechanical actuator and air load actuator interact. The air load actuator is also equipped with a by-pass valve that disconnects the hydraulic pressure from the load cylinder in case of an error in order to protect the test object.

The actuators are integrated with an electric power system and a hydraulic supply system. The electric power system is implemented as a flexible solution using programmable supply units that allow to alter the power characteristics during simulation. A distribution unit provides the electric power to all consumers, including emulating DC loads. The DC loads are programmable such that the consumed power can vary during the simulated mission.

A real-time system from Speedgoat allows the development of all models and control strategies in Matlab/Simulink. A virtual model of the aircraft and system under study is implemented and communicates with the hardware. In this case, the flight simulator runs in real-time and communicates with the actuators installed in the Iron Bird. The flight simulator calculates the required control surface deflections which are sent as commands to each actuator. To close the loop the actual actuator position is sent to the flight simulator as the resulting control surface deflection. The control surface deflection is also used to calculate the control surface hinge moment.

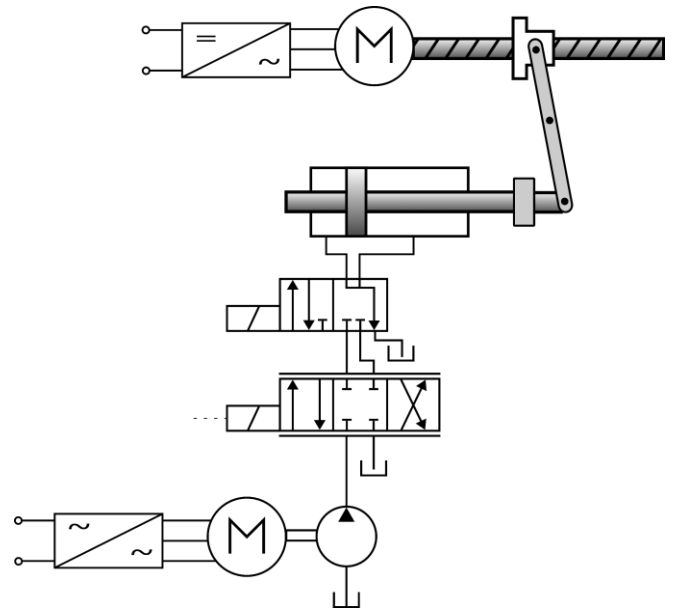


Figure 8: Schematics of the electromechanical actuator and the attached load actuator.

3 Framework for distributed testing

A model-based approach is adopted for the interconnection of the different test rigs used in this work, illustrated in Figure 9. The main purpose is to test different actuator solutions

from different perspectives provided from each test rig. A common flight simulator is implemented in each test rig creating a frame from which each test case can be defined. The flight simulator provides a definition of the flight scenario and creates the conditions for which the actuators are tested. Depending on the pilot input, as well as the flight conditions, the model provides the control surface deflection commands and hinge moment.

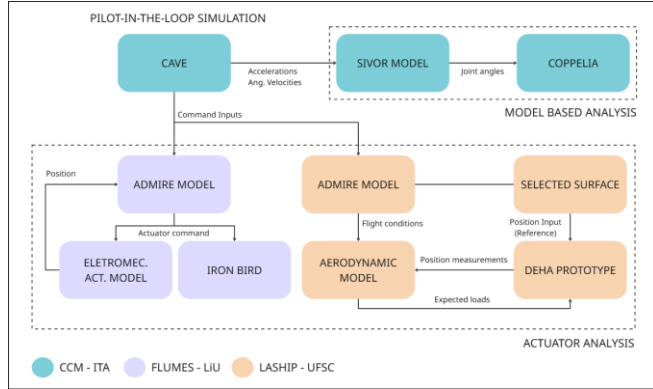


Figure 9: Illustration of the framework for interconnection of the test rigs.

By implementing the flight simulator in the SIVOR test rig, a human pilot can operate the aircraft, providing the inputs to the flight control system. The advantage of using a human pilot instead of an automated pilot is that the effects from the pilot are integrated in the test data, creating a more realistic scenario for how the actuators operate. This is further enhanced by using trained pilots with experience of how to operate the aircraft in different conditions and for different missions. Different missions are defined for the pilot to realize.

The registered pilot inputs are used as inputs to the flight simulator that is implemented in the LASHIP test rig and the Iron Bird. In this way the same mission can be reproduced to test the actuators installed in the respective test rig. Using the flight simulator enables two approaches to the testing. In one way the flight simulator provides the actuator commands and loads to ensure reproducibility for each test. In the other way, the flight simulator can be used to close the loop where the actual actuator position is fed back to the aircraft model. This means that the effects from the actuator characteristics on the aircraft performance can be evaluated.

Closing the test loop, models of the actuators under test are integrated in the SIVOR test rig. The models are first validated in the LASHIP test rig and Iron Bird. The same missions are flown again using the human pilots. The actuators' characteristics affect the flying and handling qualities of the aircraft and can be evaluated by the pilots and compared to a reference actuator.

The combination of the test rigs allows to analyse both the actuators' performance and HMI qualities.

4 System Modelling

Several models are developed and integrated into the different platforms for testing of the actuator solutions. These

models include the flight simulator, and models of the different actuator technologies.

4.1 The flight simulator Admire

At CCM-ITA, the work combines both aircraft and simulator mathematical models.

The aircraft dynamics are modelled using the ADMIRE (Aero-Data Model In a Research Environment) framework [15]. This model implemented in MatLab/Simulink provides a representative simulation of a modern fighter aircraft, Figure 10, and includes detailed representations of its aerodynamic characteristics, control systems, and flight dynamics. This model is composed of non-linear differential equations that are organized in a state vector and comprise variables such as position, velocity, angular rates, and orientation, while the outputs include relevant flight parameters such as accelerations and angular velocities.

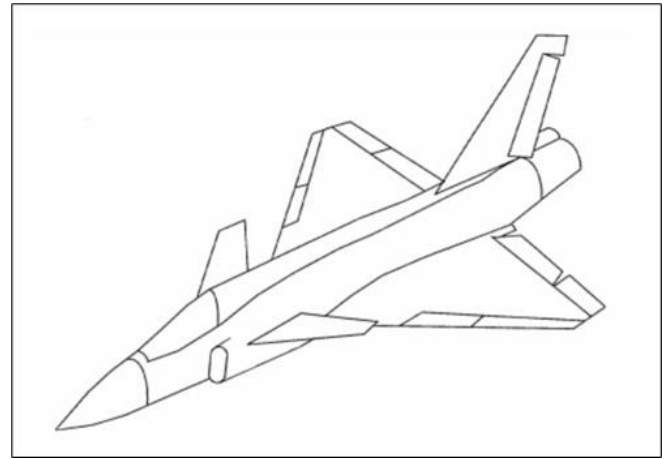


Figure 10: Representation of the aircraft model used for simulations.

4.2 SIVOR models

The SIVOR simulation model combines two main components: a motion cueing algorithm (MCA) that processes aircraft dynamics and a robotic arm model that simulates the physical response of the system. Together, these elements allow for realistic and physically constrained flight simulation.

The motion cueing algorithm is the component of the model responsible for translating the aircraft dynamics into the simulator's limited workspace [6]. In the SIVOR simulator, the MCA is a classical washout filter, [16] and [17], that takes as input the accelerations and angular velocities of the body reference system and outputs a set of commands for the robotic arm, such as joint angles and rail positioning.

The second core component is the dynamic model of the KUKA KR TITAN robotic arm. This model, developed through an identification campaign [18], is represented by a set of linear equations that describe the joint behaviour in a closed-loop configuration. It receives the MCA's outputs and simulates the robotic arm's motion in three-dimensional space.

This combined system makes it possible to assess the simulator's behaviour and evaluate how accurately it reproduces flight dynamics within the physical constraints of the robotic platform.

To enable visual validation and further analysis, the model is integrated into the CoppeliaSim environment, as shown in Figure 11. This integration allows real-time visualization, even online during flight [19], of the robotic arm's movements and is particularly useful for identifying potential collisions between the arm and the cockpit structure during manoeuvre execution.

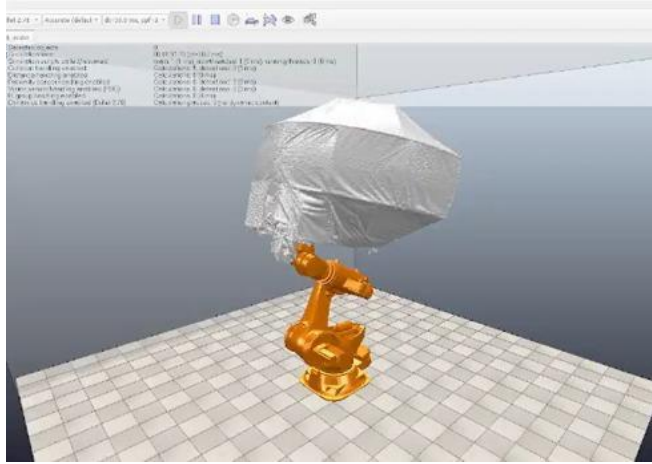


Figure 11: SIVOR model in CoppeliaSim

4.3 Hopsan digital hydraulic actuators modelling

Each of the digital hydraulic actuator topologies proposed by LASHIP were modelled utilizing the Hopsan software. These models were rigorously validated in previous research [9 to 14] and allow for an accurate representation of the existing physical actuators.

The developed models were subsequently implemented in the virtual flight simulator. The aircraft model, by default, simulates the flight control actuators as simple transfer functions causing a signal delay and attenuation. With the implementation of the Hopsan actuator models, each surface could have its behaviour associated to a specific digital hydraulic topology (or the traditional servo-hydraulics). This allowed for the evaluation of their performances and energy efficiency when subjected to a flight control surface actuation context. The inputs, however, had been previously created by defined control strategies with a solely computational implementation. [20]

In the last iterations, the Hopsan models for the DEHA and SHA were adapted and parametrized to work properly with the flight simulation implemented in SIVOR. This should allow for more realistic evaluations of the digital system in flight, as the experienced pilot engaged in the context will interact in real-time with the outputs sourced by the digital hydraulic systems. Figure 12 shows the model for the DEHA.

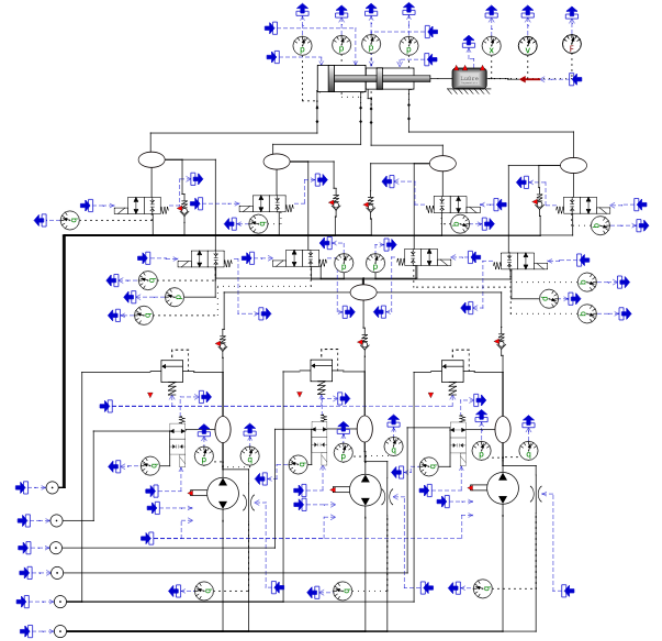


Figure 12: Hopsan model of the DEHA.

Since the model is intended for implementation within the flight simulator, all the model control and key parameters are externally provided. This promotes easier adjustments and application as a S-function in a Matlab/Simulink environment. Similarly, the outputs are externally available.

The model closely follows the schematic in Figure 5. The lower section simulates the Digital Hydraulic Pump. The three pump units are simulated as fixed-displacement pumps and have their flow selected to the system or diverted to the reservoir via an associated digital valve model. These valve models were developed by [10] based on a 2_2_Direction_Valve to accurately represent the dynamics found in the digital valves present at the research group. Additionally, the relief valves are included to allow for the simulation of valve failures in the DHP.

In the centre section of Figure 12 the manifold of on/off valves responsible for directing the flow to and from the cylinder is depicted. These valves are modelled with the same digital valve model as the DHP. Check valves are included in the model to allow proper simulation of failures in the return valves of this set.

The top section models the multi-chamber cylinder integrated with its LuGre friction model. The load on the actuator is externally provided, as it is calculated in the flight simulator. Further information on the Hopsan model implemented can be found in [11].

4.4 Modelling of the electromechanical system

The modelling of the electromechanical actuator supports the investigation of different flight control actuation system configurations. The purpose is to compare different technological solutions for several scenarios and aircraft types. Simulation and experimental testing go hand in hand, partly through model validation where the test rig provides the necessary data, and partly as simulation and real-time

testing provide different aspects. Not all details are covered by models, and not all scenarios are possible to test in the rig. Part of this work is presented in [21].

The models have been developed to run in conjunction with the hardware, enabling a virtual-physical test bed where the complete aircraft systems architecture, or parts of it (like the flight control actuation system), is represented as a model running parallel to the hardware.

The actuator can be presented with different levels of detail, and depending on the purpose a proper representation is necessary. A more detailed representation of an electromechanical actuator for performance evaluation is presented in [2]. The purpose in this work is not to study in detail one specific actuator, but to enable a greater variation of configurations and test cases. An important requirement is to be able to run the model in real-time together with the Iron Bird. A proper representation is shown in Figure 13, which includes static and inertial effects. Two feedback loops are present for speed and position control, with gains that are tuned to satisfy the individual response requirements of each loop. A term representing the copper losses is also included to represent the thermal behaviour. The details of this modelling approach are described in [21.]

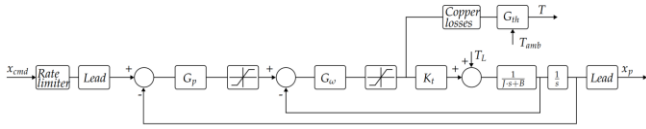


Figure 13: Model representation of the electromechanical actuator.

When the actuator model runs in conjunction with the Iron Bird, it represents the actuator intended for that specific use case. For example, in this paper, the intended use case is a generic fighter aircraft. The actuators (i.e. models) under test are therefore sized accordingly.

5 Designing the Experiments

The general experimental setup starts with the aircraft and actuators' mathematical models implemented in the SIVOR and Cave simulator, to generate data with human-in-the-loop. The next step is to execute tests in the LASHIP test rig for the digital hydraulic actuator and the Iron Bird environment to extract complete behaviour data sets.

5.1 Human-in-the-loop flight simulation

The experimental campaign involves a military professional fighter pilot performing a predefined set of flight manoeuvres under two distinct test conditions: high-altitude flight and low-level navigation. These tests are designed to assess pilot interaction, workload, and simulator behaviour under realistic mission profiles. Human-in-the-loop simulations are essential for capturing pilot responses and evaluating the overall effectiveness of the simulation environment.

For the Low-Level test case, the pilot performed 3g turns without afterburner at altitudes around 200ft following the instructions in Table 1.

Table 1: Low Level Navigation.

Subtask	Manoeuvre	Speed	Heading	Time
1	Level flight	M0.7	360	20 seconds
2	Right turn	M0.7	360-030	
3	Level flight	M0.7	030	20 seconds
4	Left turn	M0.7	030-360	
5	Level flight	M0.7	360	20 seconds
6	Right turn	M0.7	360-330	
7	Level flight	M0.7	330	20 seconds
8	Right turn	M0.7	330-360	
9	Acceleration	M0.7-M0.9	360	
10	Left turn	M0.9	360-030	
11	Level flight	M0.9	030	20 seconds
12	Left turn	M0.9	030-360	
13	Level flight	M0.9	360	20 seconds
14	Right turn	M0.9	360-330	
15	Level flight	M0.9	330	20 seconds
16	Right turn	M0.9	330-360	
17	Level flight	M0.9	360	20 seconds

The second test case, again with no afterburner, the pilot executed right and left yo-yos, loops and an Immelmann turn for the conditions listed in Table 2.

Table 2: Advanced Manoeuvres.

Subtask	Manoeuvre	Entrance Speed/Alt	Pull-up load factor	Top of manoeuvre	Exit load factor	Exit Speed/Alt
1	Yoyo right	M0.9/13000 ft	4g	M0.9/13000 ft	4g	M0.65/13000 ft
2	Yoyo left	M0.65/13000 ft	3g	170 KIAS/19000 ft	4g	M0.7/13000 ft
3	Yoyo right	M0.7/13000 ft	4g	M0.45/17000 ft	4g	M0.65/13000 ft
4	Yoyo left	M0.65/13000 ft	4g	200 KIAS/19000 ft	4g	M0.5/10000 ft
5	Loop	M0.75/10000 ft	4g >alpha12	M0.4/18000 ft	alpha14 >4g	M0.75/10000 ft
6	Loop	M0.75/10000 ft	4g >alpha15	190 KIAS/19000 ft	alpha14 >4g	M0.75/10000 ft
7	Immelmann turn	M0.75/10000 ft	4g >alpha12	190 KIAS/18000 ft		

For each test case, all command inputs were recorded along with aircraft data.

5.2 Digital Hydraulic Actuation test setup

At LASHIP, the performed experiment is applied on the DEHA system (shown in Figure 5). The actuator commands are recorded in the flight simulations performed with professional pilots at ITA and used as inputs for the test bench. The respective aerodynamic loads are applied by the load simulator while calculated in real time based on the actual actuator position and the flight data generated by the previous simulation.

Currently, the test rig can perform with 160 mm of available stroke and up to 10 kN of counter load. The stroke is sufficient to simulate the operation of any control surface in the recorded flights. The load on some surfaces, however, exceeds the bench's capability. In these cases, a scale is applied to the calculated loads, therefore maintaining a coherent experiment.

The actuator movement obtained can be compared to the outputs of servo-hydraulic (conventional) and electromechanical actuators exposed to the same situation, allowing the analysis on the performance difference between technologies.

5.3 Electromechanical Actuation test setup

Several test scenarios are possible to evaluate in the Iron Bird, both electromechanical actuators and hydraulic actuators, separately and in an integrated scenario together with electric and hydraulic supply, as well as other electrical consumers. This work focuses on evaluating the electromechanical actuator's performance and characteristics using the recorded pilot input. Since the same flight simulator model is used as in the SIVOR test rig, the actuator commands can be recreated from the pilot's input, as well as the hinge moments from the aerodynamic loads. Two approaches are possible as illustrated in Figure 14. For option 1 the aircraft control loop is closed by feeding back the measured actuator position as a representation of the control surface deflection in the model, thereby analysing the impact on aircraft performance from the actuator characteristics. This approach requires monitoring the aircraft attitude since different actuator characteristics might alter the actual control surface deflection. To ensure the aircraft follows the same flight trajectory an offset can be introduced to the stick input depending on the attitude deviation between the recorded data and simulated data from the test rig.

Option 2, used in this work, is an open loop approach where the physical actuator and a virtual model run in parallel. The aircraft feedback loop is provided through the virtual model to ensure integrity between the test cases in all test rigs. During the experiment several sensors provide information of the actuator performance: actuator commanded position, actual actuator position, motor winding temperature, control unit temperature measured at the motor control switches, motor current.

Since the actuator load is defined by the aerodynamic model for the generic fighter, they must be scaled to suit the installed actuator's maximum load capacity. This is done linearly by taking the ratio of the aircraft model's maximum load and the physical actuator's maximum load.

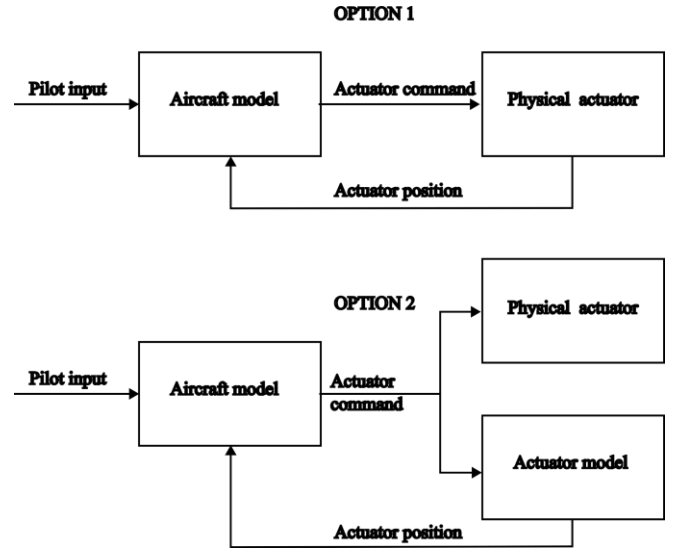


Figure 14: Two approaches for how the interaction between the models and physical hardware is setup in the Iron Bird.

6 Results and Analysis

6.1 SIVOR model response

To evaluate the feasibility of the defined test cases within the physical constraints of the SIVOR platform, recorded flight data from the Cave simulator was used. The relevant aircraft outputs linear accelerations and angular velocities, and were extracted from the two test cases described in Section 5 and processed through the SIVOR simulation model. This enabled visualization of the simulator's behaviour in CoppeliaSim and assessment of potential collisions.

The resulting flight paths for each test case are illustrated in Figures 15 and 16. For the low-level navigation scenario (Test Case 1), shown in Figure 15, no collisions were detected during simulation, suggesting that this test case is feasible for execution on the actual SIVOR platform.

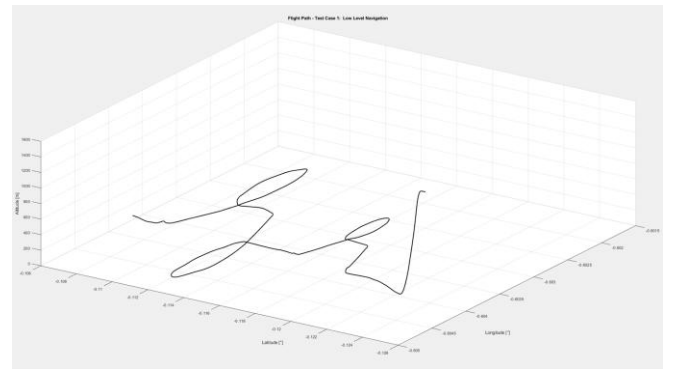


Figure 15: Resulted flight path from the Low level navigation

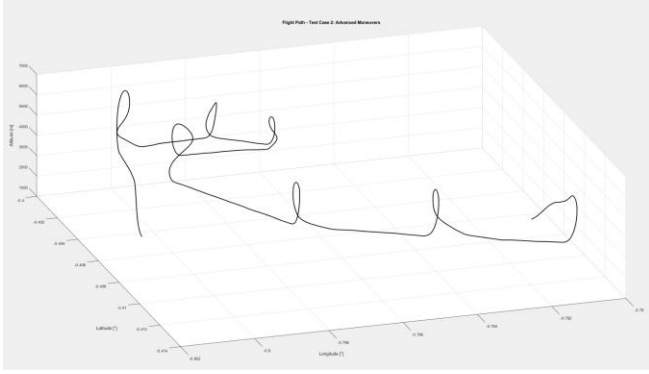


Figure 16: Resulted flight path from the Advanced Manoeuvres

In contrast, Test Case 2, depicted in Figure 16, revealed a collision during the last manoeuvre, as highlighted in Figure 17. These results indicate that this specific test case exceeds the physical limitations of the platform. In a real-world application, the collision avoidance system would be triggered, compromising motion fidelity to prioritize safety.



Figure 17: Collision visualization using CoppeliaSim

Based on these findings, further refinement of the motion cueing algorithm is necessary to better adapt the simulated trajectories to the platform's operational constraints. Once the test cases are adjusted to fit within the SIVOR's capabilities, future experiments can focus on analysing the impact of actuator technologies from a human factors perspective.

6.2 EMA performance test with pilot input

The Low-Level flight was used for initial testing in the Iron Bird. The left outer elevon (LOE) control surface with the electromechanical was chosen for this test. The recorded pilot input from the SIVOR simulator was used as input to the aircraft model. The actuator commands are sent to the EMA, as well as air loads are sent to the load actuator. The complete scenario was completed, and the resulting actuator position and load are shown in Figures 18 and 19. The commanded actuator position is also shown indicating the actuator's tracking performance. The commanded load is also shown to verify that the air load system is performing well.

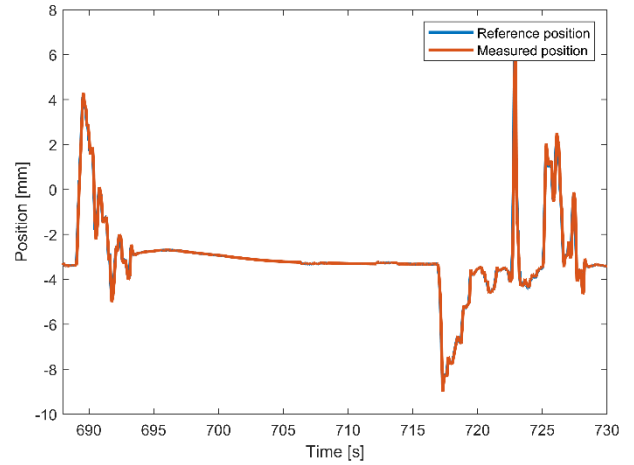


Figure 18: Test run in the Iron Bird with the recorded flight from SIVOR showing the EMA commanded position and measured position. Only a small portion is shown for clarity.

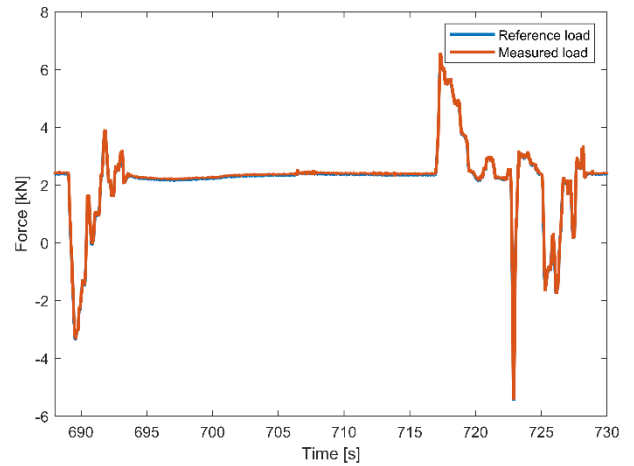


Figure 19: Test run in the Iron Bird with the recorded flight from SIVOR showing the actuator load together with the reference load. Only a small portion is shown for clarity.

6.3 DEHA performance test with pilot input

Both test cases were applied to the digital hydraulic test bench, with the DEHA simulating different flight control surfaces at each experiment. The experiment regarding Test Case 1 has its data shown in Figure 20. The actuator was implemented as the left outer elevon (LOE) of the simulated aircraft. Additionally, the aerodynamic loads calculated and applied, scaled down for the test, are rescaled to their original range for presentation.

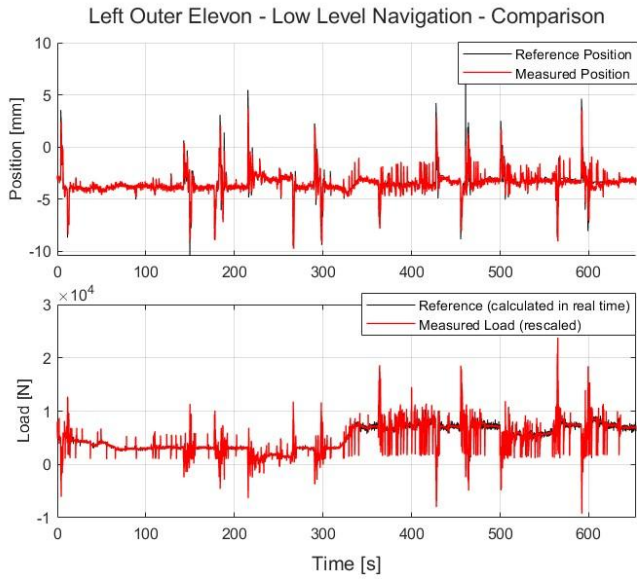


Figure 20: DEHA as LOE in Test Case 1 - Full experiment

The experiment was conducted over an extended period, with both the DEHA and the load simulation system demonstrating robust performance throughout the test. A shorter time span is shown in Figure 21, providing enhanced visualization of the analysed outputs. As observed, the actuator position closely tracks the commanded input signal. Similarly, the load simulation accurately follows the real-time calculated values, except for brief transient peaks during load rate reversals.

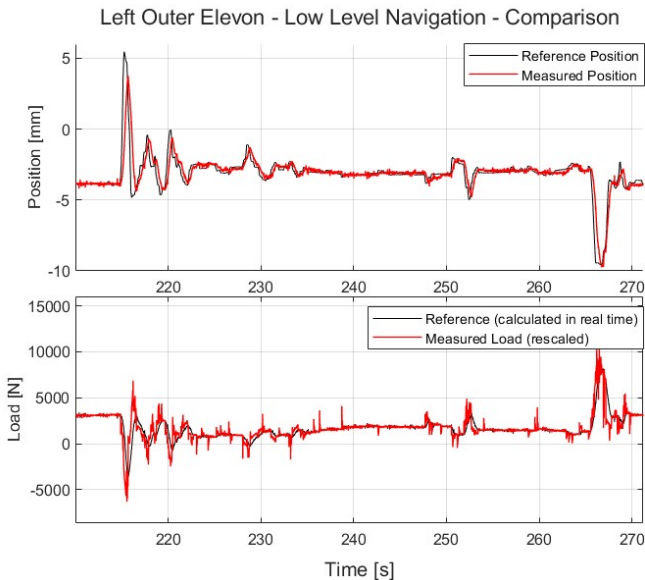


Figure 21: DEHA as LOE in Test Case 1 - detailed view

6.4 Actuator comparison

In addition to the experiments on each test rig, the presented framework facilitates the comparison of different actuator technologies across in the collaborating research groups. For the previously mentioned experiment, Figure 22 presents the position and load simulation performed during the experiments from both the Iron Bird and the LASHIP test rig.

The profiles were normalized to the original range for comparative analysis.

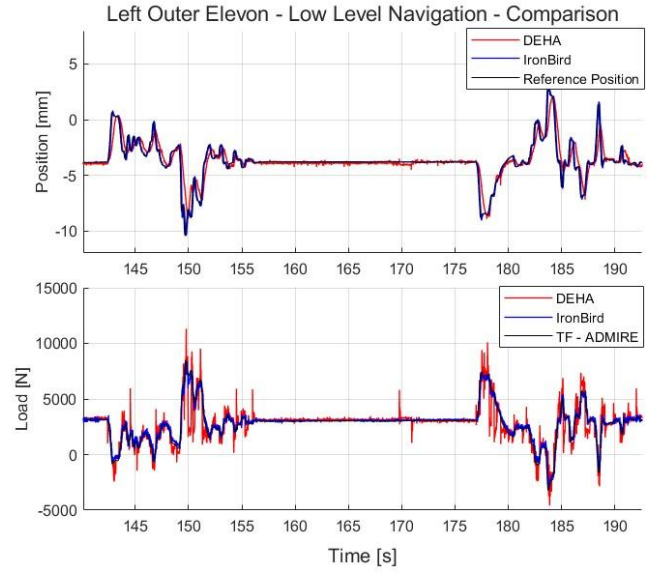


Figure 22: Actuator comparison as LOE in Test Case 1

Beyond the actuators, Figure 22 also includes the aerodynamic load calculated inside by the flight simulator and the position command as references. The control surface actuation within the flight simulator is modelled simply by a transfer function applying a small delay, rate limiter and saturation to the input signal. Consequently, this composition achieves near-perfect tracking of the commanded position. The close agreement between the experimentally applied loads and positions and these references demonstrate the high accuracy of the apparatus employed in both test rigs.

7 Conclusion

This work has presented an approach to distributed experimental testing of flight control actuation systems, connecting three test facilities in two different countries, using a model-based approach. Two different actuator technologies have been used as test objects. The main purpose is to compare the actuator performance for different flight scenarios and the impact on human factors. This paper has shown how a pilot-in-the-loop flight simulator has been used to produce realistic flight data to be re-produced in dedicated actuator test rigs. The next step includes the addition of more data to support deeper studies, as well as to close the loop by implementing validated actuator models in the pilot operated flight simulator.

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