The Aeronautical Journal (2024), **128**, pp. 2754–2780
doi:10.1017/aer.2024.91

ROYAL AERONAUTICAL SOCIETY

RESEARCH ARTICLE

Simulation framework and development of the Future Systems Simulator

W.T. Korek[1,2], P. Beecroft[3], M. Lone[1], E. Bragado Aldana[1], A. Mendez[1], J. Enconniere[1], H.U. Asad[4], K. Grzedzinski[1], M. Milidere[1], J. Whidborne[1], W.-C. Li[1], L. Lu[1], M. Alam[1], S. Asmayawati[1], L. Del Barrio Conde[1], D. Hargreaves[5] and D. Jenkins[5]

[1]Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, UK
[2]Faculty of Automatic Control, Electronics and Computer Science, Silesian University of Technology, Gliwice, Poland
[3]Rolls-Royce plc, Derby, UK
[4]School of Science and Technology, City, University of London, London, UK
[5]DCA Design International Ltd, Warwick, UK
Corresponding author: W.T. Korek; Email: w.t.korek@cranfield.ac.uk

Received: 26 January 2024; **Revised:** 5 June 2024; **Accepted:** 13 August 2024

Keywords: flight simulation; human-computer interaction; human factors; flight deck design; aircraft modelling

Abstract
The Aerospace Integration Research Centre (AIRC) at Cranfield University offers industry and academia an open environment to explore the opportunities for efficient integration of aircraft systems. As a part of the centre, Cranfield University, Rolls-Royce, and DCA Design International jointly have developed the Future Systems Simulator (FSS) for the purpose of research and development in areas such as human factors in aviation, single-pilot operations, future cockpit design, aircraft electrification, and alternative control approaches. Utilising the state-of-the-art modularity principles in simulation technology, the FSS is built to simulate a diverse range of current and novel aircraft, enabling researchers and industry partners to conduct experiments rapidly and efficiently. Central to the requirement, a unique, user-experience-centred development and design process is implemented for the development of the FSS. This paper presents the development process of such a flight simulator with an innovative flight deck. Furthermore, the paper demonstrates the FSS's capabilities through case studies. The cutting-edge versatility and flexibility of the FSS are demonstrated through the diverse example research case studies. In the final section, the authors provide guidance for the development of an engineering flight simulator based on lessons learned in this project.

Nomenclature

AIRC	Aerospace Integration Research Centre
AOI	area of interest
CD	checklist display
CFD	computational fluid dynamics
COTS	commercial off-the-shelf
CU	Cranfield University
CUD	central upper display
ECAM	electronic centralised aircraft monitor
EFS	engineering flight simulator
E-PILOTS	Evolution of cockPIt operations Levering on cOgnitive compuTing Services
FGFS	FlightGear Flight Simulator
FoV	field of view
FSS	Future Systems Simulator
FTD	flight training device
GUI	graphical user interface

HCI	human-computer interaction
HMI	human-machine interface
IOS	Instructor Operating Station
IP	intellectual property
MCP	mode control panel
METAR	Meteorological Terminal Air Report
MSFS	Microsoft Flight Simulator
ND	navigation display
PF	pilot flying
PFD	primary flight display
PINES	Powerplant Integration of Novel Engine Systems
PM	pilot monitoring
PS	performance score
RTC	real-time computer
SA	situation awareness
SUS	System Usability Scale
TRANSIT	Towards a Robust Airport Decision Support System for Intelligent Taxiing
UDP	user datagram protocol
XP	X-Plane

1.0 INTRODUCTION

The commercialisation of new technologies has the potential to revolutionise the aviation industry and transform future aircraft design [1]. Smart engines are now capable of collecting vast amounts of data and making autonomous decisions [2], leading to a need to reconsider how this information is presented to the pilot. Electric and hybrid vehicles, which are expected to become more prevalent in the future [3–6], will further alter the relationship between the engines and the pilot, as well as the task of flying the aircraft. However, predicting and understanding the interaction between the pilot and the aircraft is a complex task. The best way to explore these interactions is to observe them through scenario-building in a simulated environment, which is both practical and safe [7]. Furthermore, the integration of airframe and propulsion systems in traditional aircraft is becoming increasingly challenging [8–10]. Depending on external suppliers with their own intellectual property (IP) restrictions and development constraints [11] limits the possibility of rapid iteration of flight control and cockpit display concepts. This can lead to sub-optimal solutions and a lack of consideration for the "human-in-the-loop" [12]. It is critical to account for the human element in the design process, particularly given the growing complexity of automation and shift in the pilot's role from aviator to "mission manager" in conventional aircraft [13,14].

Over the years, Cranfield University (CU) has collaborated with both academic and industrial partners in integrating flight simulation technology [15]. As part of the Open Flight Deck Project [16–18], CU, Rolls-Royce, and DCA developed the Future Systems Simulator (FSS), shown in Fig. 1. The FSS features an innovative and highly reconfigurable flight deck design incorporating an all-touchscreen panel and a physical cockpit fuselage component.

This article describes the FSS simulation framework for research into various aerospace technologies, ranging from engine systems displays to hybrid/electric aircraft concepts, and provides insight into its development process and human factors aspects. The main section of the paper starts with the FSS design process (Section 2). Following that, Section 3 presents the simulator framework, including its modularity, physical characteristics, and hardware specifications. Additionally, the authors outline the aircraft development and modelling processes, as well as the visualisation system and network architecture. Next, in Section 4, case studies demonstrate the FSS effectiveness in enabling various research goals. Finally, recommendations for the development of engineering flight simulators are presented in Section 5, and the work is concluded in Section 6.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

Figure 1. *Future Systems Simulator in a working implementation of a conventional multi-crew configuration setup.*

1.1 Flight simulation

Simulators are invaluable assets in flight training (both civil and military), safety procedures, aircraft design, and research in the aeronautics field. In particular, engineering flight simulators (EFSs) can be used to conduct scientific research by providing a safe and cost-effective environment to simulate actual flight conditions. Researchers can gain valuable insight into the science of flight and develop new technologies that improve aircraft safety and efficiency. Additionally, EFSs can be used to investigate how pilots interact with novel types of aircraft, manoeuvres, and safety procedures, thus helping to ensure the safety of passengers and crew at later stages. As such, EFSs can be a valuable tool for the scientific, engineering, and industrial areas [19].

Many universities and research centres are developing their own EFSs that facilitate a range of research from basic flight dynamics to complex human-machine interactions and new control technologies. Examples of such facilities are shown below, along with the comparison with the FSS.

Texas A&M University (TAMU) Engineering Flight Simulator: The TAMU simulator utilises a network of multi-processor computers to enable efficient simulation of complex flight dynamics, contrasting with the FSS's use of single Real-Time Computers (RTCs) like Speedgoat or dSPACE. TAMU simulator features modular components allowing for flexible aircraft model configurations and includes a 6-DOF moving base for realistic motion cues; however, its visual system uses non-bent screens with visible corners that disrupt visual continuity. In contrast, the FSS offers a seamless panoramic view and operates on a fixed-base platform, focusing on precise flight model accuracy and control responsiveness. Additionally, the TAMU EFS cockpit uses the fuselage of a decommissioned USAF Cessna T-37, whereas the FSS adaptable interface supports various aircraft types for broader research and training applications. Both simulators incorporate touchscreen displays, enhancing user interaction and operational efficiency [20].

Both TAMU and CU EFSs cater to slightly different needs within the research and training spectrum. The TAMU simulator offers a more physically immersive experience with its moving base and authentic cockpit setup, ideal for pilot motion studies. In contrast, the FSS's strength lies in its flexibility and the ability to simulate various aircraft through a configurable interface and high-fidelity visual systems, making it particularly suitable for human-factors-based research projects.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

University of New South Wales (UNSW) Engineering Flight Simulator: The UNSW EFS features a closed cockpit repurposed from a Boeing 747, similar to the CU Large Flight Simulator (LFS), which limits its configuration but provides an authentic environment for operational and maintenance training. In contrast, the FSS has an open cockpit design, enhancing its modularity and allowing for easy reconfiguration to simulate different aircraft types, which is essential for researching novel concepts in aerospace. While the UNSW EFS primarily serves educational purposes, helping students gain hands-on experience with real aircraft systems [21], the FSS is utilised predominantly for advanced research projects that explore innovative flight technologies and human-factors engineering. This distinction highlights the UNSW EFS's focus on practical training and familiarity with aircraft operations, whereas the FSS is designed to push the boundaries of aviation technology and theoretical applications.

NASA Advanced Concepts Flight Simulator (ACFS): NASA's simulator at Ames Research Center is renowned for its full mission functionality and complete programmability for any research need, akin to the FSS's flexibility. The FSS shares many of these traits but could benefit from NASA's approach to integrating varied air traffic control scenarios and external system linkages, enhancing its simulation environment. Similar to TAMU EFS, the NASA ACFS has a movable platform, in contrast to the FSS fixed base [22].

The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) Air Vehicle Simulator (AVES): The DLR AVES features interchangeable cockpits and high-performance motion and visual systems, facilitating rapid changes between different aircraft setups for successive experiments [23]. One specific example is the transition between motion-based and fixed-wing cockpits during one day [24]. While the FSS offers substantial adaptability in simulation environments and allows a rapid switch between aircraft models and flight deck layouts, it lacks the physical modularity to switch hardware as rapidly as the AVES system, highlighting a potential area for future development. Moreover, the FSS is a fixed-base-only simulator; however, this has been proven sufficient for human factors and aircraft modelling studies [25].

Merlin MP521 Engineering Flight Simulator: The Merlin MP521 is designed primarily for educational use, offering a cost-effective platform for studying aircraft dynamics [26, 27]. It provides a fundamental environment suitable for undergraduates learning about flight principles. The FSS, while also capable of educational roles, is engineered for more complex research and higher fidelity simulations, and its source code is opened for students to modify according to the research needs.

Cranfield University Large Flight Simulator (LFS): Besides the FSS, CU operates two more EFSs. The Large Flight Simulator (LFS) serves as a valuable tool for integrating advanced avionics, simulation technologies, flight control systems, and human factors research. It can be configured to simulate different aircraft types, including both Boeing and Airbus. However, software modifications require specialist knowledge in low-level programming, and its physical flexibility is limited. Compared to the FSS, the LFS offers a more immersive experience due to the fixed-base reproduction of a Boeing 747-100 cockpit, with the addition of the Airbus sidesticks. While the FSS also supports high-fidelity simulations, the LFS's specific focus on automation and human factors provides complementary insights into the operational challenges of existing flight decks [28].

Cranfield University EFS500 Engineering Flight Simulator: The EFS500 is an engineering flight simulator designed to support research and development in aerospace engineering [29]. This simulator excels in demonstrating and studying aerodynamics, flight mechanics, avionics, and flight control system design. It includes a generic single-pilot cockpit layout, adaptable to a limited number of aircraft types. Notably, the EFS500 has been instrumental in several industrial projects, including the Airbus Agile Wing Integration and ONEheart projects, showcasing its capability to support cutting-edge aerospace development. Its software architecture is identical to the CU's LFS, sharing its advantages and disadvantages in comparison to the FSS, having high reliability in terms of using the available code, but on the other hand, requiring low-level programming knowledge for layout and model modifications.

2.0 DESIGN PROCESS

The design of the FSS was a complex and challenging task, as it had to meet a wide range of requirements and specifications: apart from conventional simulator capabilities, it had to be designed to support the assessment of emerging and disruptive cockpit technologies. This required the development of advanced software and hardware that could simulate these technologies and their interactions with other systems in the cockpit. A thorough design process was followed to ensure that the FSS fulfilled all of these concept requirements. This involved the identification of the key requirements and specifications, the selection of appropriate technologies and components, the development of detailed design models and prototypes, and the testing and validation of the final design. This section provides a detailed overview of this design process and the steps taken to ensure the success of the FSS.

Traditional flight simulators are designed to replicate the flying experience of an existing physical aircraft and primarily serve to support pilot training. Their approach is to train the pilot and assume that the aircraft design is correct and fixed [30]. In contrast, the FSS is developed with a different philosophy, focused on exploring how iterative changes to the cockpit design could influence the performance of the human-machine system. Instead of adapting the pilot to fit the fixed cockpit design, the aim of the FSS is to adapt the cockpit to improve the human-machine system performance.

A core philosophy running through the project was that the graphical user interface (GUI) and the physical components in the system should have parity. This meant designing both in tandem rather than starting with the physical interface. Careful consideration was made as to which controls should be handled by touchscreens and which required more traditional physical input. This early consideration of the GUI led to changes in the number of displays, their size, orientation and positioning.

Starting points: The physical layout of the cockpit displays and controls was informed by the ergonomic needs of the pilot. While this started on paper, with anthropometric mannequins, a full-sized MDF[1] rig was built early in the project to test assumptions with pilots and to gain additional feedback. This philosophy of stakeholder engagement continued throughout the project. Multiple interface layout iterations were assessed with test pilots in the physical mock-up. The final position, reach, and size of elements were particularly influenced by this feedback.

The graphical elements: It was intended that the simulator HMI graphics (its GUI) should start from a blank sheet of paper unencumbered by existing conventions.

With an environment that is rapidly modified and iterated, there is a clear risk that it quickly feels disjointed. To combat this, an organic-like "style guide" was developed to create harmony between the different elements of the FSS. An appropriate aesthetic strategy was developed that defined all of the appropriate information, colour and how they should be presented. This guide has been faithfully followed when new graphic elements have been created.

Another key aspect in creating this harmony involved ensuring that the interface works at multiple levels of abstraction. The human factors specialists (with expertise in user experience design) worked closely with both the technical teams and the test pilots to establish the hierarchy of needs for the design. This involved considering higher-order goals alongside the need to understand the status of physical components. Key vignettes, typically safety-critical events, were used to stress test this. This focus on presenting what is important at the right time, in the most optimal and efficient way, guided the team through the detailed decisions when designing the HMI.

Each graphical element was structured in ways that meant that they could be easily modified. The user experience team spent time demonstrating to the wider team how the graphics were built. This helped to remove the mystery behind the creation of the graphics, meaning that traditionally non-creative team members could feel comfortable challenging and building upon the work. The graphics were created through a series of workshops. Initially, ideas were brainstormed using paper and online co-collaboration tools and then moved through graphic development tools (including *Marvel* and *Figma*) before being

[1] Medium-density fibreboard.

implemented in the game engine Unity[2] on to the FSS for testing. At each step of the way, the solutions were shared with the wider team and optimised based on their feedback. The collaborative nature of some of the digital tools was critical to this. Rather than waiting for formal review meetings, stakeholders could "check-in" and provide comments and suggestions as the design develops.

The physical elements: From the initial briefing by Rolls-Royce, it was clear the design and construction of the FSS was an ambitious project that needed to be completed within seven months. The temporal and fiscal demands encouraged the adoption of 'off-the-shelf components' where possible; however, it was acknowledged that many elements of the system would need to be purpose-designed or adapted from existing solutions.

The physical design of the simulator was designed to be generic in format rather than being aligned to any one particular aircraft type. It was developed to feel realistic and representative to pilots undertaking user testing. It was also important that it should have an aesthetic representative of a flight deck of the future.

Following some research studies in a range of flight simulator environments, it became apparent that the simulator needed to be more structurally robust than initially anticipated. In demanding flight situations, 'Test Pilots' could get very physical with the controls and interfaces.

As well as being robust, the FSS was designed to be easy to repair. The team designed the physical form of the simulator to be built from rapid prototyped parts where possible. This means that parts that are damaged or need to be upgraded can easily be replaced. Using rapid prototyped parts also helps to minimise simulator downtime due to their low production lead times.

The design process was highly iterative. Each step involved collaboration and stakeholder input. [nosep]

- **2D desk-based research:** A brief desk-based human factors review of the proposed flight deck console, the pilot seating positions and the various optional primary and secondary control formats, locations and orientations.
- **3D CAD review:** Once the fundamental layout had been agreed upon, the design quickly moved to 3D. This was viewed in VR for different sign-offs along the development path.
- **Low fidelity rigs:** Several low-fidelity rigs were produced for localised user testing at a range of review meetings and workshops throughout the development process.
- **Ergonomic rig:** Once the fundamental elements of the design had been defined, a basic ergonomic rig of the proposed modular flight deck console arrangement was constructed. This formed the basis of a human factors review of the proposed system's ergonomics and usability. At the review workshop, fundamental changes were made to the ergonomic rig as assessments were made. These changes were made rapidly, allowing the refined design to be re-assessed as part of the same workshop.

Manufacturing Phase: Once the design was agreed, the project moved into a manufacturing phase. This included: [nosep]

- **Part fabrication:** Once the design had been finalised, the bespoke parts and sub-assemblies were constructed using a range of low-volume manufacturing techniques. These included 3D printing, CNC-machining, and laser cutting sheet material.
- **Assembly:** The FSS was assembled at DCA's large-scale model-making facility, and once it had been inspected by the key stakeholders, it was transported to the AIRC for final installation, testing and commissioning within the control room space.

[2]unity.com.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

Figure 2. *Future Systems Simulator's cockpit close-up conceptual render. Many of the HMI features seen in this design concept have already been implemented. Every physical or digital element can be repositioned or removed according to research requirements.*

The cockpit design was developed with the engagement of DCA [31], test pilots and aerospace engineers at every stage of the process to provide the best flying experience while keeping the modularity and elasticity of the project. The result is a cockpit made of up to six configurable touchscreens, sockets for extra tablets, and extendable trays, as seen in Fig. 2. The selected seats can be found on in-service Gulfstream G450 aircraft. The seats, sidestick and throttle pedestals can be physically moved to different slots on the flight deck platform. The cockpit "shroud" was designed to provide an immersive feel to the pilots, but it can also be removed if needed.

3.0 INTEGRATION & ARCHITECTURE

This section describes the key steps and milestones of the FSS integration, highlighting the challenges and successes encountered along the way. An overview of the tools, technologies, and methodologies that were used to design, prototype, test, and validate the FSS components will also be provided, as well as the key factors that influenced its development. This will provide a comprehensive understanding of the development process and the considerations that went into creating the advanced capabilities of the FSS.

3.1 Human-machine interface

The HMI forming process began with the development of several prototypes for the primary flight display (PFD) based on DCA's initial designs. They led to finalising the arrangement of crucial components such as the attitude indicator, navigation display, engine information, digital levers for landing gear, flaps, and spoilers, and other cockpit systems such as the mode control panel (MCP). Once the base design was approved, it was implemented in the Unity environment to develop and maintain the HMI easily. Additional features, such as radio control, flight management system, checklists, electronic centralised aircraft monitor (ECAM), and map, were subsequently added as modules.

The overhead panel, which includes components such as engine ignition and safety switches, electronics, fuel, hydraulic, pressurisation, and other control systems commonly found in aircraft cockpits, was represented as multiple tabs on the central lower display called synoptic pages. Unity software enables full flexibility in design [32]. The HMI remains in constant development to adapt to the experiment's needs, with almost unlimited possibilities in terms of layout and special functions, limited only

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

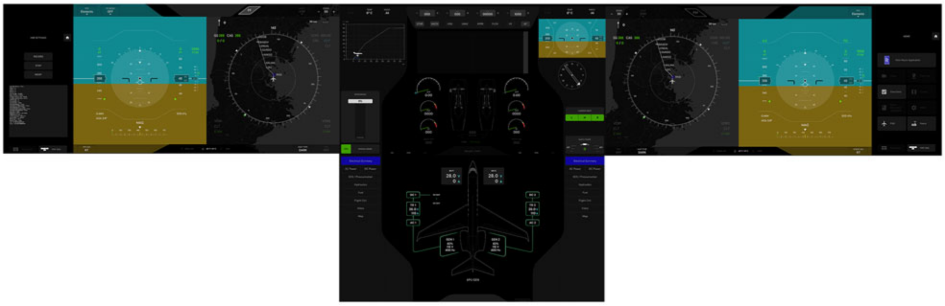


Figure 3. *Example of a working implementation HMI for a business jet aircraft. The flight deck consists of six touchscreen monitors mounted on a stable base. The monitor layout and the HMI elements can be freely repositioned to accommodate any research requirements.*

by the number of touchscreen monitors. This allows for the replication of any existing aircraft cockpit for testing purposes, with a digitised representation of buttons, levers, and other controls. Figure 3 shows an example of HMI configuration.

There are standards such as CS25-1302/RP-505 for embedded systems in the cockpit [33] and ARINC 661 for the unified preparation of flight cockpit indicators [34]; however, these solutions are limited by existing specifications and aim to speed up the process of preparing virtual cockpits in simulators. The rapid prototyping technique used in the FSS allows for almost non-constrained proposals of novel cockpit elements, such as hybrid-electric indicators.

The sidestick controller was based on an off-the-shelf *Thrustmaster HOTAS WARTHOG* gaming joystick. The upper part was removed, and a custom-made handle designed by DCA was created to ensure the pilot's comfort and ergonomics. The sidestick is also equipped with directional, push-to-talk, and autopilot-disengage buttons. The armrest pedestal for the sidestick is a custom-built unit that is motorised to allow easy adjustment to the pilot's comfort. The rudder pedals are off-the-shelf models from *Logitech's G Saitek PRO Flight* series, mounted on a platform with adjustable position.

The throttle in the FSS cockpit is fully custom-built, consisting of two independent and motorised thrust levers, a push-to-disengage auto-throttle, and two additional functional buttons. An Arduino processor operates the throttle, which is connected to the PC via a USB port and communicates with the PC using an RS232 connection. Any additional inceptors, such as a landing gear lever or flap/slat control, are integrated within the HMI.

3.2 Flight simulation modelling

The physics simulating the engine has been programmed in-house using MATLAB & Simulink/Simscape; features from the Aerospace Blockset Toolbox provide the backbone for modelling all desired physical behaviour. This also includes the physical signals that drive the HMI and instruments displayed to the pilots. The use of this simulation environment enables the flexibility for programming a bespoke range of simulation fidelities whilst providing the clarity of a graphical programming language that viscerally depicts the interactions and interfaces between aircraft systems. Depending on aircraft type, e.g. fixed-wing or rotorcraft, code repetition is minimised through a standard format of model parameters that populate key aerodynamic properties of the flight physics models. With this common modelling architecture, the FSS has the capability to quickly change between chosen modelled airframes whilst providing flexibility to investigate novel parameter tuning, even online, during simulation sessions.

For more bespoke sub-systems, the models are developed as independent masked blocks in Simulink. As an example, a fuel system model captures the mass transport properties of pumping fuel from key

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

nodes within the aircraft. The main contributing time constants are considered rather detailed computational fluid dynamics (CFD) modelling of fuel flows. Such a model then feeds the weight reduction and balance shifting due to fuel consumption into the flight dynamics model. Furthermore, the component characteristics and system logic of the main pumps and valves have been modelled to respond to critical pilot interactions derived from fuel imbalance. Fuel leaks can be simulated online; fuel balancing will occur in accordance with the operational procedures followed by the pilot and input through the HMI. Ultimately, the sub-system models can be linked to engine models provided by Rolls-Royce or to other available engine models, which can be run in parallel in a block-box approach (hiding any sensitive engine modelling IP).

The effect of powertrain performance, both in steady-state and transient regimes, can be faithfully simulated and, therefore, can provide representative visual cues of the resultant powertrain/airframe coupling. This is particularly important for future unconventional aircraft designs, such as eVTOL aircraft, which require an in-depth understanding of the complex interactions between powertrain and airframe geometry.

This modelling environment provides functionality to integrate power sources independent of the physical domain; battery electric, hybrid electric and conventional heat engine power can all be readily integrated into the FSS if appropriately scaled system data, which matches real-world compatibility, is available. Alternatively, dummy parameters or desirable behaviour can also be programmed into the FSS.

Through pilot-in-the-loop simulation, meaningful feedback from the end-users of the aircraft system can be integrated into engineering development and research. This can, therefore, enable the prototyping of control systems early on in the development cycle of a new engine or airframe (or both simultaneously) to allow more informed decision-making during an engineering programme, saving time and costs in dealing with integration issues that could emerge at much later design cycles.

The high-level MATLAB/Simulink models are compiled into C code and uploaded to a dSPACE SCALEXIO[3] real-time computer (RTC) for real-time simulation (configured from the host PC, specified as “dSPACE/aircraft model management + Scenery PC” in Fig. 5). Once the aircraft model is built and deployed on the RTC, the RTC manages the communication between the systems on the network in real time. Communication occurs through a centralised network switch, described in Section 3.3. Emulating component physics in real-time enables hardware-in-the-loop simulation for testing other real components, such as FADECs, that can be exercised and validated with signals from the RTC.

Aircraft Subsystems

The aircraft platform is built around a generic architecture detailed in Fig. 4. This platform was developed in MATLAB/Simulink, providing rapid prototyping flexibility with real-time features. Four key components can be seen:

- The Aircraft Dynamic model is organised around the use of look-up tables for the definition of the aero-derivatives. This approach is usually considered valid for small perturbations for angle-of-attack below 10 degrees. The actuators are currently modelled as transfer functions. Non-linear behaviours caused by landing gear aerodynamics, spoilers, under-carriage aerodynamics, stall and ground effects are also accounted for in the model through adds-on based on empirical and semi-empirical approaches.
- The Powertrain encompasses a dynamic engine model and a fuel system. The engine model can range in complexity from a simple transfer function all the way to a turbofan transient performance platform. A propeller model is also available, accounting for the interaction between propeller slipstream and wings.

[3] https://www.dSPACE.com/en/pub/home.cfm

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

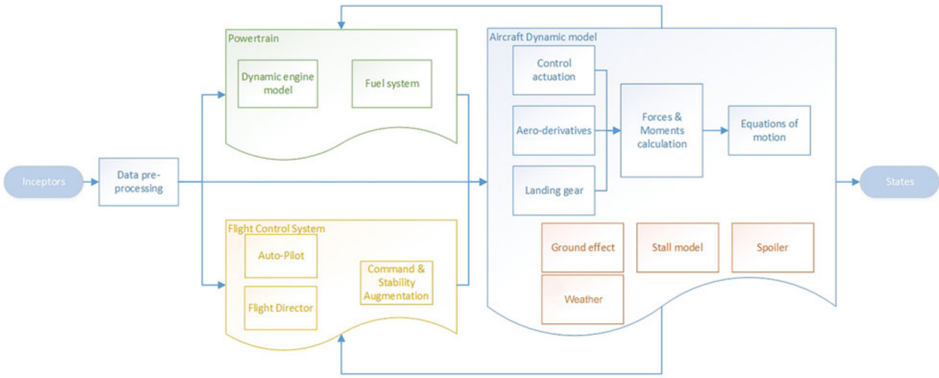


Figure 4. *Aircraft dynamic model platform*

- The Flight Control System block includes command and stability augmentation, which is found in most contemporary commercial aircraft. It is associated with a flight director and auto-pilot offering a number of typical modes (LNAV – lateral navigation, HDG – heading, APP – approach, VS – vertical speed, FLCH – flight level change, and ATHR – auto-throttle)
- The weather block uses the Simulink Aerospace Library through three sub-models: steady wind, turbulence and discrete gusts, which can be independently activated in real time. Doing so is possible thanks to the RTC used to run the models, and with computing power still on the rise, could even calculate CFD in real-time.

Each sub-model of the platform can be substituted for another depending on the simulation needs. A library of models has been purposefully built to that end. The aircraft aero-coefficient tables can be populated with wind tunnel data or data generated through various aerodynamic analyses, which are out of the scope of this paper. The relative simplicity and flexibility of the model architecture allow for rapid prototyping of novel vehicle designs within its flying envelope at a reasonable computational cost, making the model real-time compatible.

3.3 Architecture

The FSS undertakes a broad range of computational tasks, which have been divided between several computers and dSpace RTC. This distributed network of computers is depicted in Fig. 5. All modules use the user datagram protocol (UDP) packets for bi-directional communication across the network. Despite its intrinsic flaws, the FSS uses UDP for its superior speed and efficiency. The UDP packet structure is explained in more detail in the next paragraph. At the core of this distributed network is the dSPACE unit, which manages and connects every process on each computer: it receives and processes pilot input from the HMI PC, calculates and sends the aircraft model data packet to the HMI PC for cockpit display and to the Instructor Operating Station (IOS) PC for data collection, and sends positioning data to visualisation software (latitude, longitude and altitude). The other important computer responsible for a large proportion of the simulation is the HMI PC: it displays the information from the aerodynamic model on the screens and collects the inceptor inputs and other commands from the cockpit, sending the control data packet across the network to the dSPACE (for input) and IOS PC (for data recording).

UDP Network Protocol Implementation

The FSS utilises the UDP network protocol to manage communication between various components efficiently. There are two primary types of data packets essential for simulator operation:

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

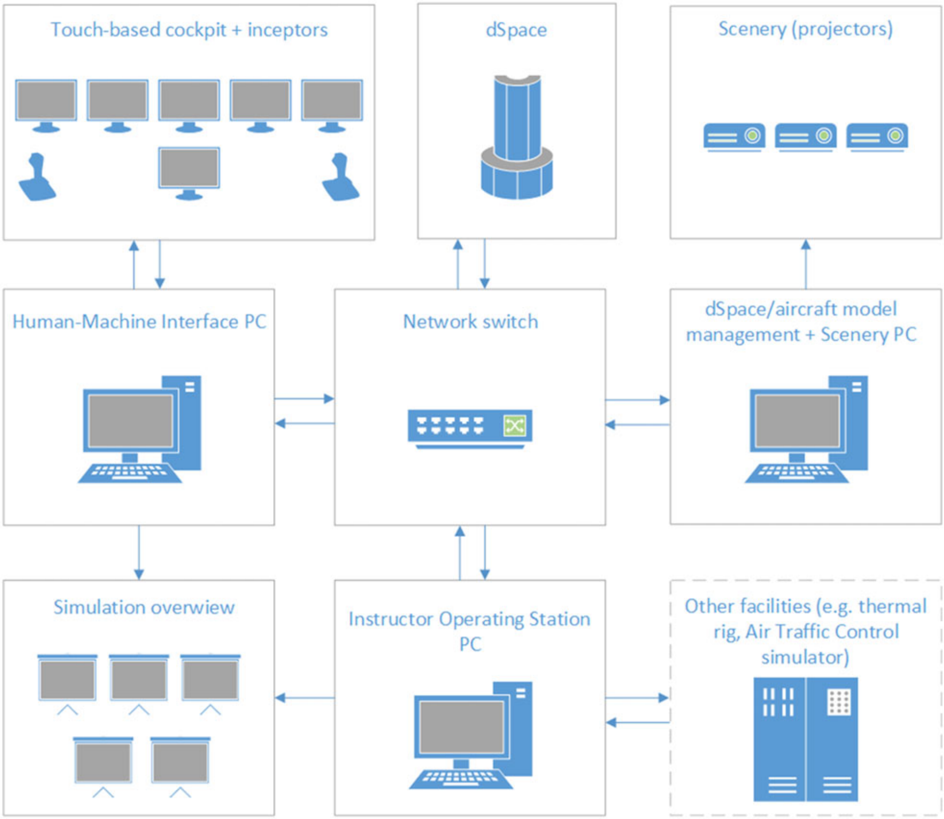


Figure 5. *Distributed computing network of the FSS.*

- **Data Packet:** Originating from the dSpace machine, this packet includes complete information about the aircraft's flight dynamics, systems, navigation, and engine status. It is transmitted to the HMI and IOS PCs to ensure that both the simulation environment and the operators have real-time access to flight data.
- **Control Packet:** Generated by both the HMI and IOS PCs, this packet contains inputs from inceptors, flight deck actions, and crucial simulation control variables like the reset signal. The reason that the same packet is created in both the HMI and IOS PCs is due to the fact that the simulation can be controlled from within the cockpit, for example, in the situation where the researcher sits on one seat and the test subject on the other. The priority, which packet takes precedence, can be set manually so the packets do not clash with each other. Such a setting minimises the personnel requirements during tests.

Additional packets facilitate further customisation and integration of various simulation aspects:

- **Scenery Packet:** Communicates the aircraft attitude and world position from dSpace to the Scenery PC and, if necessary, to the IOS for a simulation overview.
- **Ground Elevation Packet:** Ensures synchronisation with a visual system. This is a small packet with current ground elevation, based on the latitude and longitude location, sent from Scenery PC (generated by FlightGear or X-Plane) to the aircraft model on dSpace.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

(a) (b)

Single-crew configuration. Remote-crew configuration.

Figure 6. *Conceptual renders with possible configurations of the FSS.*

- **Custom Packets:** Designed for specific modules, these packets are tailored to carry appropriate data for external modules linked to the FSS (such as the thermal rig or Air Traffic Control simulator.

Data within these packets are stored as variables (ranging from simple booleans and integers to floats and double floats), which are converted into a binary format for UDP transmission. To avoid the time-consuming process of resizing packets with each addition of a new variable, a method of using placeholder variables is employed. These placeholders can be allocated as needed for specific experiments or features, significantly reducing the need for frequent structural changes and thereby enhancing the FSS's capability for rapid prototyping and flexibility during engineering sessions.

Modularity

One of the key features of the FSS is its portability – it is possible to create a desktop version of the simulator in a short time. It is easy to compile an executable for a specific layout, which can be transferred between target computers. The inceptors are off-the-shelf, plug-and-play devices that only need to be remapped in the Unity interface, except for the throttle; however, the HMI software can also accommodate a regular plug-and-play throttle device. The aircraft models are developed using MATLAB/Simulink, which means they can be compiled independently of dSPACE RTC on a regular PC provided it has sufficient processing power to handle the mathematical complexity of the chosen aircraft model. The simulator can be reconfigured for single-pilot or remote-operator setups, as seen in Fig. 6.

Mechanical Construction

The mechanical construction of the FSS is designed with high modularity to accommodate various experimental scenarios. The cockpit features a versatile seating arrangement where seats can be positioned along one of three rails (left, centre, and right), with each position having an associated slot for rudder pedals.

Furthermore, the sidestick and throttle controls are mounted on a base that can be connected to eight slots, as illustrated in Fig. 7. These slots, covered with metallic plates in the figure, provide flexibility in the placement of control inceptors. Each slot is equipped with dedicated power and USB connections to ensure seamless integration with the PC. Such an arrangement supports the rapid reconfiguration of the cockpit layout.

The cable management system is meticulously organised, as depicted in the fragment of the cable reference document in Fig. 8. This document outlines how each cable, numbered and colour-coded, connects various components within the simulator. It ensures that modifications and maintenance can be made efficiently without disrupting the overall system functionality. For instance, cables are designated

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

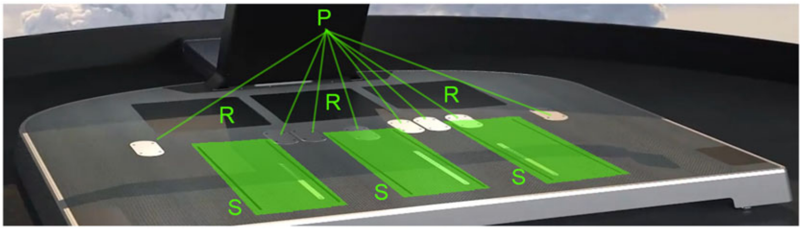


Figure 7. *A design render with the base of the FSS cockpit. It shows the slots for cockpit reconfiguration. The eight slots for throttle and sidestick pedestals are marked with "P", slots for rudder pedals are marked with "R", and rails for seats are marked with "S" and green overlay.*

RR91 Cable Reference Document

from	to	Cable ID	Description	Route	Notes
1	28	1-USB-3M-1-28	USB-A Female to USB-A Male 3m	From Left Side Stick (Dual pilot config) to USB HUB #2&3 (in Lower Pedestal)	None
1	26	2-DC24-3.5M-1-26	Bulgin 2 Pole Female to Screw Terminal Male 3.5m	From Left Side Stick (Dual pilot config) to 24V DC Supply (in Upper Pedestal)	None
■					
■					
■					
13	27	54-DC20-2M-13-27	5.5mm Barrel Jack Male to Screw Terminal Male 2m	From Right 4k Screen to 20V DC Supply #4 (in Upper Pedestal)	4k Screen Power
29	30	55-AC-5M-29-30	Screw Terminal Male to Caravan Plug Male 5m	From Consumer Box to Rear of screen	Mains power supply 16A min

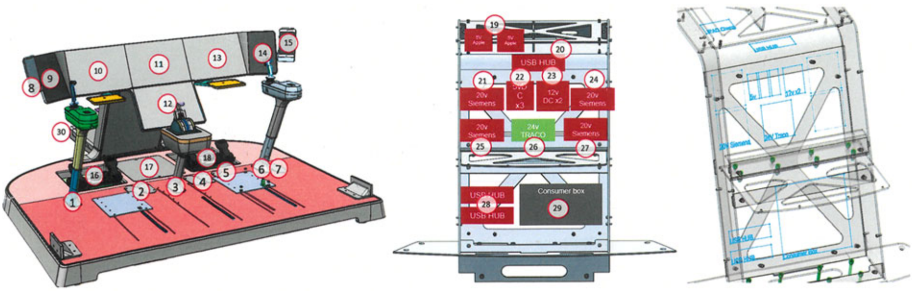


Figure 8. *A fragment of cable reference document outlining the connections for the FSS cockpit.*

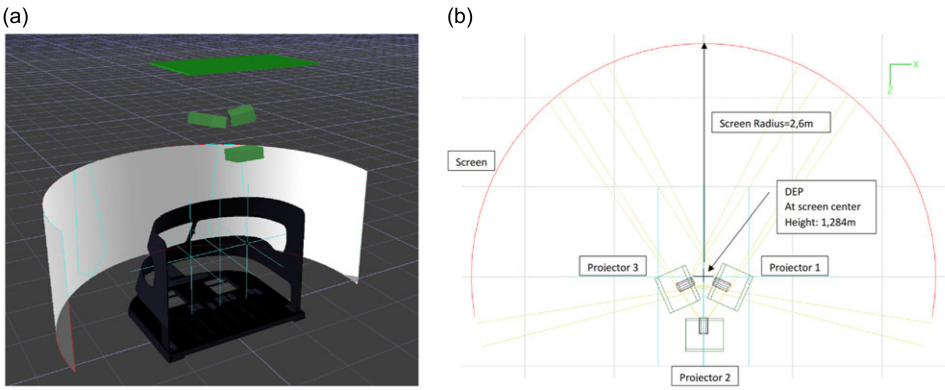
to specific slots on the base, facilitating quick changes in the hardware setup while maintaining reliable electrical and data connections.

Visual System

Data representation is a key aspect of the complete integration of the human-in-the-loop within the modelling and simulation of any technology. The academic and industrial nature of the FSS vision demanded the creation of an immersive sensorial environment for pilots in order to become another means to use and validate the data effectively. For this reason, a multi-projector visual display was combined with a cylindrical screen to create an enclosing atmosphere within the cockpit, supported by the flexibility of the FlightGear Flight Simulator for image generation. The outside simulation display architecture is presented in more detail in Section.

FlightGear Integration. Currently, the three most commonly used desktop-based COTS flight simulators are Microsoft Flight Simulator (MSFS), Laminar Research X-Plane (XP), and open-source FlightGear Flight Simulator (FGFS) [35]. FSS required a visual system that was realistic enough to immerse the pilots in their tasks. The FGFS was chosen for this purpose. This open-source flight simulator supports the flexibility and adaptability required by the FSS in both industrial and academic

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press



3D view perspective of projector setup. System plan view of projector setup.

Figure 9. *Different views of the projector setup in the FSS.*

environments. FGFS has been developed as a highly configurable tool that allows simultaneous integration with multiple external software and hardware setups. The FGFS built-in flight dynamic model has been entirely substituted by the in-house models through the network communication of the internal states of the aircraft. Such an interface further enables reconfiguration to easily replace the aircraft model to be flown in each scenario. Moreover, FGFS also supports multi-screen visualisation, which has been configured to agree with the FSS's multi-projector setup and Design Eye Points. Additional FGFS capabilities are used to tailor the test requirements to each simulation scenario. For instance, manipulation of weather conditions can be crucial to replicate scenarios for model and data validation. FGFS provides various means to either control weather at specified regions or to interpret METAR[4] reports around the given airfield. Another feature to be implemented in the FSS is the ability to have air traffic. Three-dimensional objects can be placed as dummy aircraft at any arbitrary location in the scenery. Alternatively, the networked multiplayer feature will expand the FSS research capabilities by enabling interaction with other aircraft flying in other flight simulators at CU in scenarios such as formation flight or air-to-air refuelling. As an alternative, the FSS can also support integration with the XP flight simulator.

Projectors Setup. The visual display system of the FSS consists of three ceiling-mounted Optoma EH515TST projectors and a cylindrical screen provided by 3D Perception.[5] This includes a multichannel image processor and display manager with a user-friendly interface for system setup, control, and maintenance. The screen is a 2.6m radius by 2.1m height cylinder with a 1.0 gain HD progressive surface to improve edge blending around the curvature. This setup provides a projection with a 200° horizontal field of view (FoV) and a $+21^\circ/-22^\circ$ vertical FoV for full coverage from both Design Eye Points inside the cockpit, which can be seen in Fig. 9.

The projection is enhanced by a 3D Perception nBox display processor, which receives the video signal from the Scenery PC and performs re-alignment, colour calibration, warping, and blending onto the screen. The nControl management software centralises the control and maintenance of the entire display system to ensure consistent, high-quality visualisation for any cockpit seating configuration or represented flight scenario.

[4]Meteorological Terminal Air Report.
[5]3d-perception.com.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

3.3.1 Hardware specification

The hardware specifications for the HMI and visual display systems of the FSS are designed to meet the demands of a high-fidelity, high-frame-rate training environment. The use of state-of-the-art gaming PCs and advanced displays ensures that the FSS can provide a realistic and engaging experience for pilots.

The HMI of the FSS consists of 2D graphics displayed on six 4K LG screens and two HD screens. Four of the 4K screens are part of the cockpit, and two are used for the development station. The six touchscreen panels in the cockpit allow for full flexibility and customisation. Four of the screens (two central and two "main-side") are 21.5-inch monitors with a resolution of $4,096 \times 2,304$ pixels, and the other two (situated on the left and right far sides) are vertically mounted 13.3-inch monitors with a resolution of $1,920 \times 1,080$. The FSS uses Huawei VR2 cables to transmit video data from DisplayPort outputs on the GPUs to USB-C inputs on the monitors. The PC that runs the HMI is a bespoke system from Renda Solutions[6] designed specifically to meet the FSS requirements. It is water-cooled for quiet operation and consists of:

- Graphics cards: 2x ASUS GeForce RTX 2080 Ti Turbo 11GB GDDR6
- Memory: 4x 8GB DDR4
- Motherboard: Asus ROG Maximus XI Hero Intel Z390 DDR4 ATX
- Processor: Intel Core i9-9900KS 5.2GHz

To generate the outside world imagery, the FSS uses either FGFS or XP on a state-of-the-art gaming PC equipped with:

- Graphics card: MSI GeForce RTX 3090 Ti Suprim X 24GB GDDR6X
- Memory: G.Skill Trident Z5 Neo 64 GB (2x 32GB) DDR5-6000 CL30 Memory
- Motherboard: Gigabyte X670E AORUS MASTER
- Processor: AMD Ryzen 9 7900X 4.7 GHz 12-Core

The visual display system in a flight simulator is a critical component that plays a significant role in creating a believable and immersive training environment for pilots [19, 36–38]. To achieve this, the visual display system must have a fast and powerful processor and graphics card that can support a high refresh rate. This helps to reduce latency and improve the sense of immersion by allowing the visual display to update quickly and smoothly in response to the pilot's actions and movements. This is especially important in situations where the pilot needs to make rapid and precise movements, such as during emergency procedures.

3.4 Simulation operation

This section outlines the operational procedures of the FSS, emphasising the integration and management of software components that enable efficient simulation.

Software Management

The software management of the FSS is designed to be intuitive, allowing researchers to set up the entire simulation quickly. A comprehensive operation manual is provided, detailing each step required to initiate and run the FSS effectively. The setup process involves powering on the necessary PCs; the HMI and the dSpace/aircraft model management + Scenery PC are essential, while the Instructor Operating Station (IOS) PC is optional for a minimal configuration.

[6] www.overclockers.co.uk/renda-solutions

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

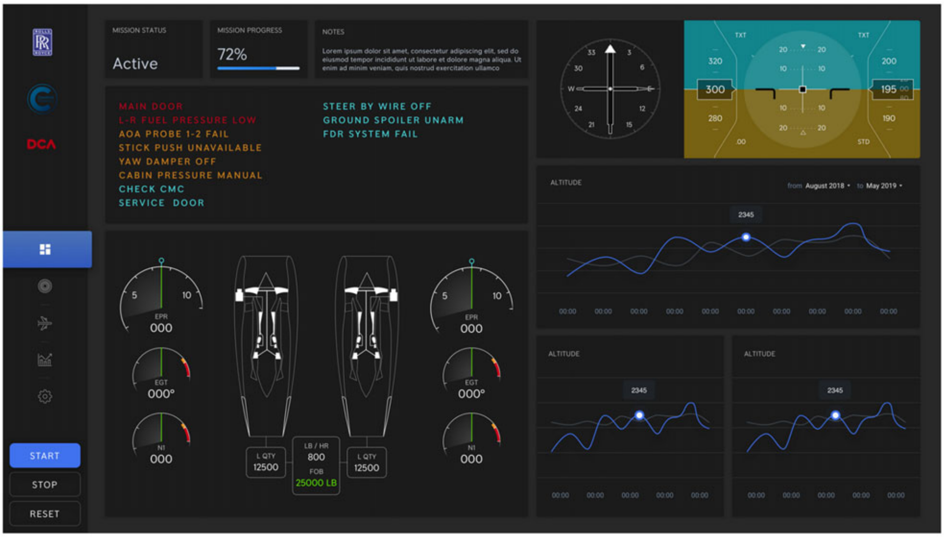


Figure 10. *A design concept for the Instructor Operating Station interface.*

Once the PCs are activated, the flight deck layout executable (spanning across all connected cockpit monitors) can be launched directly from a single desktop shortcut on the HMI PC. Aircraft models are managed on the dSpace/aircraft model management + Scenery PC using the dSpace ConfigurationDesk software, where each aircraft model is maintained as an individual project. These can be swiftly loaded into the dSpace hardware, ready for simulation. The same PC runs a single instance of either FlightGear or X-Plane, outputting to three connected projectors. Both visual systems are pre-configured to deactivate their internal flight dynamics models and to await external data via UDP packets, ensuring they integrate seamlessly with the FSS setup.

Projectors may be activated manually with a remote or automatically through a script executed from one of the PCs. The system components, including the HMI, visual system, and IOS, are operational but will not display updated information until they receive the corresponding data packet from the dSpace system. The simulation works when the model is started from the dSpace ConfigurationDesk software. During the experiment execution, the model does not need to be restarted between the sessions, as a reset signal can be sent from the HMI or IOS.

Instructor Operating Station

The Instructor Operating Station (IOS) allows the operator to control various aspects of the simulation process in the FSS, such as changes in the daytime, weather conditions, other traffic, and flight parameters. The interface is presented in Fig. 10. The IOS also allows the researcher to turn data recording on or off by sending commands to the aircraft simulated model.

The engineering station provides an overview of all aircraft systems and data coming through the simulator. Images from the synoptic pages can be transmitted to a remote control room for monitoring the simulation. The FSS provides multiple views, including HMI displays, video streams from the cockpit (front view of the pilots and rear view of the whole cockpit), live data graphs, and raw text data.

The data from the FSS can be live-streamed over the network, allowing observers and researchers around the world to see the simulation in real time. This can be in the form of graphs, plots, flight deck instrument streams, video, or raw data.

Data Collection

All aircraft model and pilot input data are logged on the IOS station at a sample rate of 50Hz. There are two cameras (or potentially more) that can record the research trials for supplemental discussion (for example, gesture behaviour analysis, a general posture of the pilot, or verbal feedback). There is also a microphone for audio logging. In order to gain insight into HF and ergonomic aspects of the HMI, an eye tracker can be connected to record the gaze positions of the pilot's eyes.

3.5 Classification and limitations

The FSS is an engineering flight simulator that has been designed to provide a high level of fidelity in the research of aircraft systems, environments, and scenarios. Although it was not tested by the European Aviation Safety Agency's (EASA) authority, according to commercial flight simulator definitions and standards [39], the FSS aims to represent a "flight training device" (FTD) Level 2. This means that it is a simulator that is capable of providing training for specific tasks or manoeuvres, such as takeoff and landing, as well as evaluating the performance of pilots and other crew members. Moreover, the FSS also has many features that represent the description of a "full flight simulator" (FFS) Level A and B [39]. For example, the FSS has a high-fidelity visual system, a realistic cockpit layout (albeit represented as touchscreen counterparts), and advanced software and hardware systems that can simulate a wide range of aircraft systems and technologies. This allows the FSS to provide an immersive and comprehensive experience that closely mimics the real-world conditions of flying an aircraft. It should be emphasised that EFSs usually do not aim to meet traditional flight simulator classifications typically required for pilot certification and training hour logging. While the FSS may exhibit some features found in certified simulators, achieving such classifications is not essential for its intended purpose as an engineering tool. The primary objective of the FSS is to support research and development in aerospace engineering, not to log pilot training hours.

The FSS has a fixed base and does not include a motion system. This decision was made based on research showing that motion systems are not necessary for flight simulators to be beneficial in research and training, especially when the main focus is on human factors [25, 40, 41]. Motion systems are only necessary when the aircraft response characteristics are very sensitive and rapid [42], and they can be beneficial for novice pilots training [43]. Additionally, integrating a motion platform with the FSS could introduce substantial financial overhead, problems with cable connections and touchscreen durability, and it would require more maintenance and technical support due to health and safety regulations.

However, the FSS includes limited motion cues in the form of special seat pads to simulate vibrations (for example, caused by an engine's fan damage). This allows to simulate certain aspects of motion without the need for a full motion system.

4.0 CASE STUDIES

The capabilities of the FSS are exemplified in this section through a range of case studies. Emphasis is placed on how the FSS's advanced features and configuration flexibility have been harnessed to achieve significant insights in aerospace research. The case studies are chosen to illustrate how vital the simulator has been in validating new technologies and concepts, particularly in the domains of aircraft systems integration, human factors, and novel control methodologies. The importance of a simulation environment of such high fidelity is showcased, providing a platform for both academic exploration and practical innovation within the aerospace industry.

Powerplant Integration of Novel Engine Systems

The Powerplant Integration of Novel Engine Systems (PINES) project represents a ground-breaking collaboration in the realm of aviation propulsion systems. This joint initiative, spearheaded by Rolls-Royce, harnesses the collective expertise of esteemed academic partners, including CU, the University of Oxford, the University of Nottingham, and the University of Sheffield. It also boasts the active participation of industry leaders such as Meggitt Aerospace and HiETA Technologies [44].

The primary objective of the PINES project is to address the formidable challenges posed by cutting-edge propulsion systems like the UltraFan, Green Regional, and High Mach architectures. These innovations introduce complex heat management issues, necessitating the development of novel and integrated technologies optimised at the system level. These technologies encompass enhanced predictive capabilities for heat management systems, the optimisation of thermal performance across components, powerplants, and platforms, as well as the creation of innovative air and sensor systems with advanced control functionalities. The overarching aim is to not only enhance performance but also reduce through-life operational costs.

The PINES project is poised to deliver these advancements to platforms slated for entry into service around 2027. Notably, within this comprehensive effort, the FSS is actively used in *Intelligent Engine Technologies* research [2], contributing to drive innovations in aircraft integrated control concepts.

Open Flight Deck

Open Flight Deck is a consortium-led project involving industrial and academic partners with the aim of creating the world's most advanced flight deck. Aircraft have been in service for decades, but there is a huge barrier to adopting new flight deck technology due to the high cost of change and certification. This project aims to future-proof the flight deck by creating an open architecture platform to continuously deliver the latest advances in computing, networking, cloud-based services, AI and automation - enabling aircraft manufacturers to build and customise their own flight deck [45].

Ensuring proper integration of human factors consideration when defining such features is an essential part of the design process. Through OFD, Rolls-Royce has been able to engage with human factors experts at Southampton University to develop human-machine interfaces/applications, as well as define the test and validation scenarios using the FSS facility [46]. Implementation of these interfaces and applications using the GE Open Toolchain has enabled Rolls-Royce to act as a third-party application developer on the flight deck.

Alternative Inceptors and Human Factors Study

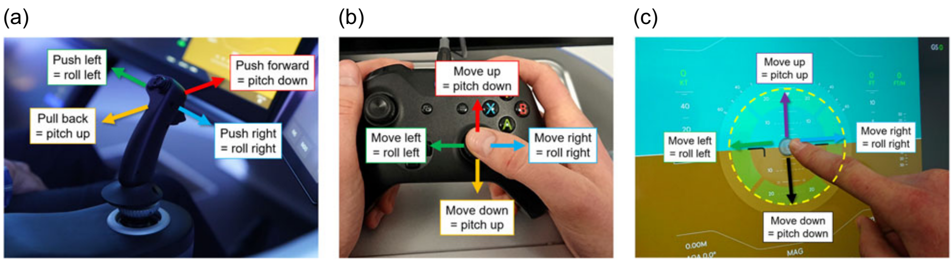
This case study presents the use of the FSS for research and validation of novel inceptors for aircraft control. The study's aim was to explore potential alternative inceptors in contrast to conventional sidesticks [47–49].

Background. Touchscreen technologies are increasingly deployed in cockpit environments, with urban air mobility sparking further interest. The author identified a research gap in inceptor design, which led to the formation of hypotheses regarding the performance impact of alternative inceptors, the effectiveness of an engineering flight simulator in research, and the influence of human factors.

Methodology. A doctoral thesis proposed investigating two alternative inceptors, a gamepad and a touchscreen, evaluated against a traditional sidestick. The control philosophy for each of the inceptors is shown in Fig. 11. The Y axis of the touchscreen controller was inversed on purpose, based on feedback from initial pilot trials and "move-where-you-point" design. FSS facilitated the comparison through simulated flight scenarios such as disturbance rejection and landings. Participants' performance was objectively measured considering recorded flight data (using a custom equation to calculate performance score (PS) based on spatial and temporal data), while their subjective experiences were assessed in terms of workload, situation awareness, and usability.

Results and Discussion. Statistical analysis revealed that the gamepad outperformed other inceptors but was less favoured in terms of usability, particularly by professional pilots. While the touchscreen showed promise in usability and learnability, it was not yet considered a viable aircraft control alternative. The use of FSS proved essential in obtaining credible results. Moreover, significant differences in

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press



Sidestick. Gamepad. Touchscreen controller.

Figure 11. *Control philosophy for each of the inceptors in the study.*

participants' performance based on flight experience (shown in Fig. 12) underscored the importance of human factors.

Conclusion. This research contributes to our understanding of alternative inceptors and emphasizes the role of engineering flight simulators like the FSS in such investigations. The insights gained may guide future aviation research, particularly around human factors and the adoption of new technologies in cockpit design.

Eye Tracking Study

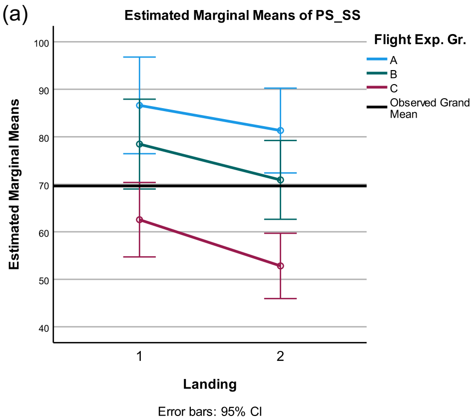
Background. Touchscreen interfaces on flight decks present a promising integration of control and display functions, offering the potential of enhanced system coherence and simplified updates [50]. However, the transition to touchscreen use in aviation necessitates consideration of its impact on pilot workload and human-computer interaction. Concerns regarding the accuracy of touch inputs in response to vibrations are being addressed by ongoing research [51]. The use of eye-tracking technology allows for a detailed examination of pilots' scan patterns and attention distribution, providing insights into their cognitive processes and situational awareness during flight operations [52]. Despite the challenges, the compelling advantages of touchscreen controls underscore the need for more research in their development, supporting the notion that they could reshape future pilot interaction within the cockpit environment.

Methodology. The FSS was used as an experimental environment to investigate the effects of innovative touchscreen controls on pilot interaction and cognitive workload. Eye-tracking technology was employed to analyse pilot visual behaviour by designating four areas of interest (AOIs) for gaze analysis: primary flight display (PFD), navigation display (ND), checklist display (CD), and central upper display (CUD) (Fig. 13). Both objective measures of situation awareness (SA) and subjective assessments using the System Usability Scale (SUS) were conducted. Twelve professional pilots participated in the study.

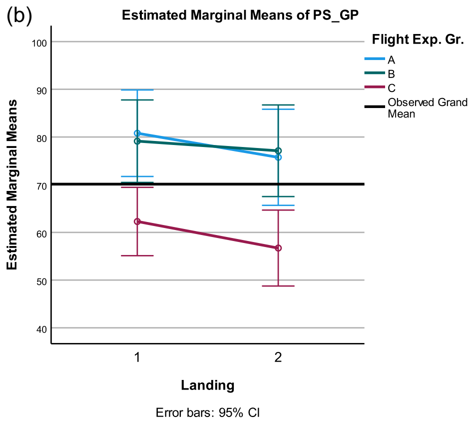
Participants completed two instrument landing sessions – each pilot acted as pilot flying (PF) and pilot monitoring (PM), interchangeably – to essentially distinguish between the tasks of aircraft control and system monitoring. Crucially, the FSS's adaptable architecture allowed for easy configuration and monitoring of eye trackers and AOIs, facilitating precise data collection particularly critical in the assessment of human-computer interactions (HCI).

Results and Discussion. The paired t-test analyses showed significant differences between the roles of PF and PM in visual parameters such as fixation count, fixation duration, and pupil dilation, particularly when interacting with the CD and CUD (Fig. 14, left). This demonstrates the FSS's capability to differentiate behavioural responses to the HCI design elements of the simulator.

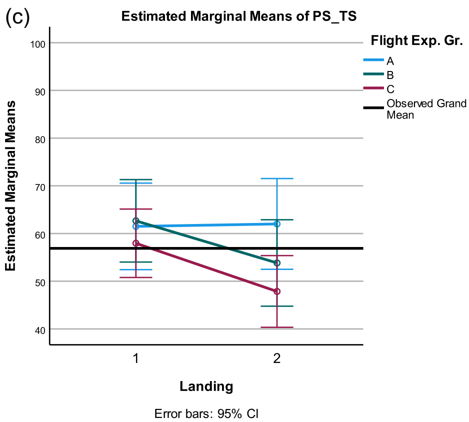
https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press



Sidestick (SS).



Gamepad (GP).



Touchscreen controller (TS).

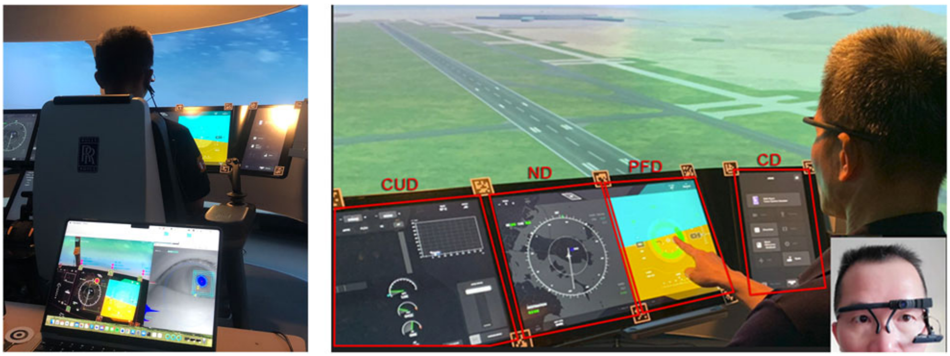
Figure 12. *Estimated marginal means for performance score (PS) using each inceptor, showing differences between two landings (with and without disturbance) within each flight experience group. Flight experience groups are coded "A" for highly experienced pilots, "B" for less experienced pilots, and "C" for non-pilots. Landings are coded "1" for landing without disturbance and "2" for landing with disturbance.*

Fixation behaviours exhibited by PFs and PMs indicated that PFs focused significantly more on the PFD – a critical display for flight control – while PMs distributed their visual attention across multiple displays due to their monitoring responsibilities (Fig. 14, centre and right). The resulting heatmaps from the data (Fig. 15) graphically underscored these findings and provided insight into attention allocation, supplementing the quantitative data with a visual analysis tool that could importantly guide the ergonomic design of future flight decks.

Subjective assessments via the SUS revealed that PFs rated the system usability lower compared to PMs, reflecting the need for improved touch interaction feedback that the PFs' active control role necessitates. These user experience insights corroborate the necessity for a tactile element in flight deck design, especially when considering the transition from conventional controls to touchscreen interfaces. A deeper analysis is disseminated by Li et al. [53].

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

(a) (b)



Eye tracker setup in the FSS.

Participant wearing an eye tracker in the FSS interacting with four main touchscreen displays marked as red colour on final approach.

Figure 13. *Eye tracker setup and usage in the FSS.*

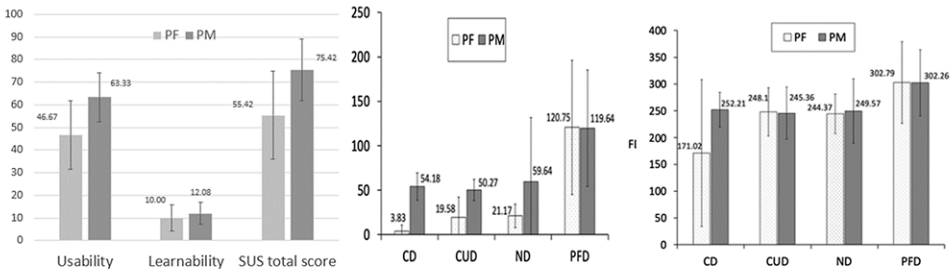


Figure 14. *PFs and PMs' assessment on the system usability of the touchscreen (left); fixation counts among four touchscreens (centre); fixation duration (ms) among four touchscreens (right) while performing instrument landing on FSS.*

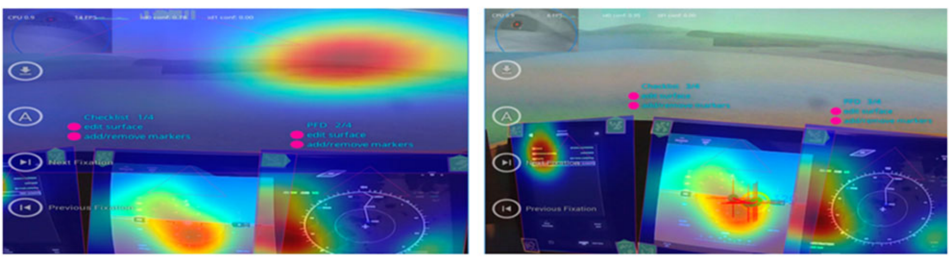


Figure 15. *Heatmaps of PFs' visual attention mainly focused on the runway, PFD and CUD (left); PMs' visual attention was moving among four touchscreens (AOIs) in the flight deck on instrument landing scenario (right).*

Utilisation of FSS for Relevant Research Outcomes

The use of the FSS was instrumental in obtaining these insights due to its open and flexible design, which allowed seamless integration of the eye-tracking equipment. The simulation capabilities of the FSS also enabled a controlled setting where the pilots' interactions with the simulation environment could be meticulously recorded and analysed. The ability to define and adjust AOIs within the setup

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

facilitated the comparative analysis across different pilot roles, making the FSS an invaluable tool for exploring touchscreen efficacy and its implications on pilot workload and HCI.

The research conducted within the FSS platform underscores the symbiotic relationship between advanced simulator technology and the fine-grained analysis required for HCI research in aviation environments. Therefore, we emphasise the FSS's importance not only in the context of its sophisticated simulation features but also in its facilitation of high-fidelity data collection, offering a replicable and informative tool for advancing cockpit interface design.

This study aligns the HCI considerations within flight operations with evolving aviation technology, situating the FSS as a critical avenue for research that integrates the human-centred design principle from the early stages of flight deck development. The findings signify the necessity of incorporating human factors considerations into the future of touchscreen interface design in aviation, advocating for a user-experience-centred approach that the FSS aptly supports.

Other Research Applications of the FSS

eVTOL/Hybrid Aircraft Interfaces. The FSS has been employed in a pioneering approach to design and test a novel HMI display tailored for electric and hybrid vehicles, utilising a "rapid prototyping" methodology. During intensive workshops, feedback from pilots was gathered, allowing iterative design adjustments to be made swiftly. The specifics of these outcomes remain undisclosed pending publication, but this work highlights the FSS effectiveness in developing new HMI layouts for futuristic aircraft. Additionally, the FSS has facilitated a study focussing on the handling quality assessment of an eVTOL aircraft.

E-PILOTS Project. In the realm of advancing pilot-machine interaction, the Clean Sky 2 joint undertaking funded E-PILOTS (Evolution of cockPIt operations Levering on cOgnitive compuTing Services) project [54] has capitalised on the modular nature of the FSS. The project's objective is to delve into the intricate dynamics of Human/Machine task sharing to integrate cognitive computing, thereby creating adaptive automation to augment pilots. Within this context, the FSS serves as a crucial experimental environment for validating concepts of single-pilot operations using an Airbus A320 model [55].

TRANSIT Project. The TRANSIT (Towards a Robust Airport Decision Support System for Intelligent Taxiing) project, a collaboration between several UK universities and endorsed by a consortium of industrial partners, is geared towards revolutionising airport routing and scheduling systems. Through the backing of the UK EPSRC (grant numbers EP/N029496/1, EP/N029356/1 and EP/N029577/1), this initiative strives to create a system that is more realistic, robust, and cost-efficient, ensuring better conformance to 4 Dimensional Trajectories for airport taxiing strategies. The functionalities of the FSS have been leveraged as a vital tool to validate and refine these taxiing strategies within the scope of the project.

5.0 RECOMMENDATIONS AND LESSONS LEARNED

In the process of developing the FSS, multiple complexities inherent to engineering flight simulator construction were encountered. Emphasis was laid on the importance of incorporating a comprehensive perspective on the design's many facets, ranging from hardware specifications to human factors considerations. It was recognised that foresight in delineating hardware requirements is crucial, critically assessing network architecture, including the PC physical positioning and the selection of cable types and lengths.

On the software front, the development of a coherent and modular system was achieved by utilising specially designed graphical user interface elements for the HMI. This approach ensures a streamlined and maintainable software infrastructure. For commercial flight simulation software developers, such as those behind Microsoft Flight Simulator, the authors recommend to facilitate the easy integration of external flight dynamic models. The adaptation would enable these platforms to serve as advanced visual cueing systems, thereby fostering the software's embrace within academic research environments and according to the insights presented by Takeda et al. [35].

Through the developmental iterations of the FSS, adopting a phased approach to system complexity was found to be advantageous. Starting with the most simplified representations and incrementally incorporating complexity allowed for more effective tuning and alignment with the simulator objectives. This was particularly evident in control system implementations, where initial strategies based on proportional control often sufficed, with integral and derivative controls introduced only when necessary. Notably, integral control could introduce cumulative numerical errors over extended simulations, and its application warranted cautious deployment, potentially with timed resets to mitigate performance issues.

Lastly, valuable time invested in refining the inner-loop command and stability augmentation systems alongside experienced pilots yielded significant dividends. Fine-tuned inner-loop controls were observed to greatly enhance the performance of autopilots and outer-loop controllers, culminating in a superior flight simulation experience.

6.0 CONCLUSIONS

Flight simulation technology has evolved at an immense pace, achieving greater realism in visual systems and more intricate pilot-cockpit interaction coupled with accurate real-time aircraft model simulations. Previous studies have shown that the engineering flight simulation discipline has not been recognised enough in aerospace-themed academic fields [7], and the collaboration between universities and centres around the world is crucial in advancing the aviation industry [56]. Having state-of-the-art simulators available for students and seeing the amount of research carried out on them just in the last few years proves that it is essential for flight simulation to be included in research programmes, and the FSS brings a great contribution to this need becoming a reality.

Oberhauser and Dreyer highlighted that while high-fidelity "engineering mock-up" simulators offer detailed realism, they fall short in terms of flexibility compared to desktop simulators [57]. The FSS, however, challenges this notion by integrating a fully flexible human-machine interface (HMI) design and physical flight deck elements. This solution allows for modifications at advanced stages of research without impacting the overall timeline of the project. This level of adaptability, especially in making swift interface changes, sets the FSS apart from most contemporary flight simulators. Modifications in other simulators often require extensive time investment and a deeper understanding of low-level programming and computer graphics. Moreover, unlike previous simulators constrained by their adherence to existing aircraft layouts, the Future Systems Simulator brings a revolutionary modular approach, enabling rapid prototyping and evaluation of innovative flight deck designs and user interfaces, as well as the examination of aircraft system safety and reliability. The FSS's adaptability has fostered research across traditional multi-crew and single-pilot operations and novel eVTOL configurations. Earning an International iF Design Award [58], the FSS cockpit has been prepared with a focus on clarity, precision, and efficiency, guided by design philosophies that emphasise approachability, lightness, and adaptability, earning considerable acclaim from leading UK flight simulation entities.[7]

The simulator does not use commercial off-the-shelf (COTS) flight dynamic models, rather it uses custom, in-house built aircraft models developed from actual aircraft data, fostering educational transparency and enabling the creation of accurate models for the FSS, validated with the help of professional licensed pilots. This hands-on approach enhances model validation and student learning. Real-time

[7] BAE Systems representative, personal communication, August 2022; Flight Simulators UK representative, personal communication, September 2022.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

computer hardware within the FSS allows for future expansion, including hardware-in-the-loop simulations and testing of emergent power systems and energy storage under flight conditions through aerospace standard communications protocols. The FSS's highly adaptable cockpit, equipped with advanced touchscreens and a modern interface, also retains the capability to replicate existing cockpits with operational familiarity for pilots in studies. This versatility, along with a comprehensive default HMI based on a business jet cockpit, offers an invaluable research asset for a multitude of aviation scenarios.

Case studies have underscored the FSS effectiveness, showcasing its utility in exploring single-pilot operations, alternative control methods [47, 49, 59], and innovative eVTOL pilot interfaces, among others, often corroborated by eye-tracking technology [14, 53, 60]. These examples not only demonstrate its robust research capabilities but also its role in generating scientifically significant insights through early user engagement. The FSS has established itself as an indispensable tool for aerospace education, research, and development, enhancing safety and efficiency with its forward-looking features and adaptable nature.

In distinguishing itself from other HMI-centred simulators, the FSS integrates exceptional flexibility and customisation capabilities that are not commonly found in the field. It has been specifically designed to accommodate the swift incorporation of feedback during pilot testing sessions, which is facilitated by its unique modular construction and real-time data handling. This allows the FSS to not only adapt to new configurations rapidly but also to implement changes and innovations without the downtime typically required for reprogramming or hardware adjustments. Moreover, the FSS's commitment to using in-house developed, high-fidelity models instead of relying on conventional COTS solutions sets a new standard in simulation accuracy and provides unparalleled opportunities for academic research and practical training. These distinctive features make the FSS a pioneering tool in the evolution of flight simulation technology, offering both researchers and trainers a more dynamic and responsive platform than those currently available globally. This visionary approach has positioned the FSS at the forefront of contemporary aerospace research, particularly in the development and testing of next-generation aircraft systems and training protocols.

Acknowledgements. The authors would like to thank Rolls-Royce Plc for allowing research studies to be carried out in the Future Systems Simulator.

Financial support. Research co-financed by Rolls-Royce through Open Flight Deck project (UKRI project ref. no. 113108) and Powerplant Integration of Novel Engine Systems (PINES) (UKRI project ref. no. 113263/project no. EDNS01000925787), and European Union through the European Social Fund (grant POWR.03.02.00-00-I029).

Competing interests. The authors declare none.

References

[1] McDonald, R.A., German, B.J., Takahashi, T., Bil, C., Anemaat, W., Chaput, A., Vos, R. and Harrison, N. Future aircraft concepts and design methods, *Aeronaut. J.,* 2022, **126**, (1295), pp 92–124. ISSN: 0001-9240. doi: 10.1017/aer.2021.110.

[2] Rolls-Royce plc. IntelligentEngine: Our vision for the future of aircraft power. Accessed 2023-11-21, 2020. https://www.rolls-royce.com/media/our-stories/discover/2020/intelligentengine-explainer.aspx.

[3] Finger, D.F., Braun, C. and Bil, C. A review of configuration design for distributed propulsion transitioning VTOL aircraft, 2017 Asia-Pacific International Symposium on Aerospace Technology October, 2017, pp 1782–1796.

[4] Alba-Maestre, J., Prud'homme van Reine, K., Sinnige, T. and Castro, S.G.P. Preliminary propulsion and power system design of a tandem-wing long-range eV-TOL aircraft, *Appl. Sci.*, 2021, **11**, (23), p 11083. ISSN: 2076-3417. doi: 10.3390/app112311083.

[5] Darrah, D., Moorthamers, B., Anemaat, W. and Liu, W. Modeling and optimization of propulsion systems for eVTOL aircraft, Proceedings of the Vertical Flight Society 78th Annual Forum, The Vertical Flight Society, May 2022, pp 1–5. doi: 10.4050/F-0078-2022-17489.

[6] Nasoulis, C., Gkoutzamanis, V. and Kalfas, A. Multidisciplinary conceptual design for a hybrid-electric commuter aircraft, *Aeronaut. J.*, 2022, **126**, (1302), pp 1242–1264. ISSN: 0001-9240. doi: 10.1017/aer.2022.32.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

[7] Allerton, D.J. The impact of flight simulation in aerospace, *Aeronaut. J.*, 2010, **114**, (1162), pp 747–756. ISSN: 00019240. doi: 10.1017/S0001924000004231.
[8] Lavelle, T.M., Plencner, R.M. and Seidel, J.A. Concurrentoptimization of airframe and engine design parameters, 4th Symposium on Multidisciplinary Analysis and Optimization, 1992, American Institute of Aeronautics and Astronautics, 1992, Reston, Virigina. doi: 10.2514/6.1992-4713.
[9] Drela, M. Simultaneous optimization of the airframe, powerplant, and operation of transport aircraft, RAeS 2nd Aircraft Structural Design Conference, 2010, pp 1–24.
[10] Chai, X., Yu, X. and Wang, Y. Tradeoff study between cost and environmental impact of aircraft using simultaneous optimization of airframe and engine cycle, *Int. J. Aerospace Eng.,* 2017, **2017**, (1), pp 1–10. ISSN: 1687-5966. doi: 10.1155/2017/2468535.
[11] Early, K. Propulsion airframe integration design, analysis and challenges going into the 21st century, *Aeronaut. J.*, 2000, **104**, (1038), pp 375–382. ISSN: 0001-9240. doi: 10.1017/S0001924000064010.
[12] Martinez-Val, R., Roa, J., Perez, E. and Cuerno, C. Effects of the mismatch between design capabilities and actual aircraft utilization, *Journal of Aircraft*, 2011, **48**, (6), pp 1921–1927. ISSN: 0021-8669. doi: 10.2514/1.C031348.
[13] Billings, C.E. Aviation Automation: The Search for a Human-Centered Approach, CRC Press, Boca Raton, Florida, USA, 2018.
[14] Korek, W.T., Mendez, A., Asad, H.U., Li, W.-C. and Lone, M.M. Understanding human behaviour in flight operation using eye-tracking technology, in *Engineering Psychology and Cognitive Ergonomics. Cognition and Design. HCII 2020*, Lecture Notes in Computer Science, Harris, D. and Li, W. (Eds), vol. **12187**, Springer International Publishing, 2020, pp 304–320. doi: 10.1007/978-3-030-49183-3\24.
[15] Golding, R.J. Flight simulation at Cranfield Institute of Technology, *Aeronaut. J.*, 1980, **84**, (835), pp 236–237. doi: 10.1017/S0001924000031183.
[16] GE Aviation, BAE Systems, Rolls-Royce plc., Coventry University, and University of Southampton. Open Flight Deck, 2018. https://openflightdeck.co.uk/.
[17] Coutts, L.V., Plant, K.L., Smith, M., Bolton, L., Parnell, K.J., Arnold, J. and Stanton, N.A. Future technology on the flight deck: assessing the use of touchscreens in vibration environments, *Ergonomics*, 2019, **62**, (2), pp 286–304. ISSN: 13665847. doi: 10.1080/00140139.2018.1552013.
[18] Banks, V.A., Allison, C.K., Plant, K.L., Parnell, K.J. and Stanton, N.A. Using the perceptual cycle model and schema world action research method to generate design requirements for new avionic systems, *Hum. Factors Ergon. Manuf. Service Ind.*, 2021, **31**, (1), pp 66–75. ISSN: 1090-8471. doi: 10.1002/hfm.20869.
[19] Allerton, D. *Principles of Flight Simulation*, Wiley, 2009, pp 1–471. ISBN: 9780470754368. doi: 10.1002/9780470685662.
[20] May, J., Doebbler, J. and Valasek, J. Simulation architecture development of a distributed multi-pilot engineering flight simulation facility, AIAA Modeling and Simulation Technologies Conference and Exhibit, Reston, Virigina, American Institute of Aeronautics and Astronautics, 2008, pp 1–7. ISBN: 978-1-62410-000-0. doi: 10.2514/6.2008-6348.
[21] University of South Wales. Engineering Flight Simulator. Accessed 2024-05-13. 2023. url: https://www.southwales.ac.uk/courses/bsc-hons-aircraft-maintenance-engineering/3950/engineering-flight-simulator/.
[22] Blake, M.W. The NASA advanced concepts flight simulator: a unique transport aircraft research environment, 1996 Flight Simulation Technologies Conference, 1996, pp 385–392. doi: 10.2514/6.1996-3518.
[23] Deutsches Zentrum für Luft- und Raumfahrt. Air Vehicle Simulator (AVES). Accessed 2024-05-14, 2024. https://www.dlr.de/en/research-and-transfer/research-infrastructure/air-vehicle-simulator.
[24] Duda, H., Gerlach, T., Advani, S. and Potter, M. Design of the DLR AVES research flight simulator, AIAA Modeling and Simulation Technologies (MST) Conference, 2013. doi: 10.2514/6.2013-4737.
[25] Allerton, D.J. Flight simulation — Past, present and future, Aeronaut. J., 2000, 104, (1042), pp 651–663. ISSN: 00019240. doi: 10.1017/s0001924000096901.
[26] Merlin Flight Simulation Group. The Merlin MP521 Engineering Flight Simulator. Accessed 2024-05-14, 2009. http://www.merlinsim.com/mp521.htm.
[27] Humphreys-Jennings, C., Lappas, I. and Sovar, D.M. Conceptual design, flying, and handling qualities assessment of a Blended Wing Body (BWB) aircraft by using an engineering flight simulator, *Aerospace*, 2020, **7**, (5), p 51. ISSN: 2226-4310. doi: 10.3390/aerospace7050051.
[28] Cranfield University. Flight Simulator. Accessed 2024-05-13, 2016. https://www.cranfield.ac.uk/facilities/flight-simulator.
[29] Künzel, D. Flight Simulator Assessment of Pilot Behaviour During Aircraft-Pilot-Coupling Events, Diploma thesis, Munich University of Applied Sciences, 2016.
[30] Viertler, F. and Hajek, M. Requirements and design challenges in rotorcraft flight simulations for research applications, AIAA Modeling and Simulation Technologies Conference. Reston, Virginia, American Institute of Aeronautics and As tronautics, 2015. ISBN: 978-1-62410-337-7. doi: 10.2514/6.2015-1808.
[31] DCA Design International. Exploring the future of cockpit design. Accessed 2022-10-12, 2021. https://www.dca-design.com/work/rolls-royceexploring-future-cockpit-design.
[32] Messaoudi, F., Simon, G. and Ksentini, A. Dissecting games engines: the case of Unity3D, 2015 International Workshop on Network and Systems Support for Games (NetGames), IEEE, 2015, pp 1–6. ISBN: 978-1-5090-0068-5. doi: 10.1109/NetGames.2015.7382990.

https://doi.org/10.1017/aer.2024.91 Published online by Cambridge University Press

[33] del Castillo, J.A.L. and Couture, N. The aircraft of the future, Proceedings of the International Conference on Human-Computer Interaction in Aerospace, ACM, 2016, New York, NY, USA, pp 1–8. ISBN: 9781450344067. doi: 10.1145/2950112.2964582.

[34] Zheng, Y. and Lei, X.Y. Research and implementation of virtual cockpit panel development platform based on ARINC 661, Proceedings of 2014 IEEE Chinese Guidance, Navigation and Control Conference, IEEE, 2014, pp 1357–1361. ISBN: 978-1-4799-4699-0. doi: 10.1109/CGNCC.2014.7007394.

[35] Takeda, K., Newman, S.J., Kenny, J. and Zyskowski, M. Convergence: commodity flight simulation and the future, *Aeronautical Journal*, 2008, **112**, (1136), pp 599–607. ISSN: 00019240. doi: 10.1017/S0001924000002566.

[36] Tian, F., Chai, W., Wang, C. and Sun, X. Design and implementation of flight visual simulation system, *Int. J. Comput. Sci. Issues*, 2012, **9**, (5). arXiv:1212.0365.

[37] Cao, Y. Design and implementation of certain type flight test simulation plat form visual system, Proceedings of the 2020 4th International Symposium on Computer Science and Intelligent Control, ACM, 2020, New York, NY, USA, pp. 1–5. ISBN: 9781450388894. doi: 10.1145/3440084.3441203.

[38] Barrio, L.D., Korek, W., Millidere, M. and Whidborne, J. Analysis of Visualization Systems in Flight Simulators, AIAA AVIATION 2023 Forum, Reston, Virginia, AIAA, 2023. ISBN: 978-1-62410-704-7. doi: 10.2514/6.2023-3476.

[39] European Aviation Safety Agency. Certification Specifications for Aeroplane Flight Simulation Training Devices. EASA Document Issue 2. 2018, p 154.

[40] Skans, N.S. and Barnes, A.G. Fifty years of success and failure in flight simulation, 50 Years of Flight Simulation, Conference Proceedings, Session 1, London, The Royal Aeronautical Society, 1979, pp 33–49.

[41] Hays, R.T., Jacobs, J.W., Prince, C. and Salas, E. Flight simulator training effectiveness: a meta-analysis, Mil. Psychol., 1992, 4, (2), pp 63–74. ISSN: 0899-5605. doi: 10.1207/s15327876mp0402_1.

[42] Perry, D.H. and Naish, J.M. Flight Simulation for Research, *J. R. Aeronaut. Soc.*, 1964, **68**, (646), pp. 645–652. ISSN: 0368-3931. doi: 10.1017/S0368393100080597.

[43] de Winter, J.C.F., Dodou, D. and Mulder, M. Training effectiveness of whole body flight simulator motion: a comprehensive meta-analysis, *Int. J. Aviat. Psychol.*, 2012, **22**, (2), pp 164–183. ISSN: 1050-8414. doi: 10.1080/10508414.2012.663247.

[44] UKRI Gateway. Powerplant Integration of Novel Engine Systems (PINES). Accessed 2023-11-21, 2023. https://gtr.ukri.org/projects?ref=113263.

[45] Astill, A. OFD central to Rolls-Royce's vision beyond the engine. Accessed 2023-11-21, 2020. https://openflightdeck.co.uk/news/ofd-central-to-rolls-royces-vision-beyond-the-engine/.

[46] Asmayawati, S. and Nixon, J. Modelling and supporting flight crew decision-making during aircraft engine malfunctions: developing design recommendations from cognitive work analysis, *Appl. Ergon.*, 2020, **82**, p 102953. ISSN: 00036870. doi: 10.1016/j.apergo.2019.102953.

[47] Korek, W.T., Li, W.-C., Lu, L., and Lone, M. Investigating Pilots' operational behaviours while interacting with different types of inceptors, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 13307, LNAI, Springer International Publishing, 2022, pp 314–325. ISBN: 9783031060854. doi: 10.1007/978-3-031-06086-1_24.

[48] Korek, W.T. Research and Development of a New Touch-Screen Based Inceptors Design for an Aircraft Control, Doctoral thesis. Silesian University of Technology, 2023.

[49] Wang, Y., Li, W.-C., Korek, W.T. and Braithwaite, G. Future flight deck design: developing an innovative touch-screen inceptor combined with the primary flight display, *Int. J. Ind. Ergon.*, 2024, **101**, p 103588. ISSN: 01698141. doi: 10.1016/j.ergon.2024.103588.

[50] Cockburn, A., Masson, D., Gutwin, C., Palanque, P., Goguey, A., Yung, M., Gris, C. and Trask, C. Design and evaluation of braced touch for touchscreen input stabilisation, *Int. J. Hum. Comput. Stud.*, 2019, **122**, pp 21–37. ISSN: 10715819. doi: 10.1016/j.ijhcs.2018.08.005.

[51] van Zon, N.C.M., van Borst, C., Pool, D.M. and van Paassen, M.M. Touchscreens for aircraft navigation tasks: comparing accuracy and throughput of three flight deck interfaces using Fitts' Law, *Hum. Factors J. Hum. Factors Ergon. Soc.*, 2020, **62**, (6), pp 897–908. ISSN: 0018-7208. doi: 10.1177/0018720819862146.

[52] Yang, W., Sun, Q., Gao, X., Dong, D. and Ma, X. Human interface research of civil aircraft cockpit based on touch control technology, *IOP Conf. Ser. Mater. Sci. Eng.*, 2019, **608**, (1), p 012018. ISSN: 1757-8981. doi: 10.1088/1757-899X/608/1/012018.

[53] Li, W.-C., Liang, Y.H., Korek, W.T. and Lin, J.J. Assessments on human-computer interaction using touchscreen as control inputs in flight operations, in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 13307, LNAI, 2022, pp 326–338. ISSN: 16113349. doi: 10.1007/978-3-031-06086-1_25.

[54] The Community Research and Development Information Service. Evolution of cock-PIt operations Levering on cOgnitive compuTing Services. Accessed 2023-11-21, 2019. doi: 10.3030/831993. https://cordis.europa.eu/project/id/831993.

[55] Gil, D., Hernandez-Sabate, A., Enconniere, J., Asmayawati, S., Folch, P., Borrego-Carazo, J. and Piera, M.A. E-Pilots: a system to predict hard landing during the approach phase of commercial flights, *IEEE Access*, 2022, **10**, pp 7489–7503. ISSN: 2169-3536. doi: 10.1109/ACCESS.2021.3138167.

[56] Lappas, I. and Kourousis, K.I. Anticipating the need for new skills for the future aerospace and aviation professionals, J. Aerospace Technol. Manag., 2016, 8, (2), pp 232–241. ISSN: 2175-9146. doi: 10.5028/jatm.v8i2.616.

[57] Oberhauser, M. and Dreyer, D. A virtual reality flight simulator for human factors engineering, *Cognit. Technol. Work*, 2017, **19**, (2-3), pp 263–277. ISSN: 14355566. doi: 10.1007/s10111-017-0421-7.

[58] iF Design. Future Systems Simulator (FSS). Accessed 2022-07-10, 2021. https://ifdesign.com/en/winner-ranking/project/future-systems-simulator-fss/314432.

[59] Li, W.-C., Wang, Y. and Korek, W.T. To be or not to be? Assessment on using touchscreen as inceptor in flight operation, *Transp. Res. Procedia*, 2022, **66**, pp 117–124. ISSN: 23521465. doi: 10.1016/j.trpro.2022.12.013.

[60] Li, W.-C., Liang, Y.-H. and Korek, W.T. Flight operations using touchscreen controls: assessing system usability and pilots' visual attention, Contemporary Ergonomics & Human Factors 2022: Proceedings for the Annual Conference of the Chartered Institute of Ergonomics and Human Factors, Balfe, N. and Golightly, D. (Eds) Chartered Institute of Ergonomics & Human Factors, 2022. ISBN: 978-1-9996527-4-6.

Cite this article: Korek W.T., Beecroft P., Lone M., Bragado Aldana E., Mendez A., Enconniere J., Asad H.U., Grzedzinski K., Milidere M., Whidborne J., Li W.-C., Lu L., Alam M., Asmayawati S., Del Barrio Conde L., Hargreaves D. and Jenkins D. (2024). Simulation framework and development of the Future Systems Simulator. *The Aeronautical Journal*, **128**, 2754–2780. https://doi.org/10.1017/aer.2024.91