Hands-On Flight Dynamics and Controls Teaching using Flight Simulators

Felix Biertümpfel * **Christophe Annon** ** **Harald Pfifer** *

* *Technische Universität Dresden, 01307, Dresden, Germany (e-mail: {felix.biertuempfel, harald.pfifer}@tu-dresden.de).*
** *Alsim Simulateurs, 44430, Le Loroux-Bottereau, France (e-mail: c.annon@alsim.com)*

Abstract: This paper presents the opportunities arising when using a flight simulator with a high fidelity software interface in higher education. A flight simulator is a powerful tool to deepen the learning experience in any aeronautical degree program. It allows students to gain practical insights into the physics of flight, the impact of control engineering as well as valuable experience in flight test engineering. Explicit experiences of simulator use in undergraduate education are provided, based on the Alsim AL250 combined with the Engineering Pack software. Moreover, concepts for simulator use in postgraduate lectures and research projects are presented.

Keywords: Flight Simulation; Engineering Education; Flight Dynamics; Flight Control; Human-in-the-loop systems; Guidance, navigation and control of vehicles

1. INTRODUCTION

The necessity of practical experiences in form of laboratories has been well recognized in engineering education (Feisel and Rosa, 2005; Ernst, 1983). Laboratories fulfill several important teaching objectives, e.g., identifying the strength and limitations of theoretical models in predicting the real world, data collection and data analysis using realistic sensors or team work. In aerospace teaching specifically, flight simulators are often used as a substitute for real flight experiments (Ruiz et al., 2014; Padfield and White, 2003; Coiro et al., 2007; Kwon et al., 2015). The latter while ideally preferred are usually of prohibitively high cost for usage at higher education institutes. Even the Royal Aeronautical Society acknowledges the high technical standards of available flight simulators to substitute for real flight tests in its accreditation guidelines (Royal Aeronautical Society, 2016), although it prefers the integration of actual flight tests in a degree program.

The authors used a flight simulator at the University of Nottingham (UoN) to establish engaging and hands-on aerospace lectures. These lectures provided the necessary practical experience in the fields of flight mechanics, aircraft design and flight controls. The flight simulator was used on top of a real flight test laboratory. However, a significantly higher student exposure to flight testing inside the aerospace program was achieved than it would had be possible when relying solely on an actual aircraft. In multiple undergraduate laboratories, students were provided with a hands-on experience in flight mechanics and control, as well as flight testing on a regular basis.

A flight simulator inside a higher education institution must fulfill a broad range of requirements. Besides the obvious cost requirement, ease of maintenance, ease of use and flexibility were identified as the main requirements for flight simulators. In general, teaching resources at an university are limited. For example, at the University of Nottingham a single lecturer and postgraduate students (the authors) were fully in charge of the operation of the flight simulator laboratory and the development of new teaching content based on the flight simulator. Hence, maintenance of the simulator (both from software and hardware side) has to be reliably outsourced to the flight simulator manufacturing company. Moreover, the main use-case for a flight simulator at university is for teaching and research. As future research directions and the developments of a degree program are often hard to predict, the simulator requires a certain level of flexibility and upgradability to meet any future demands. A key component here are built in software interfaces to , e.g., Matlab/Simulink, which allow to easily modify and access data on the simulator. Thus, the successful integration of a flight simulator at universities relies on a close cooperation between the manufacturer and the university. The Alsim AL250 in combination with its *Engineering Pack*, an advanced and proven Matlab/Simulink software interface, satisfies all requirements for a flight simulator in engineering education and research. This simulator is in successful operation in multiple aerospace degree programs, for example, at the University of Nottingham. Combined with the practical experience of the authors, the AL250 provides an excellent use-case on how to integrate a flight simulator into an aerospace degree program.

This paper presents the integration of a flight simulator into an aerospace degree program. Explicit experiences with the AL250 at the University of Nottingham in undergraduate education are provided. Moreover, concepts for the use in postgraduate courses and research projects are proposed. Section 2 provides an overview of the requirements on a flight simulator in an university environment. A special emphasis is put on necessary operational modes to address a broad spectrum of lectures and teaching goals. The Alsim AL250 flight simulator and the necessity of the engineering pack to maximize the usage of the AL250 at a university are presented in Section 3.1 and 3.2. Section 4, provides explicit examples of undergraduate laboratories using the AL250 as an integral part of the teaching and student experience. Concepts to integrate flight simulator laboratories into postgraduate flight control lectures are also presented. Section 4 concludes with an overview of postgraduate and research projects incorporating flight simulators.

2. SIMULATOR REQUIREMENTS FOR EDUCATIONAL USE

2.1 Hardware Requirements

A key requirement for any flight simulator is a maximum level of immersion. Hence, a large field-of-view (FOV) is mandatory to avoid “non-screen” areas in the pilots’ vision during operation. A realistic general aviation cockpit, preferably in two-pilot configuration is required for teaching topics like crew resource management during flight testing. Realistic avionics including a navigation and instrument landing system (ILS) are mandatory to facilitate a broad use of the simulator in lectures concerning flight controls or flight guidance. Pilot controls should provide active control loading to simulate aerodynamic forces in case of a reversible flight control system or artificial control forces in case of fly-by-wire configurations. Active control loading is paramount for teaching as well as research. Without adequate feedback from the controls to the pilot, flight tests would lack the necessary amount of realism and therefore results would be of less significance. Multiple realistic and certified flight models should be provided with the simulator. The certification of flight models is time consuming and hence related to high costs. However, such flight models are essential to provide meaningful and credible results in research without actual flight testing (which is not an option given the accompanying cost, risk, and logistics). In addition, the reconfiguration between different flight models must be fast and easy. This is highly important for teaching to reduce waiting time for students given an usually busy lab schedule.

2.2 Software Interface Requirements

For an easy integration in various lectures and research projects, data on the simulator must be easily accessible and modifiable. Hence, a software interface is necessary which connects the simulator with the numerical engineering tool used in the lecture, i.e., Matlab/Simulink. This interface should be readily available as a software package with the simulator to avoid maintenance on the university side given the regular turnaround of scientific personal. The software must facilitate an easy data transfer between an external computer running Matlab/Simulink and the simulator. Sending and receiving data to and from the simulator, respectively must be easy and sophisticated enough to run a control system in Matlab/Simulink. This control system interacts with the actual simulator model running on the simulator computer as well as the simulator’s controls and displays. Fig. 1 visualizes this setup. Furthermore, the simulator must be usable as a pure “visualization and pilot interface” for self-developed flight simulations or flight dynamics models (including control systems). These models must run in Matlab on an external computer. The simulator then basically functions as pilot environment providing visual and haptic feedback to allow for sophisticated piloted tests. This setup is depicted in Figure 2.

The development, integration, and maintenance of flight dynamics models into hardware is time consuming. Thus, an existing Simulink flight model should be provided in the software package. This flight model should correspond to one of the certified aircraft models inside the simulator. Furthermore, the model and its implementation provide an important benchmark for preparing and integrating self-developed flight dynamics models into the flight simulator environment. In case such an external Matlab/Simulink model is running, it must also be guaranteed that the pilot feels the same control loads as when flying the original certified model. Hence, the original aerodynamic loads calculation must be enabled. However, also the possibility to design and implement a custom “control feeling” must be provided to guarantee maximum flexibility in teaching and research.

The last requirement on the Matlab/Simulink interface is an easy online manipulation of the flight dynamics running on

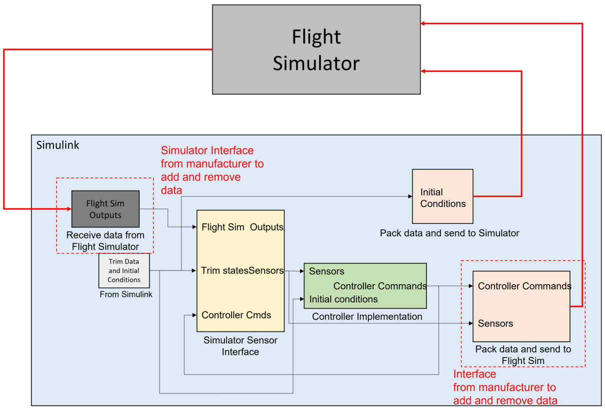

Fig. 1. Controller with flight simulator model in the loop

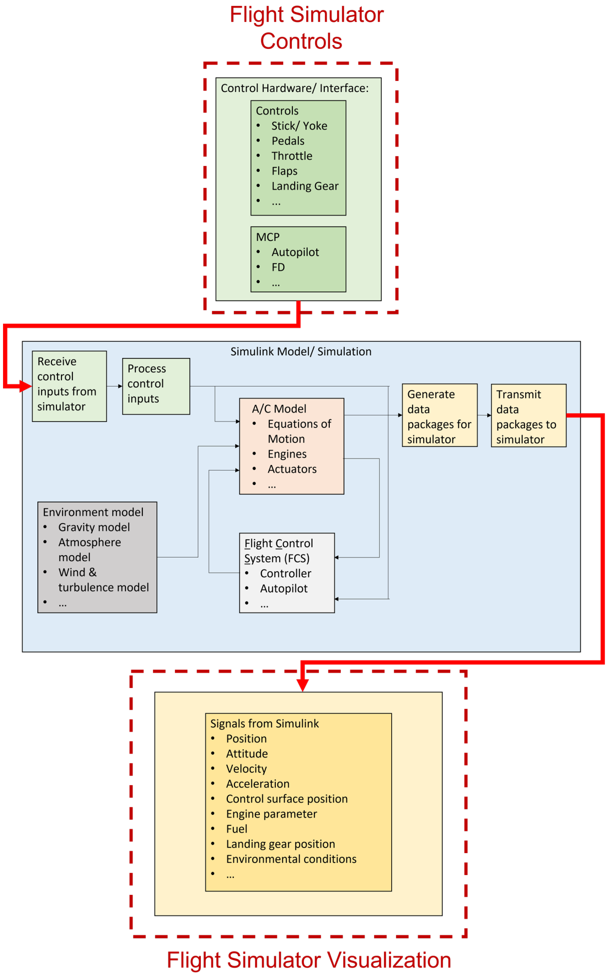

Fig. 2. Simulator as pilot environment only

the simulator. This is necessary to demonstrate parameter influences on the flight dynamics in real-time. It is directly motivated by the use in the teaching laboratories to show the influence of certain parameters on the flying and handling qualities. An “in-flight” manipulation of aircraft parameters (especial regarding its weight and balance as well aerodynamics) is also important to evaluate the robustness of a flight control system. Robustness of a flight control system towards all kind of disturbances marks an important certification requirement and hence, this simulator requirement also relates to numerous research activities.

3. FLIGHT SIMULATOR FOR EDUCATION

3.1 Alsim AL 250

The AL250 flight simulator is an original design and product of Alsim. At the heart of the AL250 is the proven Alsim software technology that is easy to maintain and provides high quality and flexibility. The fully enclosed simulator offers 250 degrees angle of view and a high resolution widescreen display. It is a reconfigurable single- and multi-engine piston simulator that meets the training requirements of PPL/CPL/IR/MEP. Its unique design solutions include a reconfigurable instrument display in the cockpit, which can be changed from classic circular dials to an advanced electronic flight instrument system (EFIS) with one click. No manual hardware change and an assembly of large instrument panels is needed.

Fig. 3. Cockpit view of the AL250

Fig. 3 shows the cockpit of the AL250 with the main instrument panel (1) in EFIS mode. The standard setup of the AL250 is fitted with a force feedback system for the yoke and rudder controls for both pilot and copilot. It further contains a default two axis autopilot system (6) and a unique avionics suite (2) that allows, for example, simulation of wide area augmentation system based approaches. Optional systems, such as a weather radar or a traffic advisory system, are also available.

3.2 The Engineering Pack

The Alsim Engineering Pack for Matlab is intended to provide an interface tool between Alsim Flight Training Devices (FTD) and Matlab/Simulink. It allows Alsim FTD data monitoring, recording and control from Matlab and Simulink software suite. The engineering pack has been specifically designed with higher education institutions in mind, as it extends the usage of Alsim FTDs from pilot training to aerospace engineering education. At its core, the Alsim Engineering Pack is a toolbox for Matlab that allows communication between the flight simulator software and Matlab. A brief overview of the data communication is provided to facilitate a better understanding of the inner workings of the engineering pack. The software structure of an Alsim FTD with the Engineering Pack is depicted in Fig. 4. Each subsystem of the FTD, e.g. pilot instruments or instructor station, communicate with each other through a local network, sharing all relevant simulation data via a common data base, denoted Network DataStore. The engineering pack allows two way access (i.e., read and write) to this Network DataStore. Hence, the engineering pack can be used on various level to interact with the simulator in order to, e.g., extract flight data parameters (airspeed, altitude, heading, power, etc.) and pass them to external computers for students to observe, log and analyze in real-time or modify the flight characteristics of an aircraft to demonstrate unusual circumstances (i.e. neutral or negative stability). It also provides the opportunity to replace aircraft systems by user written systems (, e.g., user created flight control laws).

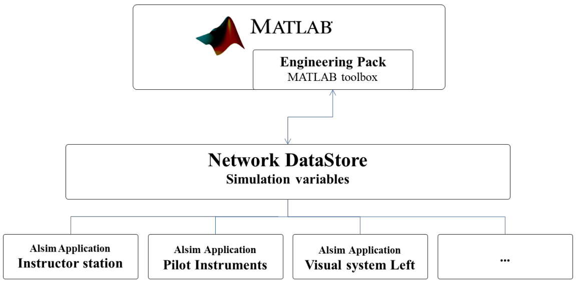

Fig. 4. Structure of the Alsim FTD Software and Engineering Pack

The Engineering Pack also provides a Simulink block library that allows implementing the main features of the Engineering Pack directly into a Simulink model. It offers a very intuitive and user-friendly interface allowing quickly obtaining results without spending too much time on development. This can be used for prototyping in research and educational projects with little to no time investment required in training new students.

The Engineering Pack for Matlab also comes with a six-degree-of-freedom rigid body flight dynamics Simulink model based on a light twin-engine aircraft. It is interfaced with the Alsim simulators to replace the built-in twin engine flight model. This Simulink model also features a graphical user interface that allows to tune the aircraft derivatives individually, by applying multiplication factors, in real-time during a flight. The impact of a modification to an aircraft derivative can be assessed by monitoring various simulation variables during the flight. Finally, the simulation model is also capable to run standalone in Matlab/Simulink. Thus, it can be used as a template to develop user-created flight dynamics models and validate them in faster than real-time scenarios before bringing them on the Alsim simulators.

4. USE OF FLIGHT SIMULATORS IN TEACHING

4.1 Conducted Undergraduate Laboratories

The AL250 flight simulator in combination with the Engineering Pack presents a hands on teaching opportunity in undergraduate level laboratories. It offers integrated teaching of theory and application of aircraft performance, and flight dynamics and controls. It allows students to deepen the understanding of the theoretical concepts learned in the classroom by applying them in flight in a high-fidelity flight simulator. At UoN, the authors run multiple laboratories in the undergraduate aerospace engineering degree program.

All conducted laboratories in Aerospace Engineering at UoN aimed to mimic at least in a simplified version a real flight test experience consisting of a pre-flight briefing and post flight data analysis. The laboratories were conducted in groups of four students. Each student had a different self-assigned role, i.e. pilot flying (PF), pilot monitoring (PM) and two flight test engineers (FE). The group nature of the laboratories highlights the teamwork aspect required in any modern engineering job.

Aircraft Performance

The laboratory was conducted for first year aerospace students at UoN, where it was embedded in the aircraft design and performance course. The number of students taking the laboratory increased from 50 in the first year to 115 students in the third year it was conducted. It was always supervised by not more than one lecturer and one postgraduate student. The core of the aircraft performance flight test laboratory was the identification of the climb performance followed by and identification of the lift-to-drag ratio. The completion of the two specific experiments in the given order is common practice in flight test engineering (Ward, 2001). The flight test can be run with a standard aircraft model of the AL250 simulator. In case of the UoN lab, the complex single engine aircraft was used.

The flight test started with the take-off, followed by a climb to pre-specified altitude. After trimming the aircraft, the PF performed a sequence of steady climbing maneuver at maximum thrust and steady glide descents with idle throttle. During these maneuvers, important aircraft parameters, i.e. indicated airspeed and altitude were called out by the PM and recorded by the FEs. In addition, the FEs timed the maneuver. An example of the flight test is shown in Fig. 5. The data was recorded using the Engineering Pack. During the experiment, a demonstrator used the Engineering Pack to display and record the altitude, indicated airspeed (IAS) and throttle position in Matlab/Simulink. Thus, he was able to give live feedback regarding the correct execution of the maneuver, provide back-up data to the students if needed and later check the accuracy of the results.

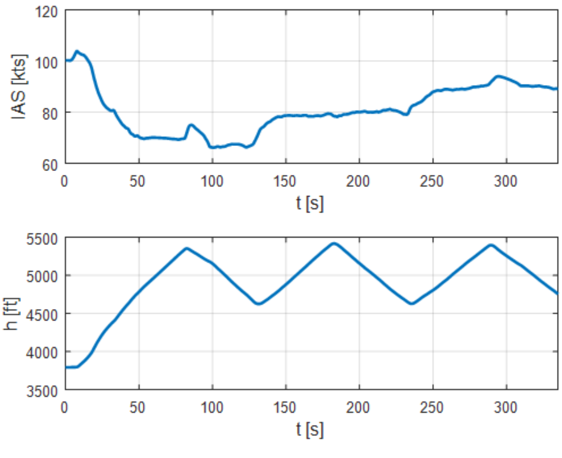

Fig. 5. Example trajectory of the performance laboratory recorded by the Engineering Pack

In the evaluation phase, the students used Matlab to calculate the climb performance and lift to drag ratio by using the collected data of the flight experiment. They were required to actively apply the knowledge acquired in the lectures on data gathered by themselves in an interesting and challenging environment. They recognized that the taught model assumption, e.g. small angle approximations for the lift and weight equality are helpful and likewise adequate. Furthermore, the students derived the lift-drag polar out of flight data. This is one of the most important diagrams in flight performance evaluations. Overall, the laboratory helped the students to understand the necessity of the theory in a hands-on fashion. The intended learning outcome, deepened understanding of the lift-drag polar and common approximations in flight performance calculations, was verified by the students' feedback. The overall student feedback was positive and saw the lab as an motivating complement to the class room exercises.

Flight Dynamics

The flight dynamics laboratory was conducted in the second year of UoN's aerospace engineering program as part of the dynamics and flight mechanics class. It was supervised by one lecturer and one postgraduate student. The AL250 in combination with the engineering pack offered an accessible way to visualize the eigenmotion of an aircraft. Consequently, the students could experience the qualitative and quantitative dynamical behavior of an aircraft. In the laboratory, the students analyzed the phugoid mode of an aircraft via flight test. This eigenmotion can be understood as an energy oscillation, exchanging potential and kinetic energy of the aircraft triggered by a velocity disturbance of the aircraft. The phugoid was chosen as it is relatively easy to visualize and the poor damping and low frequency make it easy to measure. Based on the measured data the students were able to identify the frequency and damping of the phugoid. Furthermore, they could recognize the dependence of the phugoid on aircraft configurations and trim conditions, i.e., the IAS .

The flight test started by trimming the aircraft in different configurations (i.e., clean, flaps in landing configuration) and different airspeeds. The PF initiated a disturbance in airspeed by pushing the control yoke and releases the yoke to return the controls to the trim condition. The students could then experience and record the phugoid mode of the aircraft. The experiment was timed, and zero crossings in the vertical speed with corresponding IAS and altitude were recorded. The second FE operated the Simulink interface, which is used to record data received from the simulator via the Engineering Pack. The recording started and ended simultaneously with the PM. The Engineering Pack presented an accessible and accurate way to measure and store the aircraft data/ states. Its use in this experiment can be compared to a high fidelity inertial measurement unit (IMU) installed in a flight test aircraft. Furthermore, the live data represents the data usually accessible for the FEs in ground stations. The measured data for two test points flown during a lab are shown in Fig. 6.

In the evaluation phase, the students determined the natural frequency and the damping ratio of the aircraft using the in-cockpit data and Simulink data respectively applying the transient peak ratio method (Yechout, 2000). The use of two separate calculations was motivated by various reasons. One reason was to sensitize the students to identify experimental errors, e.g. measurement errors or systematic errors and their various causes. Another reason was to stress the necessity of back up data during real flight testing of any scale. Repetition is commonly time consuming, expensive or in the worst case (loss of the test vehicle) not an option. During the calculations the students deepened their understanding of the phugoid motion, by identifying its characteristics, e.g. dominant states and dynamics, previously taught in the lectures. The use of actual, independently collected data using actual aircraft instrumentation was an engaging addition to the calculations from pure textbook examples in the classroom. Furthermore, it helped the students to better understand the assumptions made in the lectures as well as the respective influences on the results. The intended learning outcome, deepened understanding of aircraft eigenmotions through realistic application example, was verified by student feedback. The overall student feedback was positive and students saw the lab as an interactive and motivating exercise to test their knowledge.

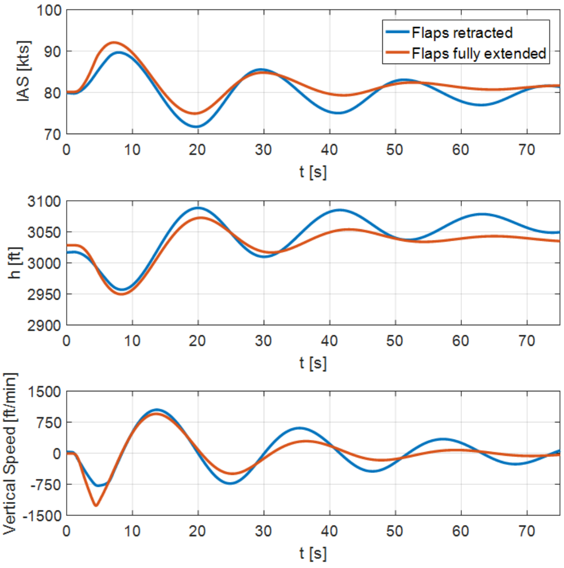

Fig. 6. Example trajectory of the dynamics laboratory recorded by the Engineering Pack

4.2 *Postgraduate Laboratory Concepts*

The positive impact on the undergraduate student experience and teaching outcomes motivates a use of flight simulators also on a postgraduate level. This section presents concepts for postgraduate laboratories and coursework focusing on classical and advanced control.

Classical Flight Controls

A flight simulator like the AL250 including a Matlab/Simulink interface is perfectly suited to accompany a ”Flight Controls” lecture in form of a “Flight Control and Flight Test” laboratory. As a supplement to the theory-heavy lecture the laboratory introduces a more practical and hands-on component to understand the influence and importance of flight controls. Moreover, continuous work over the course of the semester supports fortifying the theoretical knowledge presented in the classroom lectures. The concept of the laboratory and teaching goals of the laboratory are as follow. Students in groups of four execute a multitude of flight tests common for the identification of aircraft dynamics, such as, tests for longitudinal stability and lateral-directional stability. In addition, classical flight control design methods (e.g., pole-placement, loop-shaping) for stability augmentation systems (SASs) and control augmentation systems (CAS) presented in the classroom lectures are applied by the students on the simulator. The final designs are implemented and evaluated by flight test in the simulator. A main focus is on so-called handling qualities, i.e., the perception of the pilots regarding the flyability and the aircraft’s behavior towards their control inputs. In summary, the students learn how to design a practical flight control design with the motivational goal to actually fly it in a flight simulator.

Robust and Optimal Flight Control

Modern robust and optimal control methods and their application in aerospace is a challenging postgraduate teaching subject. Among a significant amount of mathematical background, synthesis methods such as H_∞ or linear parameter-varying control are covered. Such specialized topics, naturally come with smaller student numbers facilitating alternative teaching and examination methods, such as semester-long coursework to counterbalance the theory heavy lecture.

A concept for such a semester-long coursework is provided in the following. Each student develops three control designs using modern optimal and robust control techniques for the longitudinal and lateral control system of a small general aviation aircraft. The nonlinear dynamics of the aircraft are implemented in a Matlab/Simulink flight simulation environment. The simulation environment includes trim and linearization functions calculating the linear (time-invariant) models necessary for the controller design and synthesis. After a thorough analysis in the frequency domain, the designed controllers are evaluated in the nonlinear simulation, e.g. using Monte Carlo analysis. The control designs are implemented in the flight simulator by the students. Here, the simulator can be used as pure pilot environment, i.e., the dynamics model and controller run on an external computer (see Section 2 and Fig. 2). Alternatively, the simulator’s original flight dynamics models are used and only the controller runs in Simulink on an external computer (see Section 2 and Fig. 1). Both options are feasible with a device like the AL 250 with its Engineering Pack. Afterwards, flight tests are performed to provide the students with a hands-on experience of their control designs in a realistic and motivating testing environment. These can, for example, include handling quality evaluation and comparisons of the different control design approaches. The coursework thus mimics an actual flight controller design process from requirement definition to flight testing. The positive impact on student experience and engagement on such a concept was reported by the authors in (Biertümpfel et al., 2023).

Moreover, the implementation and running of the flight controller actively sensitize the students to the importance of discretization effects and real-time capabilities impacting all on hardware implemented control systems. Hence, a more hands-on and motivating teaching element contributes to the lecture. The students learn to actually design a robust flight controller. Implementing and testing their own designs in a realistic environment is a huge motivation bonus.

4.3 *Individual and Group Projects*

Another possible application for a flight simulator in higher education is individual and group projects. For example, at UoN, the last author conceptualized an aircraft design group project in the third year of the aerospace engineering master's program. This yearlong project let four students follow an early aircraft design process. As part of the project the students implemented their final aircraft design via the Engineering Pack on the AL 250 and conducted flight tests to assess the handling qualities of the aircraft design. The students used the Simulink nonlinear rigid body simulation model, provided in the Engineering Pack, as a template to integrate their aircraft design on the AL 250. The student feedback was very positive and highlighted the satisfaction of actually "flying" the designed aircraft as a reward at the of the challenging and otherwise theory-heavy project.

In addition to the group project for master's students, in 2018 the first set of individual bachelor projects were supervised by the last author at UoN. In the first year of projects, two run specifically on the AL 250 flight simulator. One was dealing with the design of a short take-off and landing aircraft, and used the template Simulink model similar to the group project. The other project aimed to enhance the flight simulator by a fully programmable display in front of the co-pilot. The display was connected to the flight simulator via the engineering pack and allowed studying alternative cockpit instrumentation. Actively working on the flight simulator was described by the student as major motivational boost compared to simply working on a desktop computer.

4.4 Postgraduate and Research Projects

Besides the use of a flight simulator as a pure teaching device in undergraduate engineering education, it can also be used for research projects. Two possible research projects heavily involving a flight simulator for higher education are described in the following. The first project investigates the use of flight envelope prediction and protection for general aviation aircraft. The flight envelope refers to the general capabilities of the airplane in terms of load factor, altitude, airspeed and maneuverability. Flying "inside-the-envelope" is understood as operating the aircraft in its safe, designed operation region. When an aircraft is at a state "outside-the-envelope" it is considered as a dangerous situation for the aircraft, potentially leading to loss of control (Yechout, 2000; Wilborn and Foster, 2004; Pfifer et al., 2017). The research problem consists of two different questions that are both connected. First, there is the question on how to accurately predict the aircraft flight envelope and identify in advance pilot inputs that can potentially bring the aircraft outside the envelope. Second, it needs to be answered how the results of the first question can be communicated to the pilot. A simulator like the AL250 can be used heavily throughout the duration of the project. Due to the capabilities of the Engineering Pack, it is easy to set up different test cases of the benchmark aircraft to assess the capabilities of the to be developed envelope prediction algorithm. The envelope prediction can be tested in different atmospheric scenarios but also account for different model uncertainties during the development of the algorithm, e.g., uncertainties in the aerodynamic model of the benchmark aircraft. The Engineering Pack also allows for adding additional displays (e.g., a heads-up display) to the simulator environment that allow studying various visual feedback of the predicated flight envelope to the pilot.

The second project concerns pilot monitoring systems. For example, a software interface like the Engineering Pack can be used to integrate pilot monitoring systems in the flight simulator, such as eye tracking cameras and physiological monitoring equipment. This allows studying pilot work load and stress levels. Such a project also promotes interdisciplinary research with human factors research groups.

5. CONCLUSION

The usage of a flight simulator with a high-fidelity software interface to Matlab/Simulink for aerospace engineering in higher education has been presented in this paper. Explicit teaching experiences based on the AL250 in combination with the Alsim Engineering Pack are given, which highlight the impact of a flight simulator to student experience and teaching success. In addition, various use-cases of a flight simulator in an aerospace program are provided ranging from undergraduate level engineering laboratories, over postgraduate coursework, to high-profile research projects.

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