FLIGHT SIMULATION ENVIRONMENT FOR UNDERGRADUATE EDUCATION IN AIRCRAFT HEALTH MANAGEMENT

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Abstract

This paper presents a set of dedicated simulation tools, which integrates PC-based simulation with the West Virginia University 6-degrees-of-freedom motion-based flight simulator with the objective of providing an experiential and active learning environment for aircraft health management education. An undergraduate aerospace engineering course has been designed with the objective of introducing students to technical topics relevant to aircraft health management such as modeling, detection, evaluation, monitoring, and accommodation of abnormal aerospace systems operation. The dynamic fingerprints of several types of failure of various aircraft sub-systems (actuators, sensors, structure, engine) are investigated. Adverse atmospheric conditions and abnormal human pilot conditions are also modeled and implemented. Introductions to parameter identification algorithms, failure detection schemes, and fault tolerant control laws are provided and several specific algorithms are implemented for demonstration and analysis purposes. The simulation environment and the educational tools, instruments, and assignments are described in this paper with a special focus on the lab experiments and assignments. A preliminary analysis of the impact of the proposed instructional methodology reveals that the approach is perceived highly positively by the students and significantly enhances the academic process.

Introduction

Due to their complexity, physical capabilities, and technical challenges, aerospace systems require a system engineering [1] approach for their design, production, and operation. As part of this approach, Aircraft Health Management (AHM) [2] encompasses the methodologies and technologies needed to ensure safety and affordability. The “health” of a technical system can be defined as the set of all parameters that have relevance to the operation of the system within the designed range and must be addressed throughout the life cycle of the system, during the design, operation, and maintenance process.

Safety of aircraft operation has been widely acknowledged within the aerospace engineering community as increasingly important and a primary rank priority [3-5]. It has become critical that the higher education system provides adequate expertise in this domain on a large scale and that the future workforce acquires the necessary knowledge, skills, and capabilities. In response to this need, recent efforts [6,7] at West Virginia University (WVU) have been focused on integrating within the academic curriculum significant aspects relevant to aircraft health management. In particular, the use of the WVU advanced simulation environment to support a senior level technical elective course is presented in this paper. The course is aimed at introducing basic concepts and methodologies for aircraft sub-system abnormal conditions modeling, detection, evaluation, monitoring, and accommodation. The advanced simulation environment built in Matlab/Simulink is designed to provide firsthand experience on the dynamic fingerprint of sub-system failures and damages and vehicle and environmental upset conditions. It demonstrates the operation of detection schemes and fault tolerant control laws. It can be used on desktop computers or with the WVU 6-degrees-of-freedom (DOF) motion-based flight simulator.

The design of the WVU educational package for AHM instruction is focused on the implementation of active [8,9] and experiential learning [10] techniques to enhance student motivation and participation and increase effectiveness of the learning process.

General Course Design Strategy

The Flight Simulation Laboratory (Figure 1) of the Department of Mechanical and Aerospace Engineering (MAE) at WVU includes 14 stations with high-end desktops, accurate joysticks, and advanced graphic cards with dual monitors (Figure 2). The WVU 6-DOF motion base flight simulator (Figure 3) offers a very realistic flight environment with extremely low operational and maintenance costs [11]. The same customized flight simulation software can be used on the desktop computers as well as interfaced with the motion-based simulator. Typically, to maximize efficiency, the simulation experiments are first developed and tested on the desktop computers and then run in the motion-based simulator.

Figure 1. MAE Flight PC-Based Simulation Laboratory.

The undergraduate course *Flight Simulation for Aircraft Health Management* has been aimed at introducing students to technical topics relevant to aircraft health management such as modeling, detection, evaluation, monitoring, and accommodation of abnormal aerospace systems operation. The pedagogical approach is focused on creating an active and experiential learning environment through extensive use of simulation tools and significant classroom autonomy allowing students to take initiative, be creative, generalize and extrapolate, raise questions and discover answers on their own. The general course design allows the students to take on the roles of all important experts involved in flight testing and analysis. They are expected to thoroughly design the experiment as flight test engineers, perform the experiment as pilots, and analyze the data as performance and handling qualities engineers.

Figure 2. MAE Flight PC-Based Simulation Laboratory – Student Flight Simulation Station.

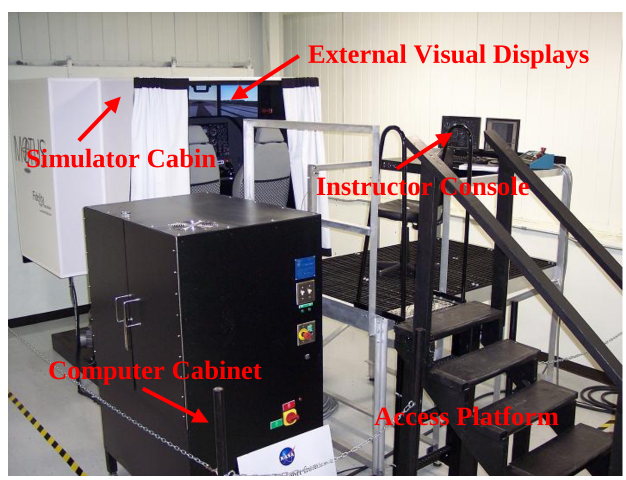


Figure 3. The WVU 6 – DOF Flight Simulator System.

Within the course, simulations are used in four distinct instances:

- Demonstrations lead by the instructor to support material presented during lectures;
- Demonstrations performed by the students in class and outside of class to confirm knowledge acquired in class or through individual study, as part of assignments or preparation for assignments;
- Tests performed by students to solve assigned problems or investigate relevant aspects (including labs and tests/quizzes);
- Tests performed by the instructor to demonstrate/confirm solutions to problems and tests/quizzes.

Course Objectives and Learning Outcomes

The undergraduate course *Flight Simulation for Aircraft Health Management* has been designed with the following objectives in mind:

- Description of aircraft health monitoring and management systems;
- Review of the most common abnormal flight conditions for fixed and rotary wing aircraft;
- Analysis of causes and dynamic effects of abnormal flight conditions;
- Assessment of dynamic signatures and impact on performance of abnormal flight conditions through simulation and tests using PC-based simulation and a 6-DOF motion-based flight simulator;
- Overview of general methodologies for abnormal flight conditions detection and accommodation through automated control laws.

The expected learning outcomes were formulated to achieve a balanced coverage of the cognitive domain as described by Bloom's taxonomy [12]. At the end of this course, the students should be able to:

- Explain the role, motivation, and means of aircraft health management systems;
- Describe the general conditions and effects of the most frequent abnormal flight conditions;
- Analyze the effects of abnormal flight conditions on aircraft control, handling qualities, and performance;
- Design and perform tests on PC-based and motion-based flight simulators followed by data processing and interpretation for the analysis of dynamic signatures and impact on performance of abnormal flight conditions;
- Describe the most commonly used methods for fault detection and accommodation and explain their principles.

General Simulation Environment Architecture

The WVU aircraft health management instruction simulation environment consists of 5 major modules (Figure 4):

- User Interface Module
- Aircraft Module
- Control System Module
- Failure Model Module
- Failure Detection and Identification Module

The *User Interface Module* allows the students to set-up the general simulation scenario through a graphical user interface, and visualize during or after the simulation the variation of relevant parameters. The main portal to the simulation environment allowing the selection of the type of simulation model is presented in Figure 5a. Figure 5b shows the menu for failure condition selection. The commands to the aircraft can be provided through the control stick or as pre-recorded data. A mathematical pilot model can also be used for analysis. An example of a typical simulation user interface with dual monitors is displayed in Figure 6 showing Simulink time history visualization and vehicle visualization provided by *FlightGear* [13], an open-source simulation code.

The *Aircraft Module* hosts several aircraft models that are implemented at different levels of complexity. The model to be used can be selected by the user through the portal menu presented in Figure 5a. To support the undergraduate course on aircraft health management engineering techniques, a supersonic fighter, a business jet, and the WVU YF22 unmanned aerial vehicle (UAV) models are typically used. The supersonic fighter model is based on the flight dynamics of a modified F-15 research aircraft [14]. The business jet model simulates the dynamics of a typical small business jet aircraft [15]. The WVU UAV model is a quasi-scaled YF-22 fighter model [16] with modified aspect ratio. All models provide easy access to stability and control derivatives for modification and analysis. The aircraft module also includes environmental models for turbulence, wind, and icing. Note that all mathematical models are developed in-house and implemented in Matlab/Simulink and *FlightGear* is used only for visualization purposes.

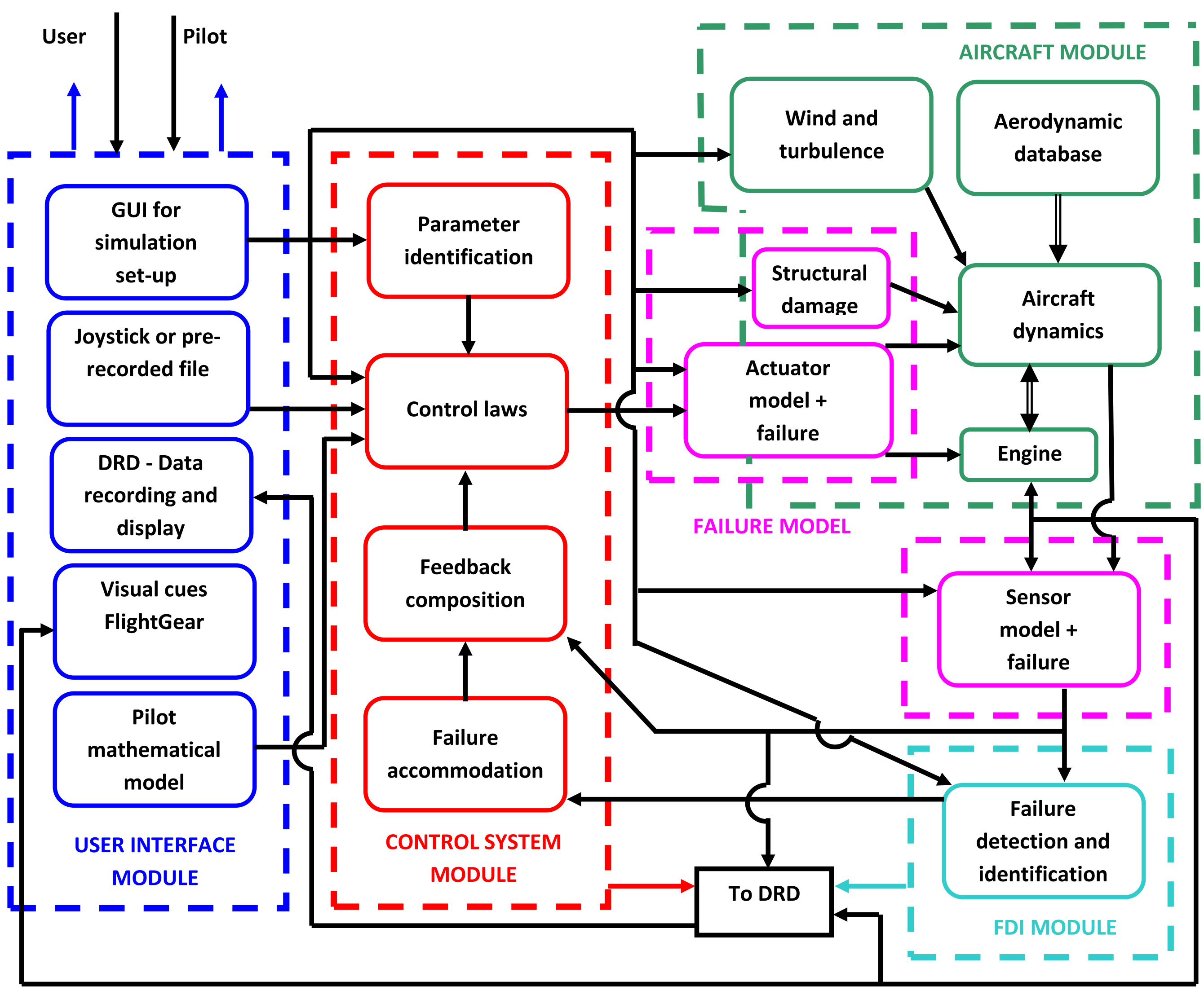
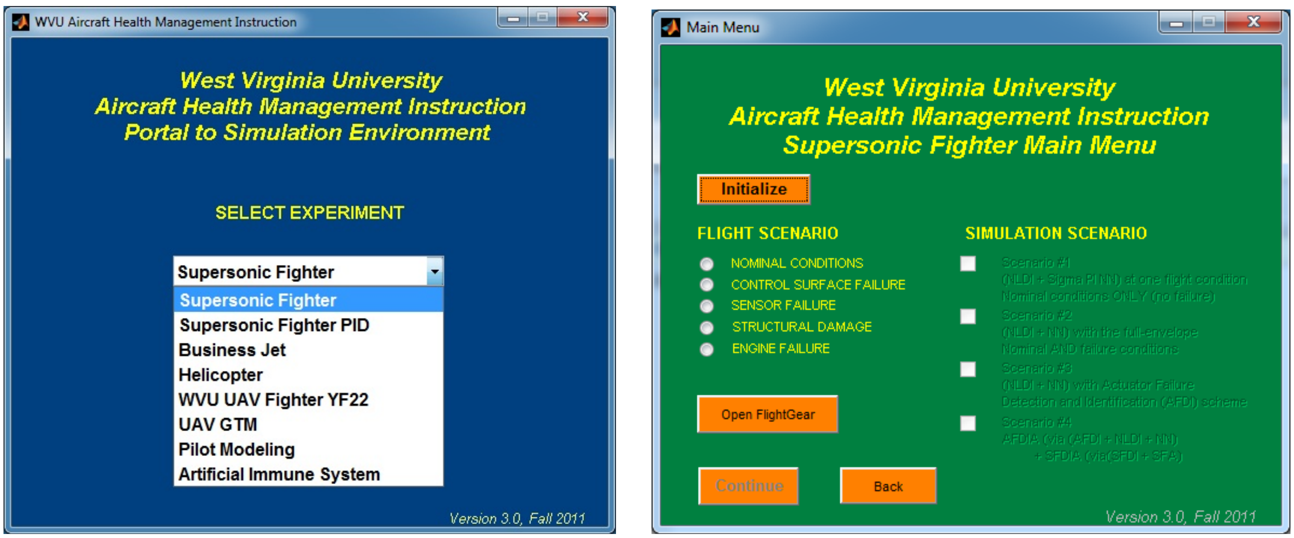


Figure 4. General Architecture of the WVU Aircraft Health Management Instruction Simulation Environment.

The *Control System Module* consists primarily of adaptive control laws with intrinsic failure accommodation capabilities [16]. They are based on a non-linear dynamic inversion technique augmented with artificial neural networks. A parameter identification (PID) sub-module is implemented to illustrate how PID operates and how it can be used on-line for abnormal condition detection and for implementation of indirect adaptive control laws with fault tolerant capabilities. Linearized vehicle dynamics models (state and control matrices) or, equivalently, stability and control derivatives are computed during simulation using a simplified frequency domain method [14].



(a) (b)

Figure 5. WVU Aircraft Health Management Instruction Interface
a) Aircraft Selection Interface b) Aircraft Failed Sub-System Selection Interface.

The *Failure Model Module* includes models of abnormal operation of actuators, sensors, and propulsion system and structural damages on the wing and the other aerodynamic surfaces. The actuators for the rudders, stabilators, and ailerons can be locked at a current deflection angle, or at an imposed deflection angle, or can exhibit reduced efficiency. The roll, pitch, and yaw rate sensors, which are used in the closed-loop feedback, can be affected by sensor bias and drifting bias with different levels of severity. The propulsion system's throttle, burner fuel flow valve, nozzle area actuator, mixer area actuator, spool speed sensor, exit static pressure sensor, and mixer pressure ratio sensor are each capable of either an actuator failure at the current or imposed positions or sensor bias and sensor constant output failure types [17]. These failures can affect either the left engine, right engine, or both engines simultaneously as the engines are modeled individually. For modeling purposes, the structural failures of the main aircraft components (wing, horizontal tail, or vertical tail) are categorized as "deformation" and "destruction". A "deformation" will result only in a change of the aerodynamic characteristics, while a "destruction" will result in both aerodynamic effects and gravimetric effects, as a consequence of mass and center of gravity modifications. The changes of the aircraft inertia are neglected. The mass alteration is modeled as a force opposing gravity equal to the weight of the destroyed component. The aerodynamic alteration is modeled by modifying the values of drag, lift, and/or pitching moment coefficients by factors set by the user.

Two different failure detection and identification (FDI) schemes are available within the *FDI Module* to illustrate how these types of schemes are designed, how they operate, and what their impact is on the general performance and safety of the piloted flight. The first scheme is based on aircraft state estimation using artificial neural networks and comparison with fixed and variable experimental thresholds [18]. The second scheme is based on the artificial immune system paradigm and incorporates a hierarchical multi-self strategy for detection and identification of various failures over wide ranges of the flight envelope [19].

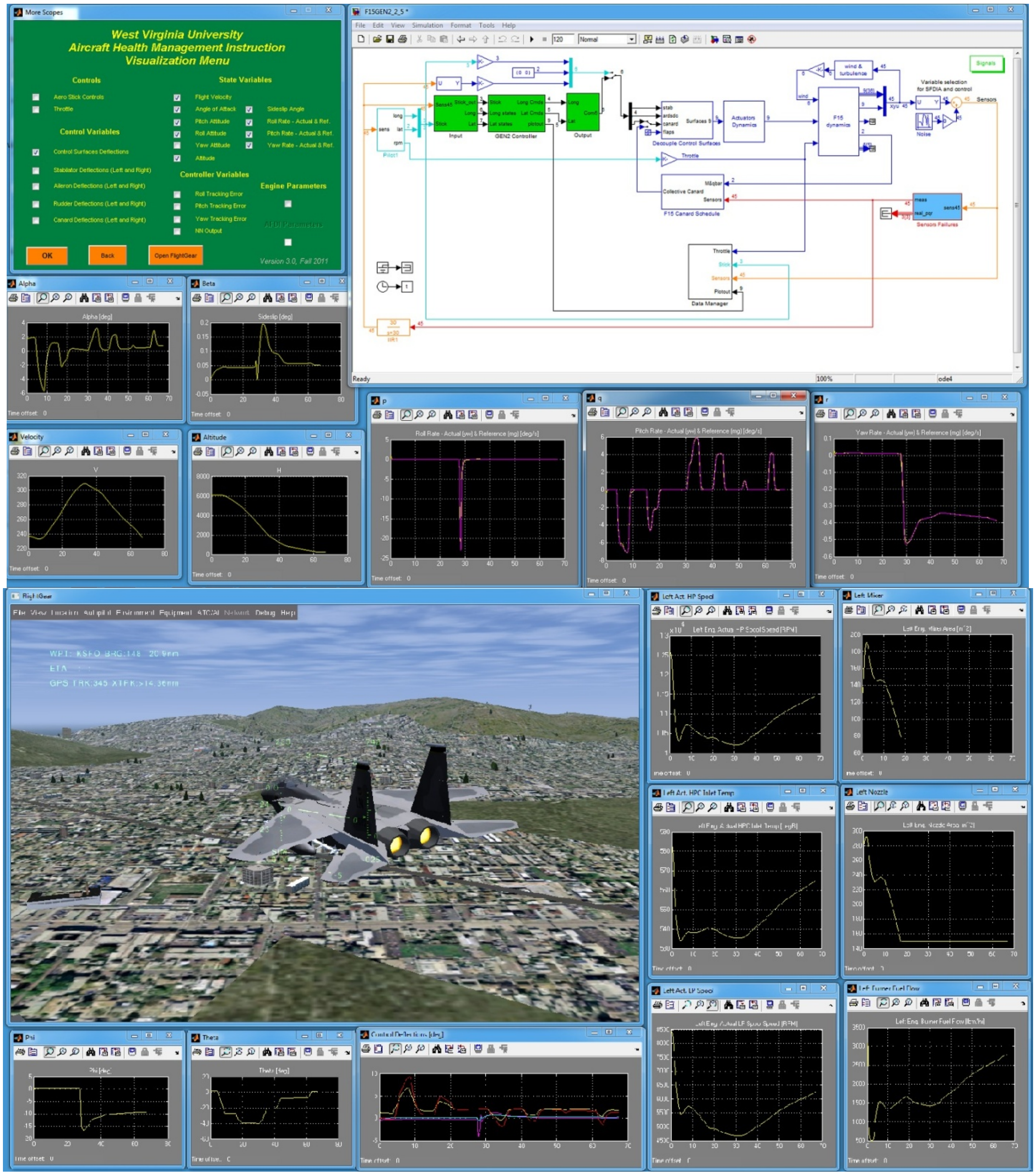


Figure 6. Dual-Screen Interface of the WVU Aircraft Health. Management Instruction Simulation Environment.

Course Assignments and Tests for Active and Experiential Learning

The undergraduate course assignments include two formal homework and six laboratory sessions, which require lab reports. The homework assignments are individual and consist of the following:

HW#01 **–** Literature survey to collect, describe, and analyze causes and implications of three different aviation incidents/accidents due to aircraft sub-system failure/damage.

HW#02 **–** Technical paper report on the application of artificial intelligence techniques to solve an aerospace engineering related problem.

The lab sessions have been designed to integrate within a consistent synergistic framework the lectures with the desktop PC-based simulation and the motion-based flight simulator. The labs are performed in teams of two students; however, it is required that both students are involved equally in all phases of the lab and the lab report must present clear/distinct individual contributions with respect to answers to questions, comments, discussion, and conclusions. A specific format for professionally written lab reports and other technical writings has been prepared, which is distributed to the students as guidelines. The students are required to perform their own experimental designs for all the lab sessions.

The labs cover the following topics:

Lab#01 **–** *Assessment and analysis of the dynamic effects of aircraft actuator failures.* The students use Desktop PC simulation and the WVU 6-DOF motion-based flight simulator to experience the dynamic signatures of a variety of control actuator failures. These include stuck elevator/stabilator, aileron, and rudder at different positions yielding several levels of failure severity. The experiments start on the Desktop PC and continue on the flight simulator for those abnormal conditions at which motion cues are most important. The students are provided with guidelines regarding the maneuvers to be performed and data to be recorded for analysis. The design of these experiments is expected to ensure that the piloting skills required are within what would be reasonably expected from an aerospace engineering student.

Lab #02 - *Assessment and analysis of the dynamic effects of aircraft sensor failures.* The general framework and requirements are the same as for Lab #01. Failure of several sensors used in the feedback control loop, such as gyros, are investigated. The types of failure include sensor bias and output saturation.

Lab #03 - *Assessment and analysis of the dynamic effects of aircraft propulsion system failure and structural damage.* The failures of the propulsion system include stuck throttle and failures of one internal engine actuator and one internal sensor with a stronger fingerprint on the dynamic response of the aircraft. The structural damage is modeled as a reduced aerodynamic efficiency of one of the wings with changes in the weight and center of gravity location. A similar damage affecting the stabilator is also considered. The general objectives and pattern of this lab is similar to Lab #01 and #02.

Lab #04 - *Assessment and analysis of human pilot and environmental abnormal conditions on pilot workload and pilot+aircraft performance.* The first task of this lab session consists of implementing in Matlab/Simulink a simplified pilot model. The model is then used to analyze the effects of the different parameters of the pilot model and how they can be used to simulate pilot abnormal conditions. Finally, the pilot model is used to investigate the effects of atmospheric turbulence on pilot workload.

Lab #05 - *Evaluation of parameter identification techniques for abnormal flight condition detection and accommodation.* The students are given the opportunity to implement in Simulink/Matlab a least square regression algorithm for aircraft PID and test a frequency domain method for on-line prediction of stability and control derivatives to be used for fault tolerant control laws update.

Lab #06 *- Assessment and analysis of fault tolerant adaptive control laws.* The purpose of this lab is to assess and analyze the operation of a set of representative adaptive fault tolerant control laws in the presence of aircraft actuator failures using the WVU 6-DOF motion based flight simulator. The control laws are based on non-linear dynamic inversion augmented with artificial neural networks. This class of control laws and the main concepts associated with it are briefly introduced in class. The students are required to design, execute, and interpret an experiment in the motion based flight simulator with the objective being to reveal the operation of fault tolerant adaptive control laws.

There are five tests/extended quizzes designed to additionally assess if the learning outcomes have been achieved. Some of them have the classic format (Tests #04 and #05), consisting of proposed problems and questions. Others are experimental tests (Tests #01, #02, and #03) that require the students to be prepared (design an experiment) to face an unknown situation (abnormal flight condition) within a given category, define it, analyze it, and take/propose counter measures. The experiment-based tests are designed as a natural continuation of corresponding lab sessions. There is no final exam for this course. The five tests/quizzes address the following topics:

Test #01 *– Design and perform a test in the WVU motion base flight simulator to detect and analyze an actuator failure.* The students will be exposed to an unknown actuator failure at an undisclosed moment. They are required to design the experiment (prior to the administration of the test) and perform it (as part of the test) such that they are capable to detect the failure and compensate in real time and identify and evaluate the failure at post-flight condition based on recorded data. The test takes place in the WVU 6-DOF motion-based flight simulator.

Test #02 *– Design and perform a test in the WVU motion base flight simulator to detect and analyze a sensor failure.* The objectives and general layout of the test is similar to Test#01, but it addresses failures of aircraft sensors that are used in the closed-loop feedback.

Test #03 *– Design and perform a test in the WVU motion base flight simulator to detect and analyze a propulsion failure or damage on main structural components.* The objectives and general layout of the test is similar to Test#01, but it addresses propulsion system failures and aerodynamic surface (wing and stabilator) damages.

Test #04 *– Human pilot abnormal conditions. Environmental upset conditions. Parameter identification and estimation.* The students are required to answer general/conceptual questions on these topics. They are expected to be familiar with modeling approaches, dynamic effects of abnormal conditions, and the main classes of commonly used PID techniques and their principles.

Test #05 *- Aircraft sub-system abnormal condition detection, identification, evaluation, and accommodation.* The students should be able to define these processes and be familiar with the basic characteristics and principles of commonly used methodologies covered in class and during the lab sessions.

Evaluation of Impact on the Learning Process

The course was offered for the first time in Fall Semester 2010 as MAE493M, a Technical Elective for Aerospace Engineering majors and Dual Aerospace and Mechanical Engineering majors. An enrollment of 22 students was recorded.

To assess the impact of the simulation-based approach on the learning process, several evaluation tools were used. In order to determine how the students perceived the active and experiential approach, an anonymous questionnaire [20] was administered in two steps to the students attending the undergraduate course. The questionnaire was adapted through minor modifications from reference [20] and included 19 implicit questions. Three example questions are presented in Table 1. The students were given two extreme alternative answers and asked to evaluate their perception on a scale from 1 to 7. The questionnaire was first administered at the beginning of the semester and the students were asked to evaluate three previously taken courses in a similar technical area, which had not benefited from simulation support. The three courses were *MAE-365 Flight Dynamics*, *MAE-426 Flight Vehicle Propulsion*, and *MAE-434 Experimental Aerodynamics*. The students were asked to provide the same info for a fourth "similar" course of their choice or a replacement, if necessary. The courses for which responses have been recorded and the number of respondents are listed in Table 2. Courses with only one respondent have not been included.

Table 1. Questionnaire [20] for Assessment of Student Course Perception – Sample Questions.

No.	Positive perception	Circle one	Negative perception
8.	I felt I could express myself easily and freely	7 6 5 4 3 2 1	My self-expression was difficult and/or discouraged
11.	Labs and/or assignments were very interesting and increased my motivation	7 6 5 4 3 2 1	Labs and/or assignments were **not** interesting and **did not** increase my motivation
14.	I felt the course required me to exercise a great deal of initiative	7 6 5 4 3 2 1	I felt the course required me to exercise very little initiative

Table 2. Courses Used in the Evaluation.

Course Nr.	Course Title	Number of Respondents
MAE-365	Flight Dynamics	19
MAE 426	Flight Vehicle Propulsion	13
MAE 434	Experimental Aerodynamics	13
MAE 336	Compressible Aerodynamics	7
MAE 335	Incompressible Aerodynamics	6
MAE 345	Aerospace Structures	6
MAE 215	Introduction to Aerospace Engineering	4
MAE 460	Automatic Controls	3
MAE 242	Dynamics	2
MAE 316	Analysis of Engineering Systems	2
MAE 331	Fluid Mechanics	2

At the end of the semester, the students were required to complete the same questionnaire, this time for the MAE-493M course. The results have been processed and are presented in Table 3 for each of the courses recorded, for the group of three significantly similar courses (MAE 365, 426, and 434) as average and weighted average by the number of respondents, for all 11 courses with more than 2 respondents, as average and weighted average by the number of respondents. In Table 3, the responses are averaged over all 19 questions (first column) and over groups of questions defined as follows.

- Group A – Questions #9, #10, and #11 related to the relevance and effectiveness of the interactive, experiential approach.
- Group B – Questions #8, #13, #14, and #15 related to the level and impact of the active learning environment.
- Group C – Questions #1, #2, and #17 related to the general level of student satisfaction.
- Group D – Questions #5 and #7 related to the perception of the learning process.
- Group E – Questions #18 and #19 related to the teaching style and instructor personality.

The results in Table 3 show that MAE-493M has received overall better evaluations based on all metrics when compared to the averages of the 3 most similar courses and the averages of all courses considered. With respect to individual courses, a few cases are recorded and highlighted that achieve higher ratings for some of the metrics (14 cases out of 66). It should be noted that this happens mostly for courses with only 3 and 2 respondents (9 cases out of 14). Analyzing only the courses with larger number of respondents (7 courses), it can be seen that MAE-493M receives higher ratings for the average over all 19 questions, for the average over Group B and for the average over Group E. Only one course achieves higher rating than MAE-493M as measured by the averages over

Table 3. Student Perception of Educational Environment (Undergraduate Course).

Course Nr.	Average Score 19 Questions	Group A	Group B	Group C	Group D	Group E
MAE-365	5.45	5.11	5.03	5.72	4.74	5.05
MAE 426	5.87	6.00	5.29	6.54	5.39	6.35
MAE 434	5.58	5.74	4.90	5.85	5.38	6.04
MAE 336	5.20	5.33	4.86	5.33	5.07	5.58
MAE 335	5.36	5.00	5.63	5.33	4.17	6.42
MAE 345	4.80	4.67	4.58	4.72	4.58	4.75
MAE 215	5.54	5.67	4.94	6.00	5.50	6.25
MAE 460	6.05	6.11	5.75	6.56	5.50	5.67
MAE 242	5.29	4.83	5.25	5.33	4.50	4.75
MAE 316	3.82	2.50	5.75	1.67	3.00	3.75
MAE 331	6.11	6.50	5.25	6.50	6.00	7.00
MAE493M	5.97	5.81	5.87	6.08	5.29	6.79
All 3 Similar Course	5.63	5.61	5.07	6.03	5.17	5.81
All 3 weighted	5.61	5.55	5.07	5.99	5.11	5.71
All 11	5.37	5.22	5.20	5.41	4.89	5.60
All 11 weighted	5.43	5.37	5.10	5.69	4.98	5.66

Group of questions A and C. These results demonstrate that the design and implementation of MAE-493M using interactive, experiential, and active learning approaches was successful and was perceived positively by the students. In response to question Group D, three courses received higher evaluations than MAE-493M. Question Group D is related to the perceived "difficulty" of the course. This result can be interpreted as being due to the fact that the learning process was not so much "more difficult" but rather "different" as compared to what the students were used to.

Due to logistics constraints, the use of a "witness" student group was not possible. To gain some partial insight into the impact the proposed approach has on knowledge acquisition, a second evaluation tool was used in the form of a basic question quiz administered first immediately after the lecture and then after the lab, a week later. Only Lab #1 was targeted due to time limitations. The 4 questions of the quiz are listed below.

For all questions assume that the aircraft is initially flying at steady state conditions, forward, uniform, horizontal, symmetrical flight and all controls are at trim.

1). At some moment, the left elevator is locked at trim position. You do not change the cockpit controls. Describe what happens and explain why.
2). At some moment, the left elevator moves by +6 degrees and remains locked there. Describe what happens and explain why.
3). At some moment you realize that your lateral control efficiency is reduced to half (for the same lateral deflection of the stick, the roll rate is only half of what it used to be). What kind of problem is likely to have occurred?
4). Without any pilot input, the aircraft starts to roll to the left. List and briefly describe all actuator failures that could cause this behavior.

The grades obtained by the 21 students who took the quiz before and after the lab are listed in Table 4. Each question was worth 25 points out of 100. Out of the 21 participating students, 16 students achieved better grades after the lab, 2 students achieved lower grades after the lab, and 3 students achieved the same grades before and after the lab (2 of them received maximum 100 points). The class average before lab was 67.52 and after lab, 85.14. Obviously, the lab contributed significantly to learning; however, it is still an open question, to what extent the result is due to the interactive/experiential approach as opposed to a more standard format.

Conclusions

An undergraduate course addressing technical issues of aircraft health management has been designed based on flight simulation tools to implement active and experiential learning methodologies.

The flight simulation environment has been proved to be an effective instrument in enhancing aerospace engineering students learning in the area of modeling, detection, evaluation, monitoring, and accommodation of abnormal aerospace systems operation.

Table 4. Results of "Before Lab" and "After Lab" Tests.

Test	Grades out of 100																				
Pre Lab	70	90	80	45	65	60	90	100	60	85	70	40	30	80	63	100	45	55	45	100	45
Post Lab	95	98	100	95	65	85	100	80	90	70	95	65	70	100	80	100	70	75	85	100	70
Improve	+	+	+	+	0	+	+	-	+	-	+	+	+	+	+	0	+	+	+	0	+

Although the impact assessment performed is partial and limited, it leads to the conclusion that the hands-on approach is beneficial and that the extensive use of simulation tools and particularly the motion-based flight simulator improves the learning process by facilitating concept understanding and increasing the motivation and interest of the students.

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