TEACHING AIRCRAFT HEALTH MANAGEMENT – A SIMULATION-BASED APPROACH

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Abstract

This paper presents the development of an innovative educational framework in the area of aircraft operational safety from a technological/engineering point of view based extensively on flight simulation. The paper focuses on the design of two courses at the undergraduate and graduate level relying on a set of customized simulation tools, which integrate PC-based simulation with a 6 degrees-of-freedom motion-based flight simulator. The overall objective of this effort is to provide undergraduate and graduate aerospace engineering students with advanced knowledge and skills in the area of modeling, detection, evaluation, monitoring, and accommodation of abnormal conditions for aerospace systems. Failures of various vehicle sub-systems (actuators, sensors, structure, and engine) as well as adverse atmospheric conditions and abnormal human pilot conditions are addressed. It is expected that this approach will considerably enhance the academic process by producing an experiential environment to directly connect theory and practice, causes and effects, engineering design parameters and performance impact.

Introduction

Safety of aircraft operation is becoming increasingly important in the context of enhancing vehicle performance and envelope[1]. This trend is expected to continue at a faster rate in the near future. The aerospace engineering community is currently involved in numerous projects addressing a wide range of issues related to the analysis, prevention, early detection, and accommodation of abnormal conditions and malfunctions of aerospace systems. New concepts such as *Integrated Vehicle Health Management*[2,3] and *Integrated Resilient Aircraft Control*[4] have received substantial attention in recent years toward the goal of increasing safety. It is critical that adequate expertise in this domain is available on a large scale as soon as possible and that future workforce acquire necessary knowledge, skills, and capabilities.

The benefits of integrating into curricula emerging new technologies in general and simulation in particular and their expected impact on education are widely acknowledged[5,6]. PC-based and especially motion base flight simulators – whenever affordable – can be extremely useful educational tools for aerospace engineering. They have been used successfully to support courses in flight mechanics and design[7,8], aircraft performance[9], testing[10], aircraft dynamics, controls and flight simulation[11].

The focus of this paper is on the design and implementation of academic activities and computational tools to provide undergraduate and graduate aerospace engineering students with advanced knowledge and skills in the area of modeling, detection, evaluation, monitoring, and accommodation of abnormal aerospace systems operation. Models of a variety of failures/damages of primary aircraft sub-systems such as actuators, sensors, structural components, and engine, as well as models of adverse atmospheric conditions and abnormal human pilot behavior are integrated to provide first hand experience on the dynamic implications of these factors, how their occurrence can be detected, and how their undesirable effects can potentially be mitigated. PC-based simulation and the West Virginia University (WVU) 6-degrees-of-freedom (DOF) motion based flight simulator are combined to support two courses at undergraduate and graduate level in the area of aircraft health monitoring and abnormal conditions compensation. The use of motion cues in analyzing aircraft sub-system failures is important due to their contribution to the failure dynamic signature and the detection process. This approach enhances considerably the academic process by producing an experiential environment to directly connect theory and practice, causes and effects, engineering design parameters and performance impact. The design of this educational package attempts to blend active learning[12,13] and experiential learning[14] to achieve effective and efficient student engagement in the learning process.

Flight Simulation Technologies at WVU

The Department of Mechanical and Aerospace Engineering (MAE) at WVU integrates flight simulation technologies of different levels of complexity within the aerospace engineering curriculum with the broader objective of supporting courses in flight dynamics, simulation, controls, aerodynamics, and aircraft design[11]. The MAE Flight Simulation Laboratory (Figure 1) includes 14 stations with high-end desktops, accurate joysticks, and advanced graphic cards with dual monitors (Figure 2) - one for cockpit and out-of-windows display and one for simulation control and management. The WVU 6DOF motion base flight simulator (Figure 3) manufactured by Fidelity Flight Simulation, Inc., Pittsburgh, PA, offers a very realistic flight environment with extremely low operational and maintenance costs[15]. The system includes the following components:

- 6 DOF motion platform driven by electrical induction motors
- Laminar Research X-Plane flight simulation software[16]
- LCD mosaic wall four-monitor external visual display
- Instructors operating station
- Computer and control cabinet

Figure 1. MAE Flight PC-Based Simulation Laboratory.

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

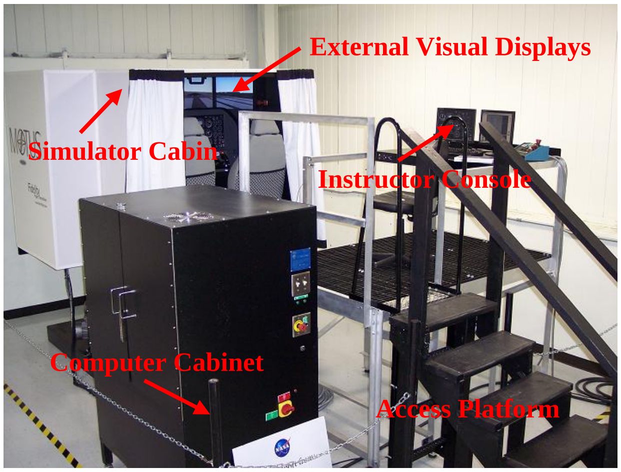

Figure 3. The WVU 6 – DOF Flight Simulator System.

The motion platform driven by electrical motors provides desirable and cost-effective 6-DOF translational and rotational motion cues.

Laminar Research X-Plane[16] is a commercial flight simulation package featuring high capabilities and flexibility in selecting the simulation scenario. It includes a large database of aircraft, airports, and sceneries around the world. Weather conditions can be selected prior and during the simulation to include cloud layers, wind and turbulence, temperature, runway condition, and a wide variety of visibility, precipitation, and other weather parameters. Additionally, malfunctions of the aircraft systems can be simulated in the following categories: overall, instruments, equipment, engine, engine systems, and flying surfaces. New aircraft models can be introduced into the database using the aerodynamic capabilities of X-Plane.

The 2-seat cockpit accommodates dual controls and instrument clusters (shown in Figure 4). Visual information in the cockpit is provided by a total of 6 LCD visual displays. Two visual displays host the instruments clusters while four monitors provide the external visual cues.

Figure 4. Visual Displays, Controls and Instrument Clusters.

A customized software has been designed by WVU researchers such that the simulator has been interfaced with an external computer on which aircraft mathematical models can be run within the Matlab/Simulink environment – in lieu of the default X-Plane environment - to drive the entire simulator system (see Figure 5). Therefore, pilot input signal are transferred from the simulator cockpit into the Matlab/Simulink model. The outputs of this model are sent to X-Plane, for the control of all the simulator sub-systems including the generation of visual cues. However, the connection of X-Plane to the motion computer is deactivated and the signals from the external computer are sent directly to the motion computer, which drives the motion base. This set-up allows the use of any Simulink aircraft model including customized failures to drive the simulator.

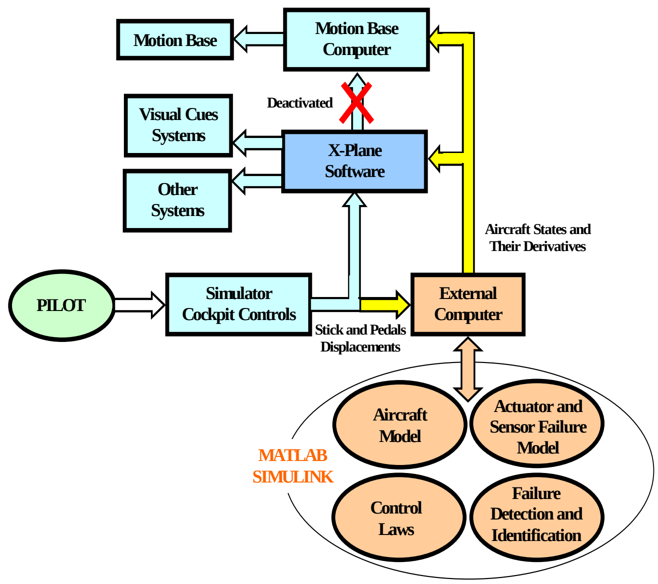

Figure 5. Interface of the WVU Flight Simulator with External Models.

Development of the Undergraduate Course *Introduction to Aircraft Health Management*

The objectives of the undergraduate level course *Introduction to Aircraft Health Management* are the following:

- 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 abnormal flight conditions addressed within this course can be categorized as:

- Related to the airframe:
  - primary control surface failures;
  - sensor failures;
  - engine failures and malfunctions;
  - structural damages to aerodynamic surfaces.
- Related to the human pilot:
  - fatigue;
  - excessive workload.
- Related to the environment:
  - atmospheric turbulence;
  - wind and wind shear;
  - icing.

In terms of learning outcomes, after the successful completion of the undergraduate course, the students are expected to be able to:

- 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 explain their principles.

Development of the Graduate Course *Aircraft Health Management*

The graduate level course lists as pre-requisites the previous undergraduate course as well as an advanced course in automatic controls. Since Matalab/Simulink is the selected computational environment, a detailed knowledge of these packages is also required. The same categories of abnormal conditions will be addressed within both courses. However, the graduate level course *Aircraft Health Management* is designed with the following objectives:

- Provide an overview of modeling and simulation techniques of abnormal flight conditions;
- Provide an overview of current methodologies for the design of safety monitoring schemes;
- Provide an overview of current methodologies for the design of schemes for abnormal flight situation detection, isolation, and identification;
- Provide an overview of current methodologies for the design of fault-tolerant control laws;
- Demonstration of performance assessment of safety monitoring schemes, fault-tolerant control laws, and schemes for abnormal flight situation detection, isolation, and identification using PC-based simulation and a 6- DOF motion based flight simulator;
- Evaluation of the impact of abnormal flight situations on reducing aircraft flight envelope;
- Assessment of reduced flight envelope using PC-based simulation and a 6- DOF motion based flight simulator.

This course is designed around a student team project involving the design of a major component of an aircraft health management system such as:

- aircraft actuator fault detection scheme;
- warning system with reduced flight envelope definition following system failure;
- safety monitoring system for intelligent adaptive control laws.

The topics and the details of the team projects are established based on students research interests and preferences from a flexible and wide area. Whenever appropriate, references to incidents in commercial aviation will be introduced to the students. This approach enhances student motivation and involvement with extremely positive impact on the effectiveness of the learning process. Student designs are typically tested and demonstrated in the WVU 6-DOF flight simulator.

In terms of learning outcomes, after the successful completion of the graduate course the students will be able to:

- Develop, implement, and test models of abnormal flight conditions using pre-exiting PC-based and motion based flight simulators;
- Design aircraft health/safety monitoring schemes;
- Design fault-tolerant control laws to accommodate for single element failure;
- Design schemes for abnormal flight situation detection, isolation, and identification;
- Use simple algorithms to estimate the flight envelope reduction following typical system failures;
- Design simulation scenarios/tests for the testing, tuning, and evaluation of aircraft health monitoring and accommodation systems.

Development of Simulation Tools

A Matlab/Simulink-based simulation environment has been developed to simulate all abnormal flight conditions covered within the undergraduate and graduate courses on aircraft health management. Several types of failures within each of the categories listed in the previous section were modeled and implemented. Upset atmospheric conditions are simulated such as turbulence, wind shear, and icing. Abnormal condition detection schemes are included to increase pilot situational awareness and to support fault tolerant control laws. The general conceptual diagram of this environment is presented in Figure 6.

Detailed graphical user interface (GUI) menus allow the students to set up the simulation scenarios. The input GUI will allow to specify:

- the faulty aircraft component (e.g. left elevator or pitch rate gyro, etc.);
- the type of failure (e.g. locked control surface or sensor bias, etc);
- the magnitude of the failure (e.g. locked surface at trim + 10degrees);
- the time at which the failure occurs;
- the activation of detection schemes;
- the activation of fault-tolerant control laws.

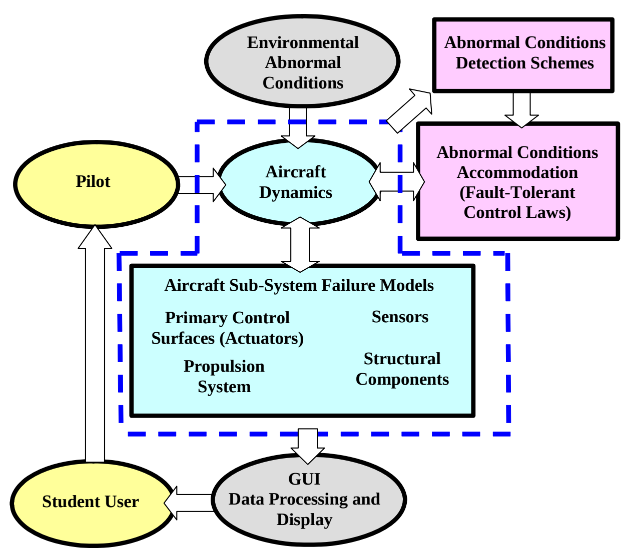

Figure 6. Conceptual Diagram of the Simulation Environment.

Both fixed and rotary wing aircraft are modeled and simulated. Examples of set up menus for actuator and sensor failure scenarios are shown in Figures 7 and 8, respectively. The set-up menu for the structural damage scenario is presented in Figure 9. A propulsion system malfunction can be set-up using the GUI menu displayed in Figure 10. Finally, the set-up menu in Figure 11 allows the simulation of an upset flight conditions scenario for a helicopter.

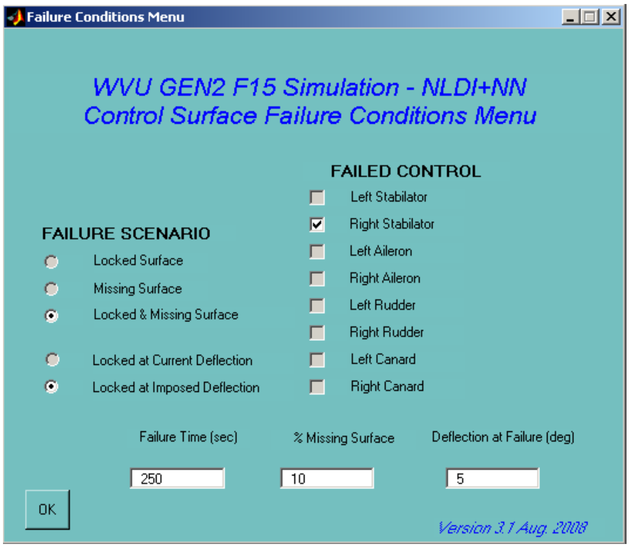

Figure 7. Graphical User Interface – Primary Control Surface Failure Menu.

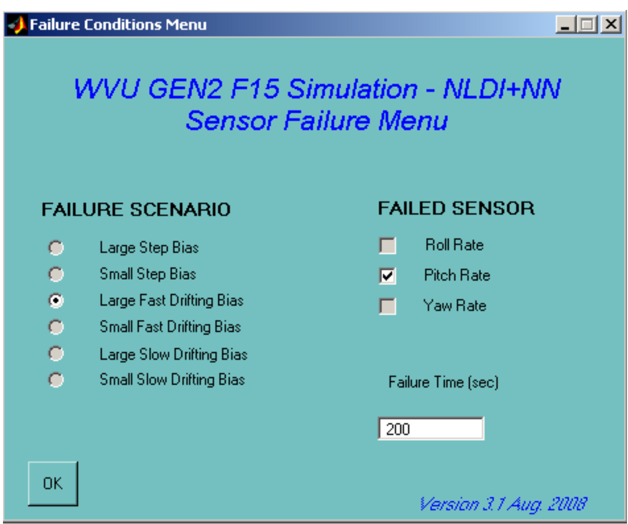

Figure 8. Graphical User Interface – Sensor Failure Menu.

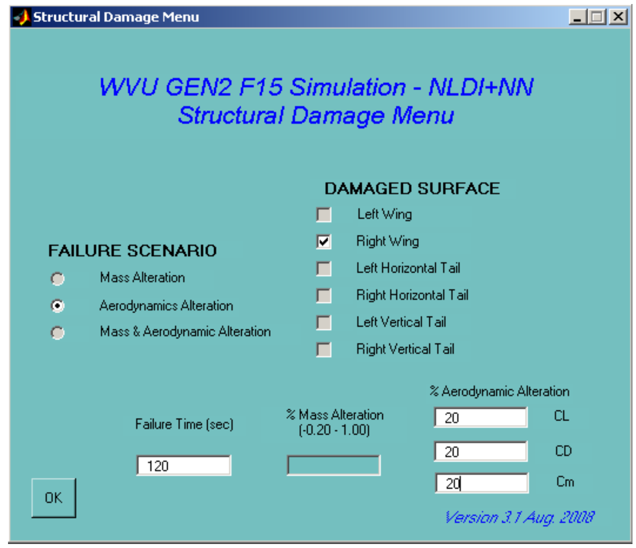

Figure 9. Graphical User Interface – Structural Damage Menu.

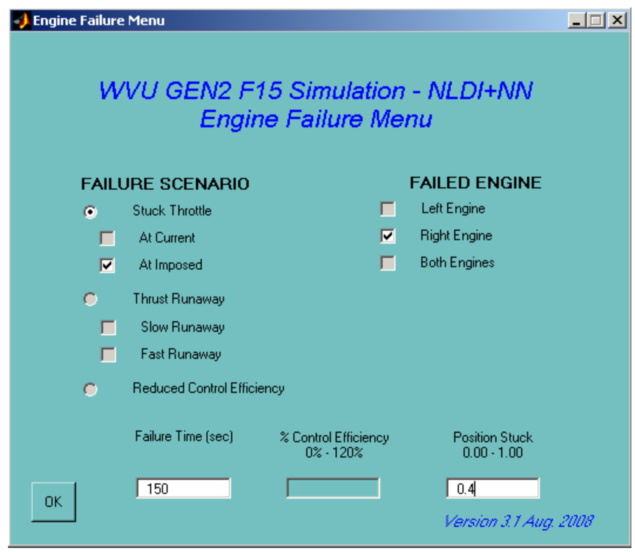

Figure 10. Graphical User Interface – Propulsion System Malfunction Menu.

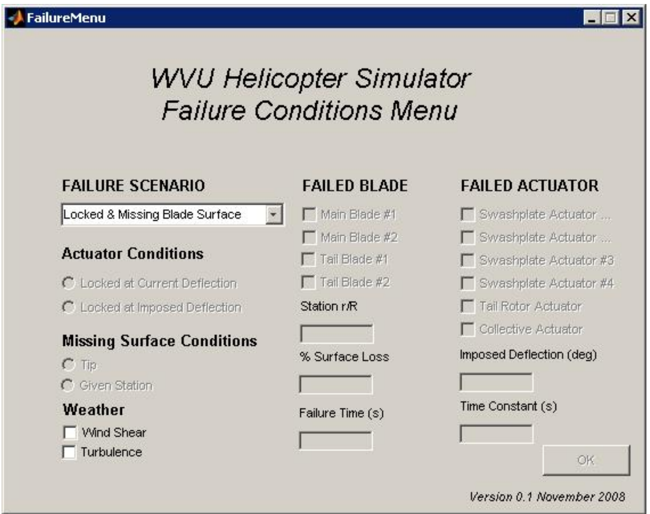

Figure 11. Graphical User Interface – Helicopter Abnormal Condition Menu.

Several abnormal condition detection schemes based on different theoretical approaches are implemented to illustrate how this type of schemes are designed, how they operate, and what their impact is on the general performance and safety of the piloted flight. One design methodology features sensor output and artificial neural network predictions for detecting failures of aircraft actuators and sensors[17]. Another approach is based on a new artificial intelligence paradigm - the artificial immune system[18] - and can detect failures of the actuators, sensors, engines, and wing structural components, identifying at the same time the failed element. The students are introduced to the properties and capabilities of the artificial immune system design via an interactive design tool based on evolutionary algorithms. The portal to this tool is presented in Figure 12.

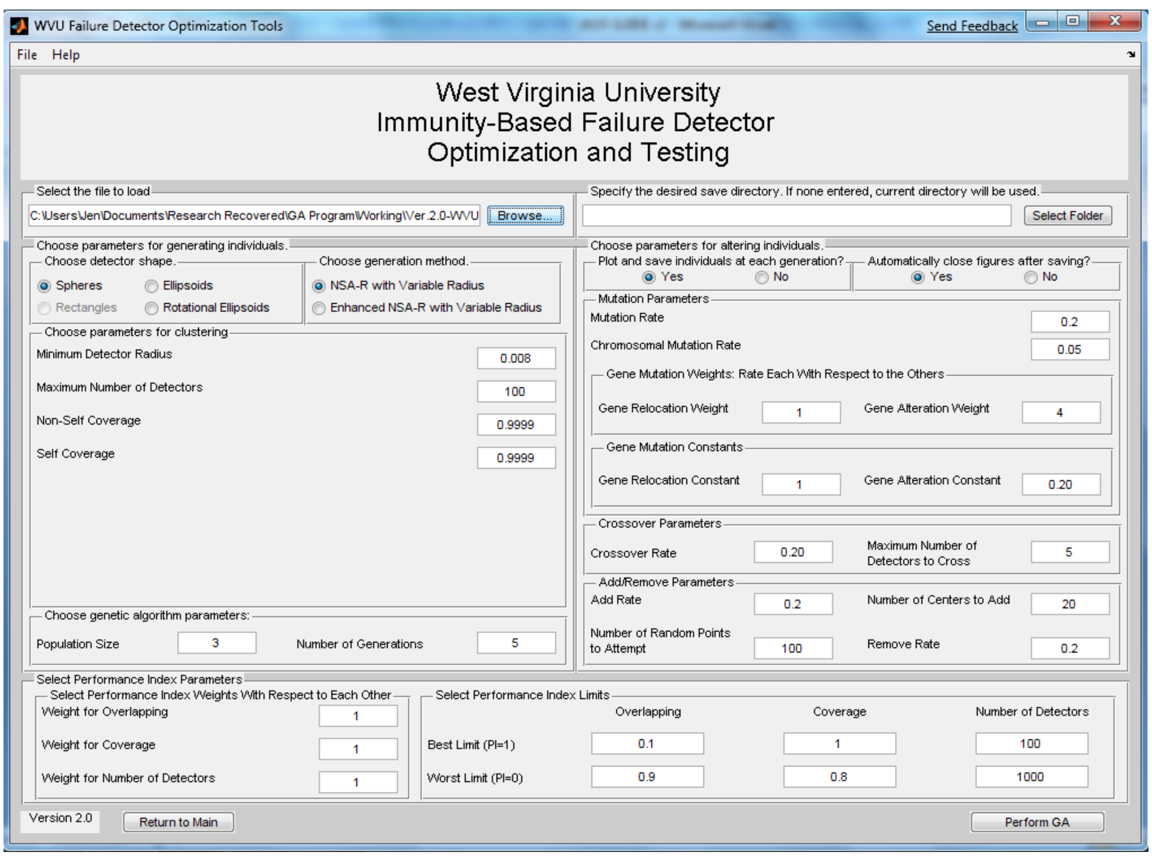

Figure 12. Artificial Immune System Detector Optimization Main Menu.

Figure 13. Pilot Fatigue Detection Demo.

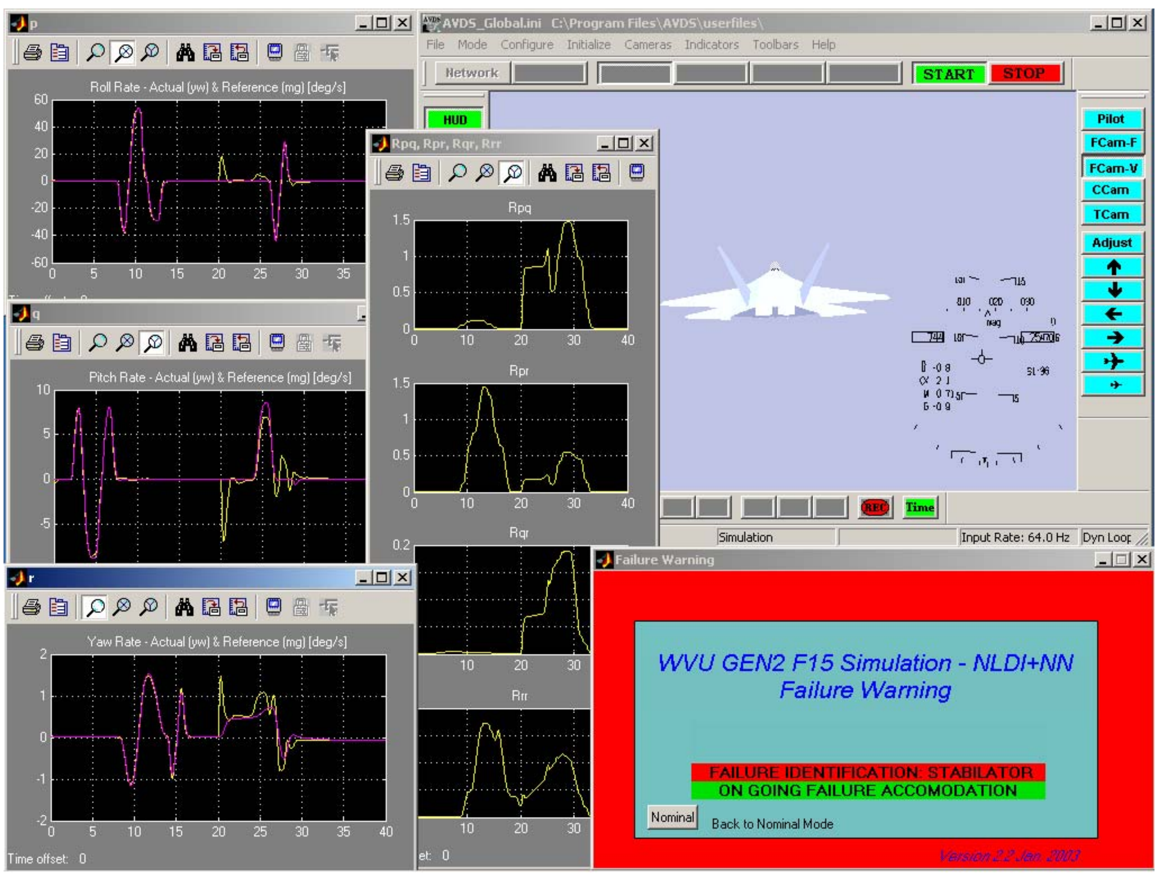

Figure 14. WVU PC-Based Simulation Environment Graphics.

Pilot abnormal conditions - such as fatigue and excessive workload - can have a significant impact on the dynamics of the pilot+aircraft system and usually represent serious threats to flight safety. A demonstration tool is included featuring flight simulator test data to illustrate the differences that occur in pilot performance for specific classes of maneuvers when the pilot is “tired” as compared to when he/she is “rested”[19]. The demo interface is shown in Figure 13.

Adaptive fault tolerant control laws based on non-linear dynamic inversion and artificial neural network augmentation[17] are implemented. The students can select among several classes of neural networks and modify the main design parameters in order to be able to understand how they work and what impact the design parameters have on the general performance and stability of the adaptive control system.

All the simulation tools can run as PC-based simulation and they also can be interfaced with the MAE 6-DOF motion based flight simulator as described in Figure 5. The motion base simulations will benefit from visual cues and instrument displays generated through X-Plane (as shown in Figure 4). The desktop computer-based simulations rely on monitoring time histories of significant parameters through regular Simulink displays and on external visual cues produced using the Matlab Virtual Reality Toolbox or the Aviator Visual Design Simulator[20] as shown in Figure 14.

These tools have the flexibility of allowing the students to design their experiments for better understanding of the material covered in class, for integrated perception of sub-system roles and effects on general aircraft dynamics, and to explore and gain new knowledge at their own initiative.

The integration into the curriculum of the new growing area of aircraft health monitoring by applying such innovative educational methods through the extensive use of flight simulation is expected to:

- Enhance the aerospace engineering curriculum by bringing into the classroom interesting and significant real world problems;
- Provide an excellent framework for improved learning effectiveness;
- Provide the students and the teachers with the framework for discovering new questions to be asked and new issues to be solved;
- Provide the students and the teachers the framework for more direct iterative interaction and increased mutual feedback;
- Provide the students with the opportunity to experience issues related to abnormal flight condition from a pilot point of view, thus reducing the gap between the aerospace engineer and pilot;
- Provide the aerospace industry with a pool of graduates with a strong background and skills in a new technical area of growing interest and importance.

Conclusions

Two courses on aircraft health management at the undergraduate and graduate level have been designed relying on advanced instructional techniques such as active and experiential learning.

A set of complex computational tools have been developed to support teaching the two courses on aircraft health management with the objective of providing the aerospace engineering students with advanced knowledge and skills in the area of modeling, detection, evaluation, monitoring, and accommodation of abnormal aerospace systems operation.

The extensive use of computer simulation and in particular motion-based simulators for teaching aerospace engineering courses in the wide area of flight dynamics and controls has an important impact on the academic process through the enhancement of active and experiential learning.

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