UNDERGRADUATE EXPERIENTIAL LEARNING LAB FOR AIRCRAFT PARAMETER IDENTIFICATION

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Abstract

This paper presents the design of an active and experiential lab assignment for undergraduate introduction to aircraft parameter identification. This lab assignment relies on advanced simulation tools developed in Matlab and Simulink. It was conceived as part of an undergraduate aerospace engineering technical elective course currently taught at West Virginia University with the objective of introducing students to technical topics relevant to aircraft health management. However, it can be easily incorporated into other courses on dynamic systems. The lab assignment is designed to provide training in implementing simple system identification algorithms, assessing their performance, and investigating their applications. The instructor experience and student feedback confirm that aircraft system identification can be successfully introduced at the undergraduate level and that the active and experiential learning approaches utilized are perceived positively by the students and significantly enhance the academic process.

Introduction

Modeling, simulation, and control of dynamic systems have been widely acknowledged as key enabling technologies for economic and social progress in the current century [1]. The demand for engineers with adequate background for developing and using tools in these areas is likely to increase significantly posing specific challenges to the engineering educational system [2]. System identification [3] encompasses a set of methodologies addressing the problem of building mathematical models of dynamic systems based on experimental data. These methodologies are widely used in a variety of engineering fields; however, a lack of system identification education has been recognized [4] outside the electrical engineering curriculum.

The introduction of system identification (SI) into the curriculum of other engineering areas faces significant challenges generated by the need of adequate mathematical background, the specificity of dynamic systems pertinent to the different engineering areas, and the availability of flexible and user-friendly dedicated software tools. Several efforts have been recently directed towards the development of software tools to support SI education at the undergraduate level. A computational package consisting of graphical interfaces illustrating the various stages of system identification has been developed for an open loop 5th order generic system [5,6]. Matlab libraries have been used as primary tools for generic SI laboratories for closed-loop modeling [7], SI based on frequency response [8], and SI for industrial process control [9].

The importance of practical, hands-on experience provided by laboratory settings has been acknowledged widely for the engineering curricula [10]. SI is one of the areas where the support of lab assignments in conjunction with active and experiential learning approaches [11-13] become indispensable due to the need of balancing the high level of abstraction of the algorithms involved and relating the SI process to the real-world systems and their practical significance [14].

Recent efforts [15] at West Virginia University (WVU) have been focused on integrating, within the academic curriculum, significant aspects relevant to aircraft health management (AHM). Advanced simulation tools [16,17] have been developed to support a

senior level technical elective course [18] aimed at introducing basic concepts and methodologies for aircraft sub-system abnormal conditions modeling, detection, evaluation, monitoring, and accommodation. In this context, approximately 5 contact hours (lecture and lab) are dedicated to SI as one of the primary methodologies used. The lab assignment presented in this paper was designed based on active and experimental learning approaches to provide training in implementing simple system identification algorithms, assessing their performance, and investigating their application for abnormal condition detection and accommodation. The lab assignment is described and briefly evaluated. The classroom implementation demonstrates that aircraft SI can be approached within the undergraduate aerospace engineering curriculum in a meaningful manner with reasonable resources.

SI Lab Supporting Background

A pre-requisite course in flight dynamics is desirable; however, the SI lab could be included in courses in other fields if only a few basic elements of aircraft modeling are provided to the students, as presented in this section.

Prior to the lab assignment, the students are provided with a handout covering some basic general concepts related to dynamic system modeling, SI, and parameter estimation techniques.

Basic concepts related to system modeling and model postulation are first introduced, such as assumptions, axioms, constitutive equations and their principles, and the main phases of the mathematical modeling process. The specifics of modeling aerospace vehicles are then briefly reviewed along with the set of 12 non-linear first order differential equations that typically model the dynamics of the aircraft as a rigid body. Within these equations, the aerodynamic forces and moments are critical components representing the result of very complicated physical phenomena. The contributions and significance of various parameters depend on the flight conditions and vehicle. However, it can be stated that – in general – the aerodynamic forces and moments are primarily non-linear functions of the aircraft states (x_i), their derivatives ($\dot{x}_i$), control deflections (u_j), and other parameters (p_k) including geometric, gravimetric, and airfoil characteristics.

If FM is any of the aerodynamic forces or moment components in an aircraft body axes, then:

$$FM = FM(x, \dot{x}, u, p) \tag{1}$$

It is convenient to express the components of the forces F and moments M in terms of non-dimensional coefficients:

$$C_F = \frac{F}{\frac{\rho}{2}SV^2} \tag{2}$$

$$C_M = \frac{M}{\frac{\rho}{2}SlV^2} \tag{3}$$

where ρ is air density, S is the wing area, V is velocity, and l is a reference length.

The resultant force is typically resolved with respect to the wind coordinate system W first and then the components are expressed with respect to the aircraft body axes B to be used in the force equations [19].

$$[\vec{F}]_W = \begin{bmatrix} D \\ Y \\ L \end{bmatrix}_W = \frac{\rho}{2}SV^2 \begin{bmatrix} C_D \\ C_Y \\ C_L \end{bmatrix}_W \tag{4}$$

$$[\vec{F}]_B = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_B = \frac{\rho}{2}SV^2 \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix}_W \tag{5}$$

The resultant moment is resolved with respect to the aircraft body axes:

$$[\vec{M}]_B = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}_B = \frac{\rho}{2} SV^2 \begin{bmatrix} bC_x \\ cC_y \\ bC_z \end{bmatrix}_W \qquad (6)$$

The non-linear functions in Equation (1) – and the corresponding non-linear functions that describe the force and moment coefficients in Equations (2) and (3) for that matter - can be polynomials or just look-up tables. Based on Taylor series expansion, these coefficients can also be expressed linearly (1st degree polynomials) in terms of the independent variables. For example:

$$C_L = C_{L0} + C_{LV}\hat{V} + C_{L\alpha}\alpha + C_{L\beta}\beta + C_{Lp}\hat{p} +$$

$$C_{Lq}\hat{q} + C_{Lr}\hat{r} + C_{L\dot{\alpha}}\hat{\dot{\alpha}} + C_{L\dot{\beta}}\hat{\dot{\beta}} + \sum_{i=1}^{n} C_{L\delta_i}\delta_i$$

$$(7)$$

where $\hat{x}$ is the non-dimensional x. In this example, the following variables are considered: velocity (V), angle of attack (α), sideslip angle (β), roll rate (p), pitch rate (q), yaw rate (r), and control surface deflections - elevator, rudder, aileron, flaps, aerodynamic brakes, etc – (δ_i). All C coefficients are defined in general (except the first term) as:

$$C_{FMx} = \frac{\partial C_{FM}}{\partial \hat{x}}\bigg|_0 \qquad (8)$$

In this formulation it is assumed that all variables are differences with respect to a reference flight condition (denoted by *0*) and that all *C* coefficients are calculated at that reference flight condition.

The derivatives with respect to state variables are also called "stability derivatives" and the derivatives with respect to control variables are called "control derivatives". Note that in this format the expressions for the force and moment coefficients are valid only in the vicinity of the reference flight condition. However, the derivatives can be scheduled depending on

relevant variables to extend the validity over larger portions of the flight envelope. ***A typical objective of the SI process for aircraft modeling is the determination, from flight data, of these derivatives.***

SI is the process through which a model of the system can be determined, if histories of inputs and the corresponding outputs are known. Most often, a structure of the model is selected and fixed and only the parameters of the model are determined, such as in the example above. In this case, aircraft system identification becomes a parameter identification or parameter estimation process, within which three major components must be considered: *an experiment producing adequate test data*, *a mathematical model of the system* (aircraft or aircraft subsystem) and *an estimation technique*.

Aircraft system identification includes the following phases [20]:

- Model postulation
- Experiment design
- Data compatibility analysis
- Model structure determination
- Parameter and state estimation
- Collinearity diagnostics
- Model validation

Model postulation. Model postulation defines the general framework for the model to be identified. It is based on prior knowledge about the dynamics of the system. It can allow for variability of the structure and parameters of the model. Very often, for aircraft system identification, general equations of motion and linear variations of aerodynamic forces and moments depending on states and controls are considered, such as in Equation (7).

Experiment design. The experiment design has to address the need for adequate instrumentation to measure all outputs and for compliance with general conditions such as aircraft configuration, flight conditions, and specific maneuvers/inputs. The success of the

system identification process depends on the "quality" of test data used.

Data compatibility analysis. The measured data is typically subject to numerous error sources. The nature and the amount of these errors have to be analyzed to ensure that the data is adequate for system identification.

Model structure determination. The model structure can be imposed based on previous knowledge or assumptions or can result based on the system identification process. The latter situation involves a more sophisticated system identification process.

Parameter and state estimation. Two large classes of methods are currently used for aircraft parameter estimation: equation-error and output-error methods. Equation-error methods are primarily used to determine unknown aerodynamic parameters (stability and control derivatives) by minimizing the sum of squared differences between measured and modeled aerodynamic forces and moments. Linear regression is typically used. The linearity refers to the estimation approach and not to the model itself. It means that the model depends linearly on the identified parameters; however, it can be non-linear with respect to states and inputs. The output-error methods are of a non-linear nature. They are used to determine unknown parameters by optimizing the sum of weighted square differences between the measured and modeled aircraft system outputs. These are computed from states, inputs, and parameters through the integration of the equations of motion.

Collinearity diagnostics. The parameters to be determined must be defined such that they are non-correlated. If strong data collinearity exists numerical problems may occur and/or the results of the identification process are incorrect.

Model validation. The model determined through the system identification process must be tested against new experimental data (which have not been used in the identification

algorithm). First, the parameters obtained must be compared with similar results and tests and analyzed for consistency. Then, the accuracy of the model output and its prediction capabilities must be evaluated.

WVU Aircraft Health Management Instruction Software

The WVU aircraft health management instruction simulation environment [18] consists of 5 major modules (Figure 1):

- 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 2a. Figure 2b shows the main menu for the parameter identification (PID) flight test scenario. The commands to the aircraft can be provided through the control stick or as pre-recorded data. An example of a typical simulation user interface is displayed in Figure 3 showing Simulink time history visualization and vehicle visualization provided by *FlightGear* [21], an open-source simulation code. Note that all mathematical models are developed in-house and implemented in Matlab/Simulink and *FlightGear* is used only for visualization purposes. State and input time histories can be monitored during and after the simulation (Figure 4), as well as the actual and estimated state and control derivatives for assessing the performance of the PID process (Figure 5).

The *Aircraft Module* hosts several aircraft models that are implemented at different levels of complexity. All models provide easy access
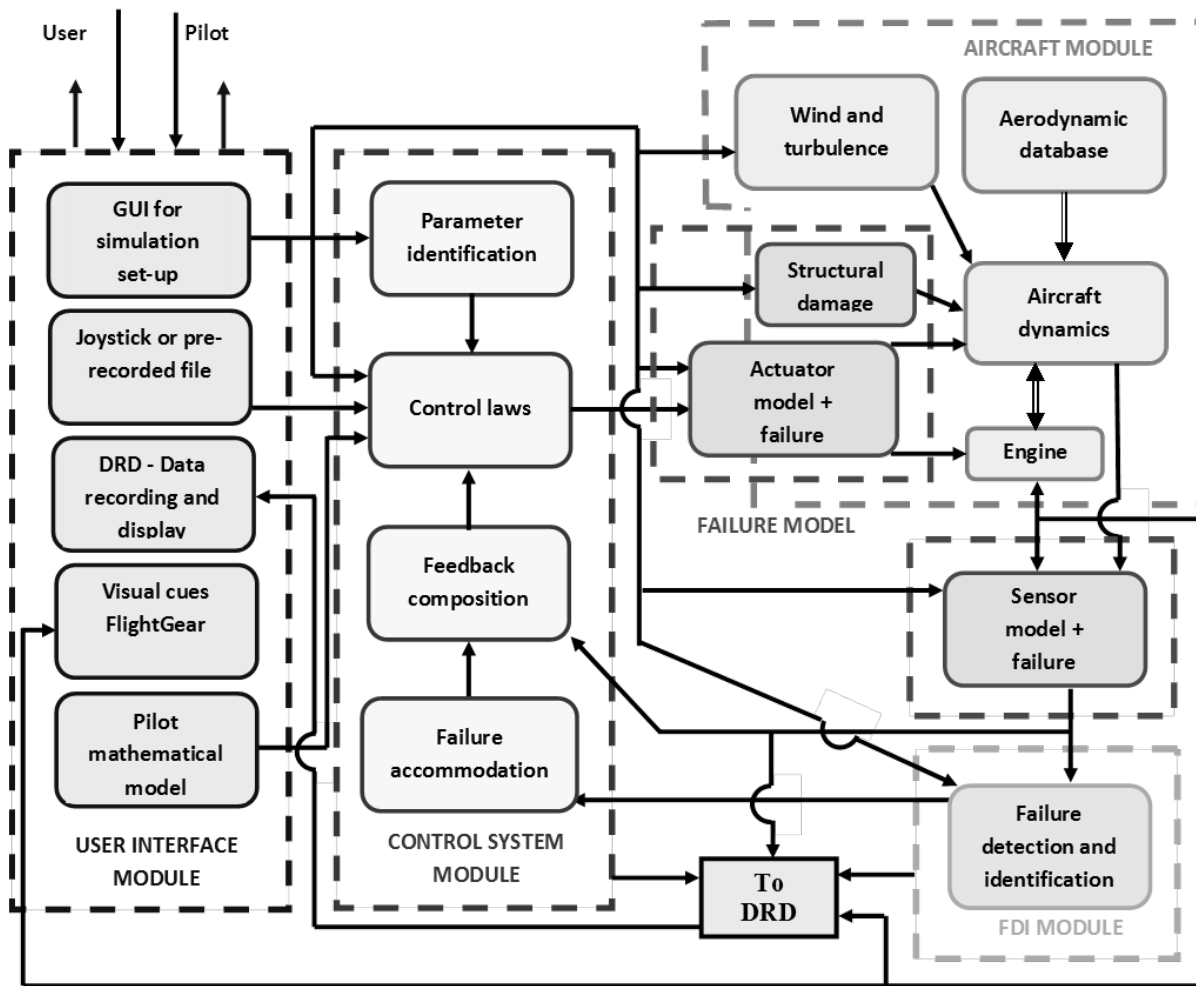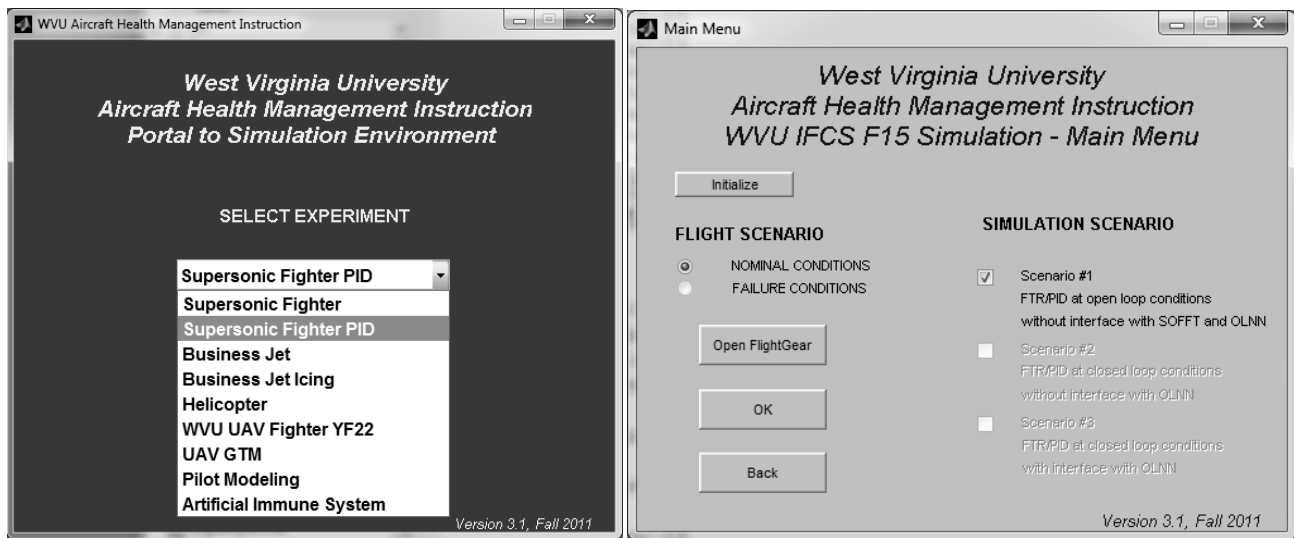
Figure 1. General Architecture of the WVU AHM Instruction Simulation Environment.

(a) Aircraft Selection Interface   (b) Aircraft PID Flight Test Scenario Selection.

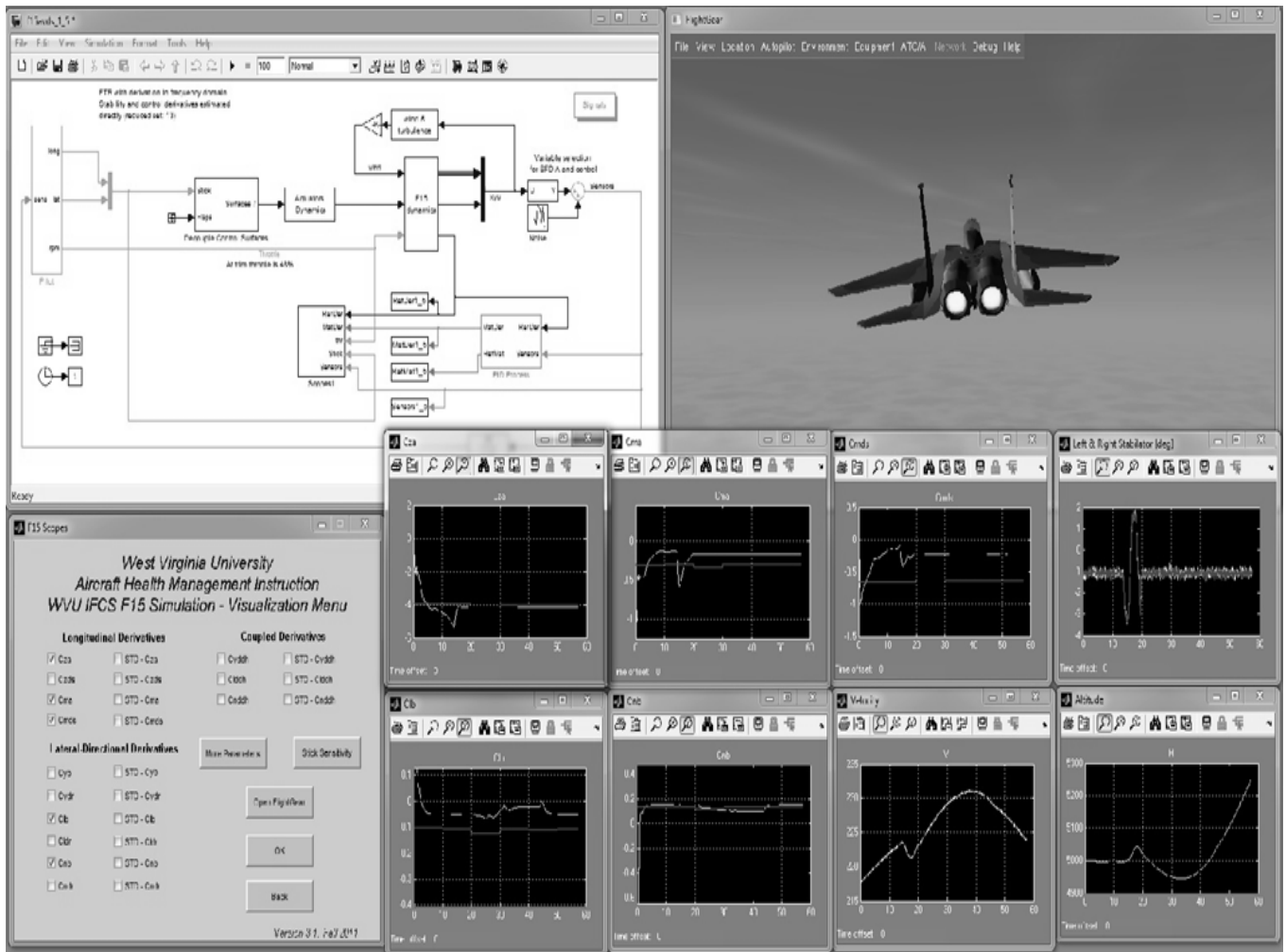Figure 2. WVU Aircraft Health Management Instruction Interface.

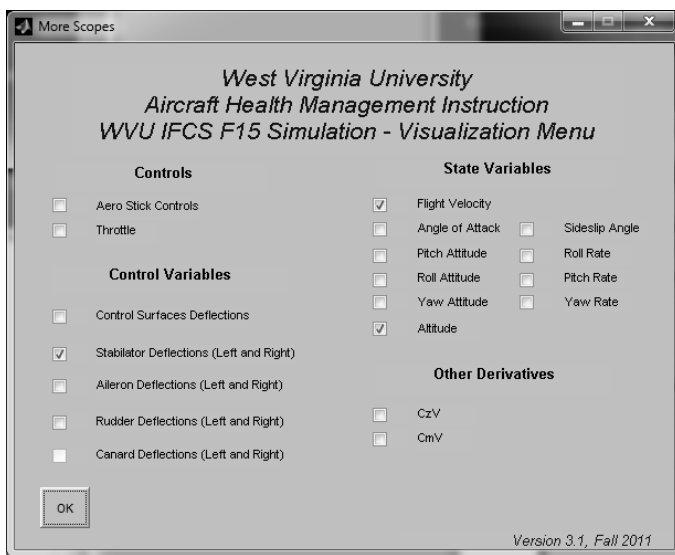Figure 3. Interface of the WVU Aircraft Health Management Instruction Simulation Environment.
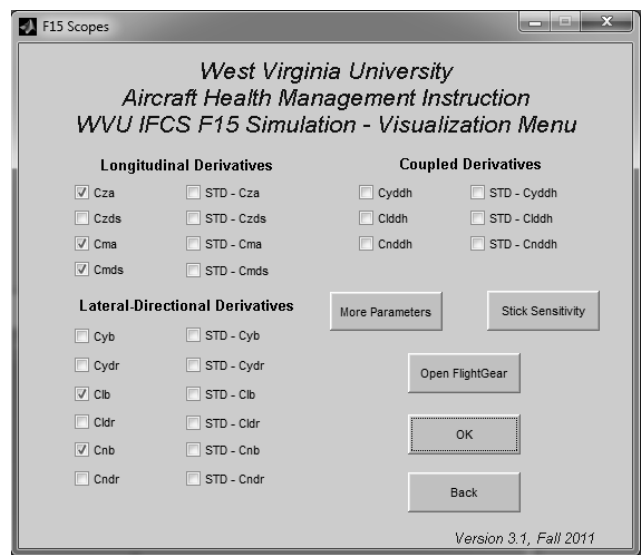

Figure 4. General Visualization Menu.

Figure 5. State and Control Derivatives Visualization Menu (Actual, Estimated, and Convergence Criteria).

to stability and control derivatives for modification and analysis. The aircraft module also includes environmental models for turbulence, wind, and icing. The model to be used for the SI lab is based on the flight dynamics of a modified F-15 aircraft [22].

The *Control System Module* consists primarily of adaptive control laws with intrinsic failure accommodation capabilities [23]. They are based on a non-linear dynamic inversion technique augmented with artificial neural networks. A 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 [22]. This sub-module is a critical component to be used within the SI lab.

The *Failure Model Module* includes models of several types of abnormal operation conditions of actuators, sensors, and propulsion system and structural damages on the wing and the other aerodynamic surfaces.

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.

Lab Objectives and Learning Outcomes

The main objectives of the SI lab and the accompanying lecture session are the following:

- outline the principles of complex dynamic system (aircraft) modeling through SI;

- provide a conceptual overview of aircraft parameter identification and estimation;

- introduce students to the linear regression least squares method formulation, application, advantages, and limitations;

- introduce students to on-line prediction of stability and control derivatives for fault tolerant control laws update;

- emphasize the importance of system excitation for successful parameter identification.

After performing the SI lab, the students should be able to:

- formulate the principles of the aircraft modeling process;

- formulate the problem and implement in Simulink/Matlab a least square regression algorithm for aircraft parameter identification;

- design and perform tests to acquire data for aircraft parameter identification;

- describe the on-line use of parameter identification for fault tolerant control;

- discuss the issues related to the on-line use of parameter identification for fault tolerant control;

Lab Outline

Desktop PC simulations are used for the aircraft SI lab. The lab is performed by teams of 2 students. It is required that both students are involved equally in all phases of the lab. They are expected to perform their own experimental designs, execute the simulation experiments, acquire, and process data. Each student must submit a separate professionally written report. The lab consists of two parts: an off-line parameter identification exercise and an on-line parameter identification exercise.

The *off-line parameter identification exercise* consists of implementing the linear regression

least squares method to identify a model of the vertical force coefficient from simulation data. For the identification method, the well-known model is assumed:

$$y = X\theta \tag{9}$$

where y is the dependent variable, a relevant physical quantity that can be measured, X is the row vector of independent variables or the *regressors*, and θ is a vector of n unknown model parameters (which need to be determined). They quantify or model the effects of each independent variable on the dependent variable. The measured y is a column vector z of size N representing N measurement samples. Therefore:

$$z = X\theta + \upsilon \tag{10}$$

where υ represents the measurement errors, which are assumed to be zero-mean and uncorrelated. We must determine θ such that the sum of squared differences between the measurement and the model:

$$J(\theta) = \frac{1}{2}(z - X\theta)^T(z - X\theta) \tag{11}$$

is minimized. The solution (= the estimate) $\hat{\theta}$ that minimizes J must satisfy:

$$\left.\frac{\partial J}{\partial \theta}\right|_{\theta = \hat{\theta}} = 0 \tag{12}$$

which is equivalent to:

$$-X^T z + X^T X \hat{\theta} = 0 \tag{13}$$

$$X^T X \hat{\theta} = X^T z \tag{14}$$

The unknown parameters can be obtained as:

$$\hat{\theta} = (X^T X)^{-1} X^T z \tag{15}$$

The matrix $X^T X$ is always square and symmetric. If the columns of X (the measurements of the independent variables) are linearly independent then $X^T X$ is invertible.

The students are required to apply the general methodology to the case of modeling the vertical force coefficient, which is expressed as:

$$C_z = C_{z0} + C_{z\alpha}\alpha + C_{zq}\hat{q} + C_{z\delta_s}\delta_s \tag{16}$$

where δ_s represents the stabilator deflection. The WVU AHM Instruction software package must be used to perform tests and acquire the data necessary for determining the free term C_{z0}, the stability derivatives $C_{z\alpha}$, C_{zq}, and the control derivative $C_{z\delta_s}$ from the model of Equation (16).

A set of simulation tests must be designed to acquire data for the PID process and to expose the importance of system excitation for a successful PID. Separate tests for model identification should include:

#1). No pilot input.

#2). Pilot input only on the lateral and/or directional channels.

#3). Pilot input on the longitudinal channel, (longitudinal stick doublet).

An additional test (#4) must be also performed with longitudinal stick doublets for model validation.

All the variables/data necessary must be identified and saved for off-line processing. A customized Matlab implementation of the PID algorithm must be used to obtain parameter estimates from test data #1, #2, and #3. Data set #4 must then be utilized to verify/validate each model. The students are expected to compare and discuss these results and to analyze the effects of input on the performance of the PID algorithm. An example plot including the estimated non-dimensional vertical lift coefficient C_z and its actual values from validation data is presented in Figure 6.
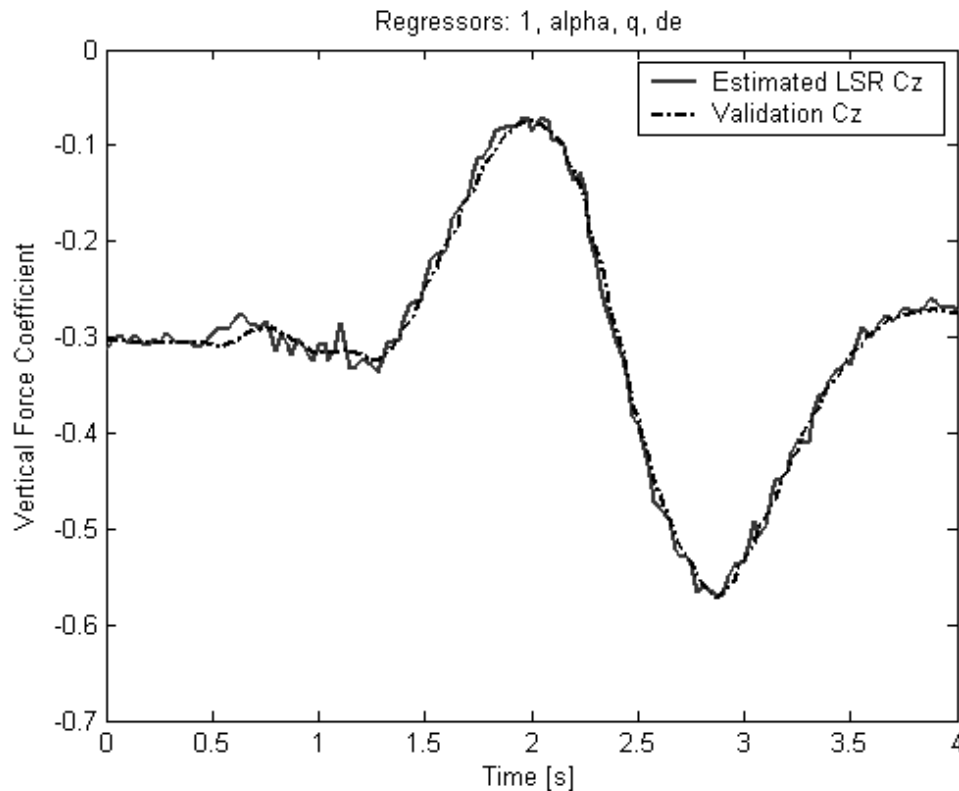
Figure 6. Estimation Results Compared with Validation Data.

The **on-line parameter identification exercise** consists of investigating the performance of a frequency domain PID method and analyzing the process of on-line stability and control derivatives determination for the purpose of updating fault tolerant control laws. Both nominal and actuator failure conditions are investigated. The following derivatives are considered in this exercise: $C_{z\alpha}$, $C_{m\alpha}$, $C_{l\beta}$, $C_{n\beta}$ and $C_{z\delta_s}$. The scopes within the Simulink model allow observing both the result of the PID and the actual values of the derivatives, which are computed every ten seconds.

The students are required to design their tests such that they expose the importance of system excitation on the success of the PID. Tests must be performed without any pilot input and with doublets on each channel, one channel at a time. The performance of the PID process must be analyzed in all cases and for all five derivatives considered. The students are expected to notice

that the PID process may not converge at all, may converge to wrong values, or may converge to the correct values. The convergence may occur after a time interval that is adequate for on-line updating of control laws or with delays that are not acceptable. The students are required to analyze these situations and attempt to explain them.

The impact of the adequate selection of excitation input is illustrated in Figures 7 through 10. If there is no input at all or no input in the channel affected by the derivative to be identified, then the results of the PID process are poor, as shown in Figure 7 for $C_{z\alpha}$ (a longitudinal state derivative) and in Figure 8 for $C_{n\beta}$ (a lateral-directional state derivative). If adequate input is provided in the appropriate channel, then the PID results improve considerably, as presented in Figure 9 for $C_{z\alpha}$ and in Figure 10 for $C_{n\beta}$.
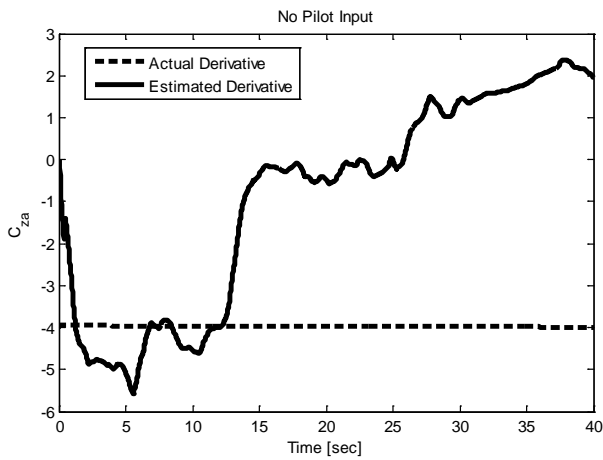
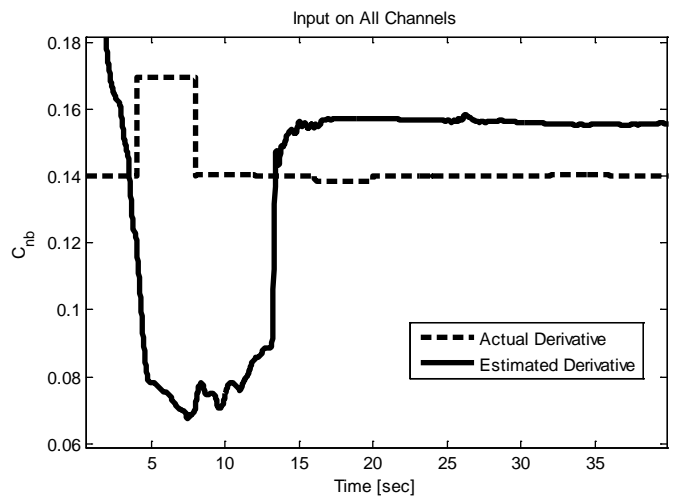Figure 7. Estimation Results for $C_{z\alpha}$ in the Absence of Pilot Excitation.
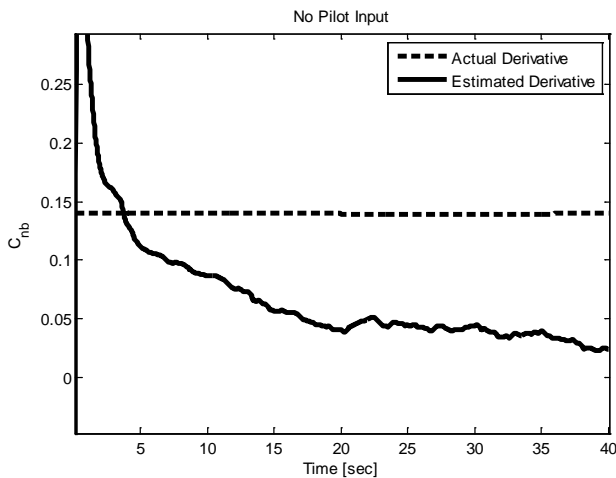

Figure 8. Estimation Results for $C_{n\beta}$. in the Absence of Pilot Excitation.

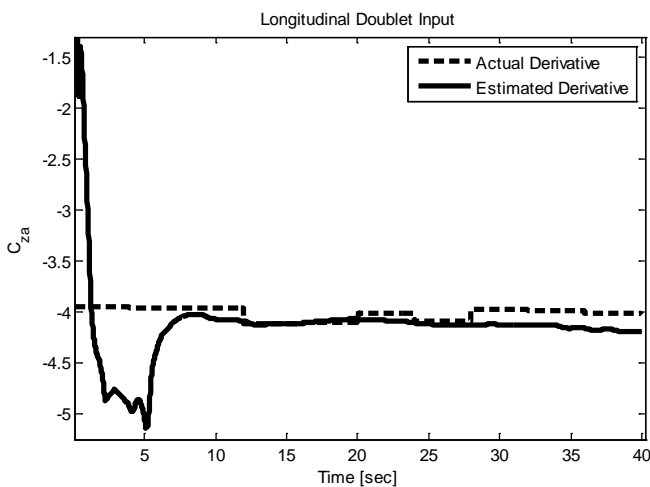Figure 9. Estimation Results for $C_{z\alpha}$ with Pilot Excitation in the Longitudinal Channel.

Figure 10. Estimation Results for $C_{n\beta}$ with Pilot Excitation in All Three Channels.

Lab Evaluation

The lab evaluation process has two distinct objectives: the assessment of the impact of the pedagogical approach utilized in the design and implementation of the lab assignment and the estimation of the level of attainment of the lab learning outcomes.

The pedagogical approach used in designing the PID lab and the entire course, which the lab is a part of, was 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 [18]. To assess the impact of the pedagogical approach on the learning process and achieve the first objective of lab evaluation, an anonymous 19-question questionnaire was adapted from reference [24] and administered in two steps to the students. First, the students were asked to evaluate at the beginning of the semester several previously taken courses in a similar technical area, which had not benefited from the simulation-supported pedagogical approach. At the end of the semester, the students were required to complete the same questionnaire, this time for the AHM course.

The questionnaire included several questions directly related to the student perception of the labs and the experiential learning approach (Set A = questions #9, #10, and #11). The questionnaire also included several questions related to the level and impact of the active learning environment (Set B = questions #8, #13, #14 and #15), which was primarily built and supported through the design of the labs. These seven questions are presented in Table 1 and will be used next to evaluate the impact of the lab pedagogical design. The students were given two extreme alternative answers and asked to evaluate their perception on a scale from 1 to 7.

The results have been re-scaled to the maximum value for the AHM course and seven other courses in similar technical areas. Averages for all questions, set A, and set B are presented in Table 2 for comparison. These results demonstrate that the lab component, as well as the entire AHM course have received overall better evaluations based on all metrics when compared to all courses considered. Only one course received higher ratings for metrics in set A.

Table 1. Questionnaire [24] for Assessment of Student Lab Perception.

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
#9	Labs and/or assignments assisted in integrating very well course material	7 6 5 4 3 2 1	Labs and/or assignments confused students
#10	Labs and/or assignments contributed to understanding the course material a lot	7 6 5 4 3 2 1	Labs and/or assignments **did not** contribute to understanding the course material
#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
#13	I felt active and "involved"	7 6 5 4 3 2 1	I felt passive and "aloof"
#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
#15	I felt the course required me to exercise independent judgment in evaluating textbook theories	7 6 5 4 3 2 1	I felt the course **did not** require me to exercise independent judgment in evaluating textbook theories

Table 2. Student Course and Lab Evaluations.

	Other Similar Courses	AHM Course
Average of 19 Questions	6.33	7.00
Set A	6.25	6.78
Set B	6.00	7.00

To assess the level of learning outcomes attainment and achieve the second objective of the lab evaluation, 23 lab reports were evaluated. For simplicity, the 5 learning outcomes of the lab have been grouped into two critical categories:

- Ability of the student to describe the aircraft and the least square PID model mathematically and demonstrate the implementation through simulation tests.

- Ability of the student to draw conclusions related to PID and address issues related to its on-line use for fault tolerant control supported by specific experiments.

The metric and evaluation scale based on these critical learning outcomes categories is formulated as follows:

A. Student demonstrated deep understanding of the aircraft and PID modeling and good ability to draw conclusions related to PID with own interpretation, including complete experimental design.

B. Student presented many conceptual details of both the aircraft and PID models and included facts when drawing conclusions based on good experimental design.

C. Student described the models with conceptual details and discussed facts with personal interpretation supported by adequate testing.

D. Student described the models with few details or described only one of the models (either the aircraft or the PID) and discussed results with few conclusions and limited tests.

E. Student did not describe the models properly and discussed the PID process unclearly without conclusions.

The results of learning outcomes attainment are presented in Figure 11. It can be concluded that 78.3% of the students meet passing requirements at the average or higher level for the first critical learning outcome and 82.6% for the second. These results are consistent with evaluations of other labs within the same course and general experience of the authors with respect to other similar lab courses. Therefore, it may be concluded that teaching PID basics at the undergraduate level was successful.
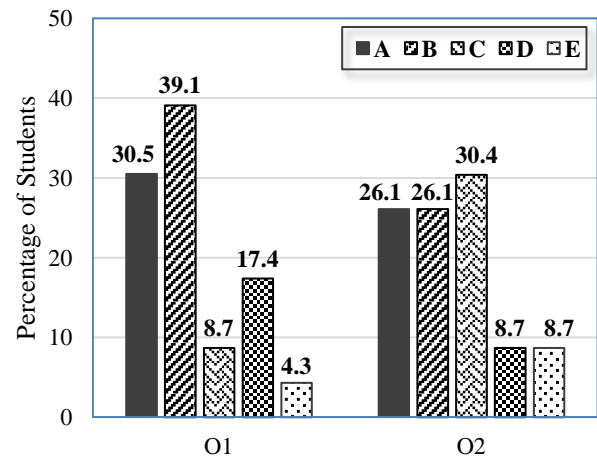

Figure 11. Evaluation of Lab Critical Learning Outcomes.

Conclusions

Active and experiential learning methodologies have been successfully implemented based on flight simulation tools for the introduction of aircraft PID at the undergraduate level.

With the support of adequate simulation tools, PID basics can be introduced at the undergraduate senior level in a meaningful manner.

Approximately 5 contact hours (lecture and lab) are dedicated to the SI/PID lab. Although designed for aerospace engineering students, the lab can be easily transferred to other engineering areas with the introduction of a few basic concepts.

Both the questionnaire and the evaluation of the critical learning outcomes lead to the conclusion that the hands-on approach on teaching PID basics is beneficial, it facilitates conceptual understanding, and increases the motivation and interest of the students.

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