

Use of Real Time Simulation in a Laboratory Course

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Abstract

Over the past few decades, computer simulations have become an important tool for flight control system design. Use of a simulation gives the engineer a safe, quick and convenient method for testing or designing new controllers. In the past several years, many colleges have begun using computer simulations in conjunction with teaching control design. At the Georgia Institute of Technology School of Aerospace Engineering, one of the senior level aerospace engineering laboratory courses, AE 4525, has developed three new experiments to utilize computer flight simulator technology. This allows the students to design and test various controllers using a high fidelity flight simulator; instead of studying only more idealized theoretical models.

Nomenclature

V	Total Velocity	feet/second
alpha (α)	Angle of Attack	radians
beta (β)	Sideslip Angle	radians
u	x-component of velocity	feet/second
v	y-component of velocity	feet/second
w	z-component of velocity	feet/second
p	Angular roll rate	radians/second
q	Angular pitch rate	radians/second
r	Angular yaw rate	radians/second
phi (ϕ)	Roll angle	radians
theta (θ)	Pitch angle	radians
psi (ψ)	Yaw angle	radians
A	State matrix	
B	Input matrix	
x	State vector	

Introduction

Computer simulations have become a valuable asset to control engineering. Simulations are often quite cheap and simple to use, compared to testing designs on real hardware, especially when that hardware is an aircraft. While designing new controllers, it is much easier to test the designs on a simulation first. This way, if there are any problems, they can be cheaply and quickly corrected without damaging any equipment. In addition, it allows the control engineers a chance to try new methods of controllers safely.

Simulator Usage

In the last few years, many colleges have begun using simulations in control classes as teaching tools. This allows students the opportunity to design their own control systems for equipment and to test them. Also, they have the ability to adjust parameters in their designs and learn the effects that this has on the simulated system. In addition, students experience all the actual variables that can affect the success of the system. Computer simulations are often used in control laboratories in a variety of ways.

Johns Hopkins University offers a course called Control Systems Design, taught by Pablo Iglesias, which utilizes simulation technology. The final project in this class is for each group of students to fly a model helicopter using a controller designed by them. Leading up to actually flying the model, students can test their controller designs on a helicopter simulator before attempting to fly the actual model helicopter.¹

The Department of Electrical Engineering at the National University of Singapore has developed a web-based laboratory simulation of a coupled tank apparatus. This simulator has the capability to implement manual, proportional integral derivative, general state-space and fuzzy logic controllers. Because of these capabilities, this simulator provides a generalized platform for testing new controllers.²

Pennsylvania State University uses a re-configurable process simulator for a senior-level feedback control class in electro-mechanical engineering technology. This device simulates the transfer functions of typical processes that might be encountered. The parameters of these transfer functions can be easily altered to allow the simulation of a variety of possible process situations. This simulator can be used to test the results of a proportional-integral-differential (PID) controller as well as verify the root locus and frequency domain calculations for lead, lag and lead / lag compensators. In addition, steady-state error and process stability can be evaluated.³

AE 4525 Simulator

Last semester (Spring 2002) three new experiments were added to a Georgia Institute of Technology School of Aerospace Engineering undergraduate controls laboratory (course number AE 4525) schedule to take advantage of computer simulation technology. The simulator used represented a Lockheed Martin F-16 jet aircraft, which was chosen because it is very difficult to

fly without stability augmentation. The students were able to fly the aircraft on the simulator with several different control systems; including ones they designed themselves.⁴

The simulator is capable of depicting three different view windows at one time, with five different view choices available. The potential views are named Cockpit, Wind Axes, Chase, Ground and Hovering. The Cockpit view is centered as if the operator was the pilot with the forward sight aimed along the body axis of the aircraft while the Wind Axes view is from the point of view of the pilot with the forward sight along the wind axes. The Chase view is that which could be seen from a chase plane and the Ground view is centered from a point near the beginning of the runway. The Hovering viewpoint is similar to Chase; however, the origin is fixed to the earth and changes periodically to remain near the aircraft. From the Chase, Ground and Hovering viewpoints, the simulator is able to depict various axes systems and parameters from a choice of six; any number of these may be depicted at one time. The possible systems of axes are the body axes and the north, east, down (NED) axes. In addition, vectors for the velocity, angular velocity, angular momentum and trajectory can also be shown on the screen. For each of these vectors, a different colored line is directed in the direction the vector points, and the length of the line gives an indication of the magnitude of the parameter.

In addition, the flight simulator contains a tabular hierarchy that permits the operator to observe the values of all flight and control parameters in real time. There also exists an autopilot system that can be toggled online. A basic autopilot was also included that allows the operator to input a set trajectory, including the velocity and altitude. Many of the values for this can be altered while flying. This allows the operator to test a designed controller on a basic flight path and also allows the operator to be sure that the aircraft is flying in the desired manner for data collection. In addition, the control parameters can be altered during flight, which allows the quick and easy testing of controller designs. Figure 1 depicts a view of the simulator with two view windows open – one in Cockpit view and one in Chase view. The Chase plane view is also showing the body axes on it. In addition an open parameter window can be seen in the figure in the lower left.

The simulator can also collect data and create plots of the data. Up to three plotting windows can be opened at one time, with up to ten parameter plots for each window. Any parameter of the simulation may be collected and plotted. The plots are generated real time, permitting the operator to see graphically what is occurring as it happens. After the desired data is collected, it can be saved as either MATLAB or a text file. Samples of this plotting capability can be viewed in Figure 2.

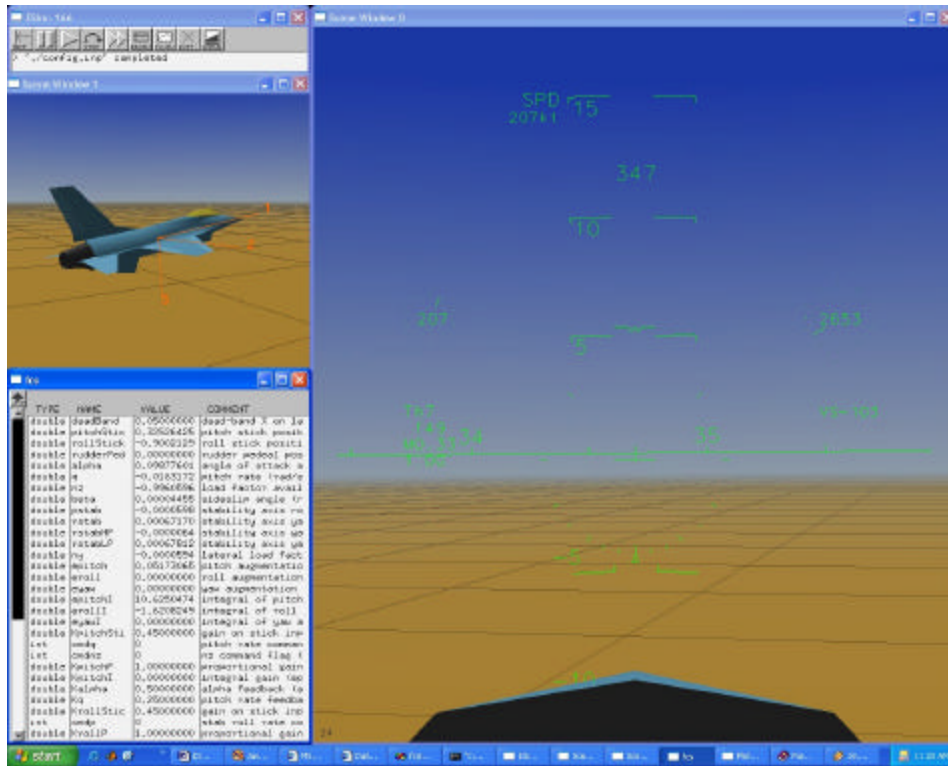


Figure 1: Cockpit and Chase View with Parameter Window

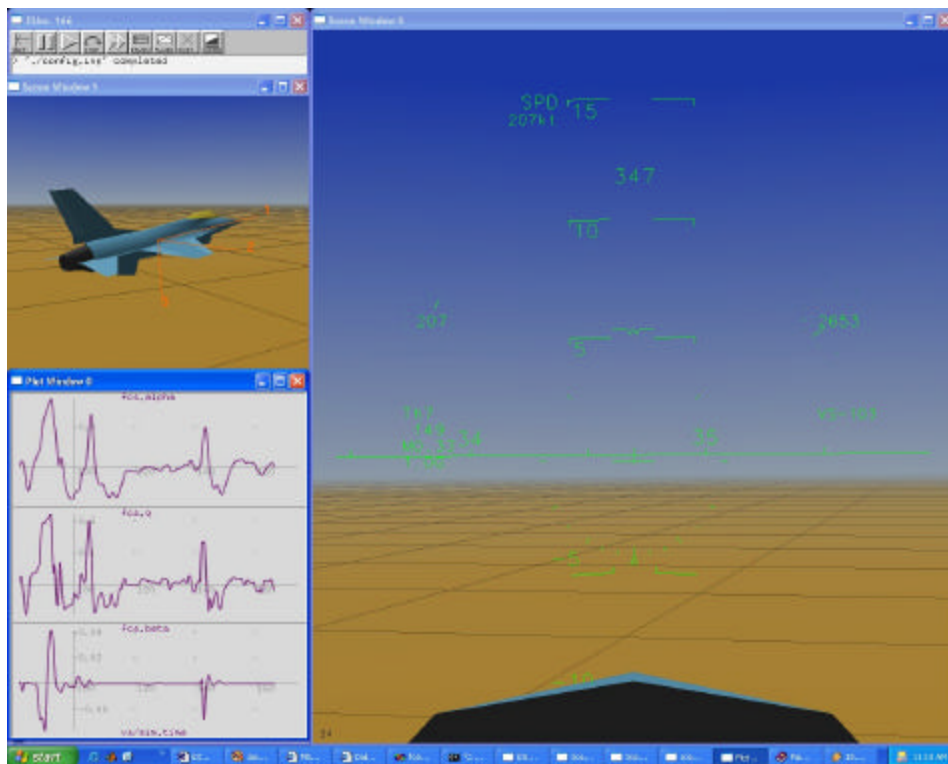


Figure 2: Cockpit and Chase View with Plotting Window

AE 4525 Experiments

When the lab experiments were performed, the plane was first flown in an open loop (no stability or control augmentation) configuration to see the need for a more advanced flight control system. In the first of these experiments, the students designed and implemented a longitudinal control system with angle of attack and angular pitch rate feedback. The second lab dealt with the lateral-directional portion of the control system while feeding-back the angular roll and yaw rates. The final experiment dealt with the design and implementation of a true stability and control augmentation system. With the simulator, the students were able to adjust their designs depending on the responses of the aircraft. After the newly designed control system was implemented, the students flew a specific test flight and collected data.

The first experiment concerned the construction of a longitudinal flight control system. Figure 3 shows the block diagram for this control system. It can be seen in the figure that the feedback variables are the angle of attack and the pitch rate. Before coming to the lab, the students were expected to calculate the necessary gains using the root locus technique. Then, in class, the students would get to fly the vehicle both open loop and with their control system implemented. During the flights, they would record flight information concerning the angle of attack, pitch rate and elevator position for further analysis. By the end of the experiment, the students would be expected to be able to plot the root loci for both gains, determine the final locations of the roots, calculate the gain and phase margins of the closed-loop system and understand the importance of the gain and phase margins. In addition, the students were to analyze the performance of the aircraft based on the collected data and predict the handling qualities rating for the vehicle using the Cooper Harper handling qualities rating system.

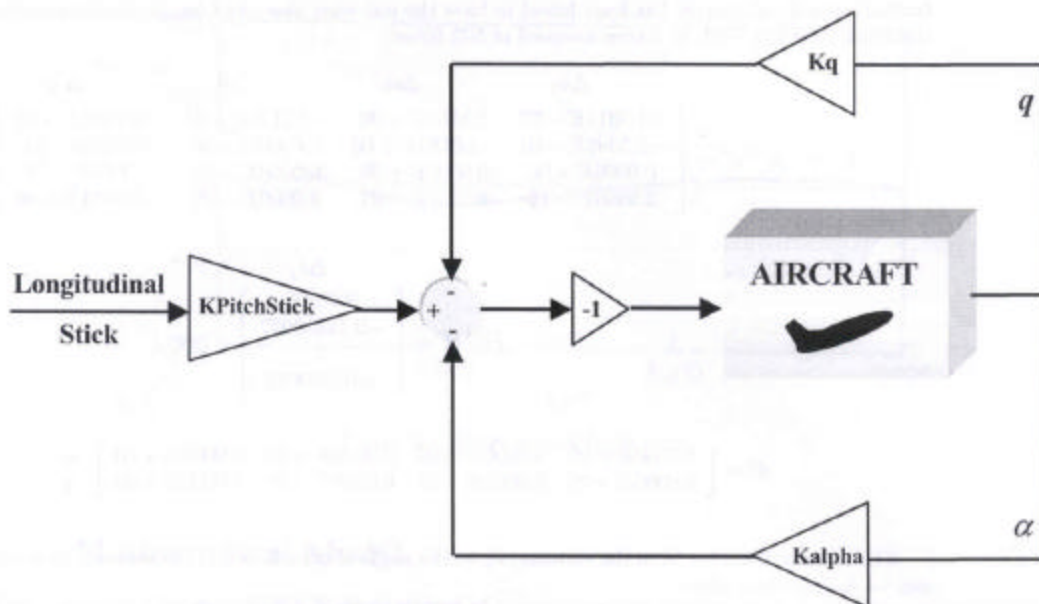


Figure 3: Block Diagram of Longitudinal Stability Augmentation System (α and q Feedback)

The second experiment dealt with designing a lateral-directional stability augmentation system. The block diagram, as seen in Figure 4, shows that the roll and yaw rates are the terms in the feedback loop. As before, the students were to calculate the gain values beforehand and then

they flew the simulator both with and without the control system implemented. In this case, data for the roll and yaw rates as well as the rudder and aileron positions were collected. The expectations for this experiment were the same as with the previous one; however, the data dealt with the lateral-directional portion.

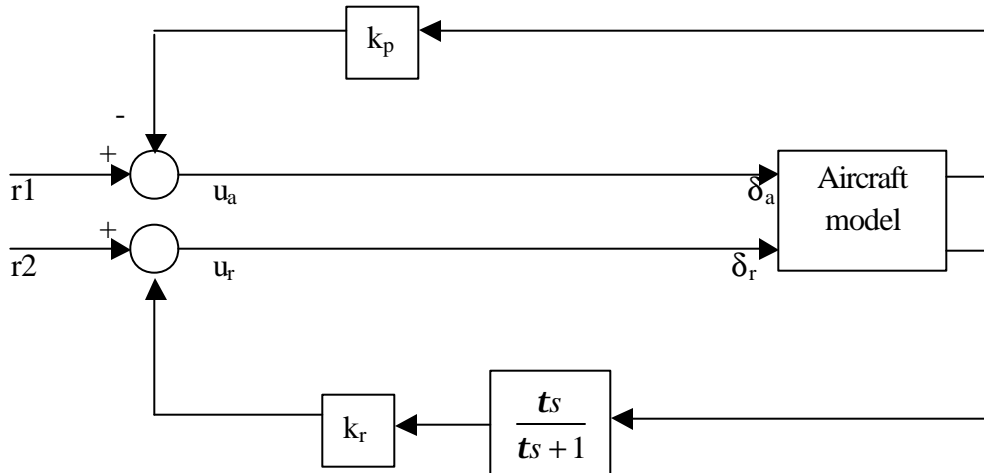


Figure 4: Block Diagram of Lateral-Directional Stability Augmentation System (p and r Feedback)

The third experiment concerned designing a stability and control augmentation system (SCAS), which included both the longitudinal and lateral-directional components of a complete flight control system. Figures 5 and 6 show the block diagrams for the longitudinal and lateral-directional SCAS, respectively. As can be seen in these figures, there were significantly more gain parameters that needed to be determined. Many of these variables could be determined easily before class; however, poor choices were often discovered with the use of the simulator – and often corrected. For this experiment, the students were able to alter some gains while flying to determine the best gain values and to see the effects these changes had on the system. For the analysis of this experiment, the students were expected to understand where the values for each gain came from and why they were chosen, analyze resulting linear dynamics of the vehicle. They were also asked to simulate this linear model on their own and compare these results to the collected data. In addition, the students took and analyzed Cooper Harper ratings for their designs.

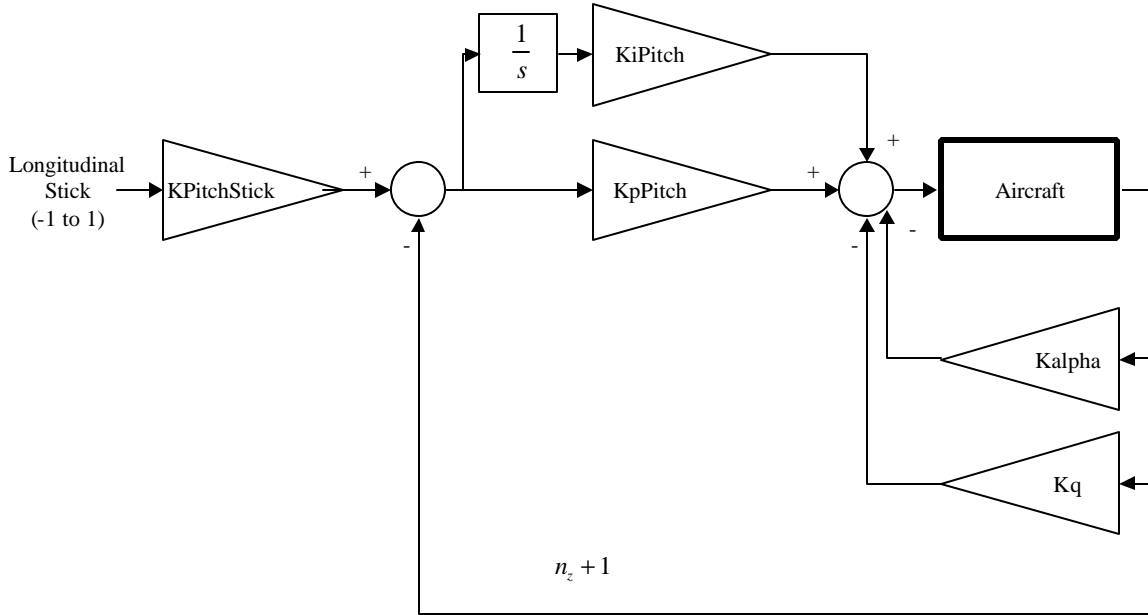


Figure 5: Longitudinal SCAS

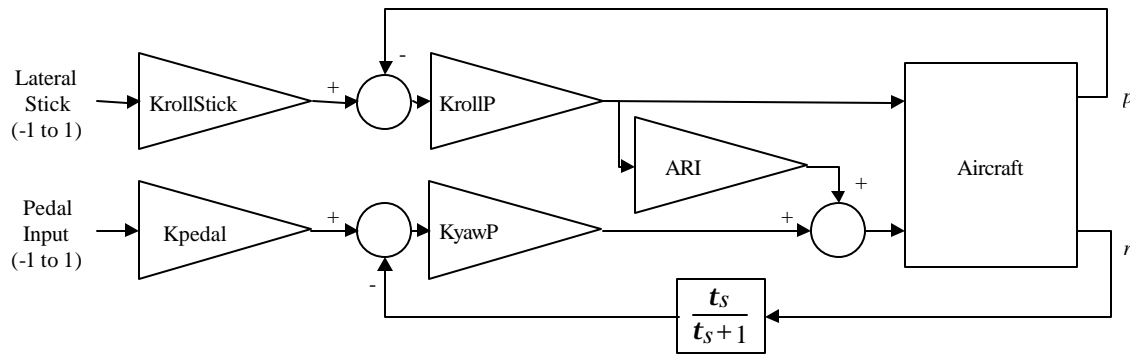


Figure 6: Lateral-Directional SCAS

Simulator Code Alterations

To improve the labs, it was decided that linear model extraction capabilities should be added to the simulator. Previously, given linear models were used as found in *Aircraft Control and Simulation* by Brian L. Stevens and Frank L. Lewis. These models, however, were only valid for a certain flight speed and altitude: sea-level at 500 feet/second or 205 feet/second for longitudinal and lateral-directional systems, respectively. The availability of a linear model extractor would allow the students to create a linear model for the actual desired design flight conditions.

However, to create the linear model extractor, the equations of motion for the simulator program needed to be rewritten and simplified. To begin with, a spherical earth model had been used that utilized body, local, atmospheric, inertial and earth fixed frames. This was changed to using a flat-Earth model consisting of just three frames – local, body and atmospheric. This effectively resulted in the inertial, earth and local frames coinciding. They were chosen to be oriented as a North, East, Down system. The body frame is situated with its origin at the center of mass of the aircraft with the x-axis pointed towards the nose, the y-axis pointed towards the right side of the aircraft and the z-axis pointed orthogonally downwards. The atmospheric axes system is oriented such that the origin is attached to the atmosphere with the x-axis directed along the mean wind velocity. In addition, many of the variables were written with respect to different frames. Creating the linear model extractor required that the relevant variables be written in the body frame.

Linear Model Extractor

The linear model extractor was then added to the simulator. It is written as a command line function – the command ‘linmod’ can be typed in the command window at any point to cause a linear model to be created. This linear model is then saved in a specified m-file.

The linear models are created in the form

$$\dot{x} = Ax + Bu$$

where x is the state, u is the input, A is the state matrix and B is the input matrix. The linear models consist of eight states: angular rate (p, q, r), velocity (u, v, w), phi and theta (the roll and pitch angles). The equations for the first six states were determined by first perturbing each state along its axis. The value for each state derivative was then calculated with respect to the perturbed state, then recorded in the A matrix. The values in the A matrix for the derivatives of phi and theta were determined with the use of the following kinematic equations.

$$\begin{aligned} p &= \dot{\mathbf{f}} - \dot{\mathbf{y}} \cos(\mathbf{f}) \\ q &= \dot{\mathbf{q}} \cos(\mathbf{f}) + \dot{\mathbf{y}} \sin(\mathbf{f}) \cos(\mathbf{q}) \\ r &= -\dot{\mathbf{q}} \sin(\mathbf{f}) + \dot{\mathbf{y}} \cos(\mathbf{f}) \cos(\mathbf{q}) \end{aligned}$$

A similar method of perturbing the aircraft was used to create the B matrix. There were four inputs used in this simulation: ailerons, rudder, throttle and elevators.

A MATLAB function was also created to alter the A and B matrices so that they could be easily split into longitudinal and lateral-directional components. In addition, a calculation was added to change the u, v and w velocity components to total velocity, beta, and alpha, respectively. The final linear model consisted of states in the following order: V , alpha, theta, q , beta, phi, p and r . In this form, the first four rows and columns comprised the longitudinal A matrix while the lateral-directional portion was found in the final four rows and columns. The input variable for the longitudinal B matrix was the elevators while the inputs for the lateral-directional B matrix are the ailerons and rudders.

The linear model matrices given in the book *Aircraft Control and Simulation* by Stevens and Lewis are as follows. The longitudinal matrices are

$$A = \begin{bmatrix} -0.019311 & 8.8157 & -32.17 & -0.57499 \\ -2.5398 \times 10^{-4} & -1.0189 & 0 & 0.90506 \\ 0 & 0 & 0 & 1 \\ 2.9465 \times 10^{-12} & 0.8225 & 0 & -1.0774 \end{bmatrix}, \quad B = \begin{bmatrix} 9.95301 \\ -0.12319 \\ 0 \\ -10.059 \end{bmatrix}$$

The lateral-directional matrices are

$$A = \begin{bmatrix} -0.13150 & 0.14858 & 0.32434 & -0.93964 \\ 0 & 0 & 1 & 0.33976 \\ -10.614 & 0 & -1.1793 & 1.0023 \\ 0.99655 & 0 & -0.0018174 & -0.25855 \end{bmatrix}, \quad B = \begin{bmatrix} 0.006903 & 0.018849 \\ 0 & 0 \\ -5.910507 & 1.202467 \\ -0.122219 & -0.61392 \end{bmatrix}$$

The longitudinal matrices are calculated at an airspeed of 502 feet/second at sea-level while the lateral-directional matrices were determined at the same altitude with an airspeed of 205 feet/second.⁴

The corresponding matrices found with the new linear model extractor are as follows. The longitudinal matrices are

$$A = \begin{bmatrix} -0.0371 & 9.0006 & -32.17 & -0.5676 \\ -2.56 \times 10^{-4} & -1.0651 & 0 & 0.9008 \\ 0 & 0 & 0 & 1 \\ 0 & 0.8186 & 0 & -1.0738 \end{bmatrix}, \quad B = \begin{bmatrix} 9.9667 \\ -0.1287 \\ 0 \\ -9.6176 \end{bmatrix}$$

while the lateral-directional matrices are

$$A = \begin{bmatrix} -0.1370 & 0.1495 & 0.3175 & -0.9415 \\ 0 & 0 & 1 & 0.3189 \\ -11.7284 & 0 & -1.1862 & 0.9697 \\ 1.003 & 0 & -0.0071 & -0.2502 \end{bmatrix}, \quad B = \begin{bmatrix} 0.0072 & 0.0196 \\ 0 & 0 \\ -5.9271 & 1.1922 \\ -0.1323 & -0.6066 \end{bmatrix}$$

The values in these matrices match quite well. The slight differences would be due to the fact that the altitude could not be matched exactly and the difficulty in holding the aircraft exactly level in flight in order to perform the linear model extraction. Slight changes in the orientation will effect some of the values significantly.

Conclusions

Using simulators to test new controllers has become an important stage in control design. Many colleges are now introducing this process in control classes so that students are exposed to this practice. At the Georgia Institute of Technology, the students of AE4525 now have the opportunity to use a flight simulator to test various controllers that they have designed. In addition, starting in the Fall, 2003, semester, the students will also have the chance to generate linear models for the aircraft, at multiple flight conditions, before designing their controllers.

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