Model-Based Design of a New Light-weight Aircraft

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This paper uses a combination of free and commercial off-the-shelf (COTS) modeling and simulation software to simplify and accelerate the flight vehicle design process. Using an example of a new light-weight aircraft the paper shows how a vehicle's geometry can be optimized, stability and control coefficients calculated, open-loop plant model created, flight controller designed, and closed-loop simulation run, all in a rapid iterative fashion, to confirm that system level requirements are satisfied.

Nomenclature

C_l	=	lift coefficient
C_m	=	pitching moment coefficient
Θ	=	aircraft pitch angle

I. Introduction

CREATING a new or modifying an existing flight vehicle is a complex and time-consuming process. Engineers have to make decisions about vehicle configuration and flight control design that will ensure that system-level specifications are met. Any changes to hardware are very expensive and time consuming. Therefore it is important to finalize and verify the design as much as possible before any hardware is built. Model-Based Design enables engineers to test and verify their ideas in the early stages of the design process when making changes to the design is still relatively easy and inexpensive.

In this paper we use an example of a design of a new light aircraft to present a method for rapid iteration over vehicle geometric configuration and flight control design. The paper describes the steps that stability and control engineers typically go through in the early stages of the design process. These steps include: definition of the vehicle's geometry, determination of the vehicle's aerodynamic characteristics, creation of a simulation to verify the performance, and design of flight control laws.

Each of these steps can be a time-consuming task. In this paper we present tools and techniques for streamlining these steps and ensuring rapid iteration over the design. We first talk about a method for determining the vehicle's aerodynamic characteristics based on its geometry. We discuss US Air Force Digital Data Compendium (Datcom) software and present results of Digital Datcom analysis of our particular vehicle configuration. We then demonstrate how to rapidly and easily import results obtained from Digital Datcom into MATLAB® for further analysis. We illustrate what preliminary analysis of aerodynamic stability and control coefficients and derivatives can reveal about the vehicle's performance and stability.

We then show how to quickly create a simulation of a flight vehicle. We discuss modeling equations of motion, calculating forces and moments acting on the aircraft, modeling vehicle components such as sensors and actuators, and modeling environmental effects such as atmosphere, gravity, and wind gusts. We demonstrate how aerodynamic coefficients from Digital Datcom can be used in the simulation to rapidly calculate aerodynamic forces and moments acting on the vehicle.

Next, flight control design techniques are discussed. Using the example of longitudinal control design for our aircraft we show how the simulation model can be easily linearized and how a controller can be designed that meets both time domain and frequency domain specifications. We also show how, for our specific example of longitudinal flight control, we design the inner- and outer-loop controller effectively.

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We close by discussing how the results of closed loop nonlinear simulation can be used to verify that system level requirements have been met. We also discuss how simulation results can be visualized in a high-fidelity, three-dimensional environment for detecting anomalies in flight vehicle behavior.

II. Establishing System Level Requirements

Every new aircraft project or existing aircraft modification starts with system level requirements. Examples of system level requirements include maximum take-off weight, range, level cruise speed, stall speed, maximum altitude, rate of climb, and a multitude of other specifications. System level requirements drive the design decisions and serve as the ultimate criteria for judging whether the design was successful. For the purposes of this article, we assume that our design requirements called for a light-weight four-seat monoplane with a certain level cruise speed, a certain maximum take-off weight, and a certain altitude ceiling. A more detailed description of the aircraft and system level requirements is available in Ref. 1. Figure 1 shows the general configuration of the aircraft to be designed. For simplicity purposes, in this paper we will specifically address only one requirement, namely the rate of climb for the aircraft. We will design our aircraft so that its rate of climb should be greater than or equal to 2 meters/second at an altitude of 2,000 meters above sea level.

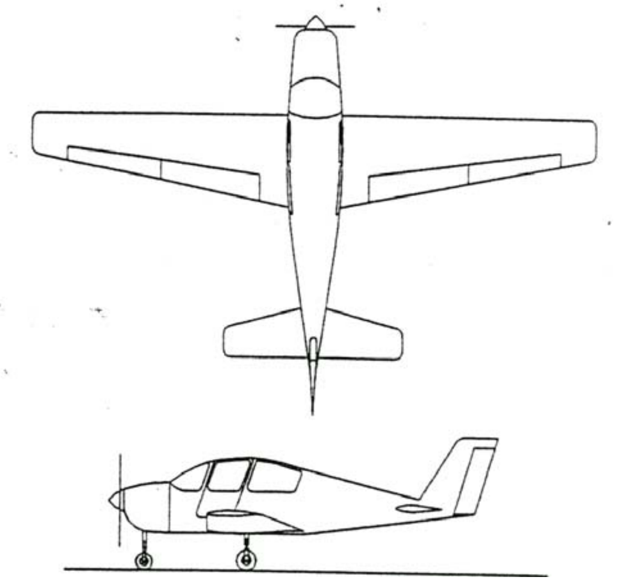


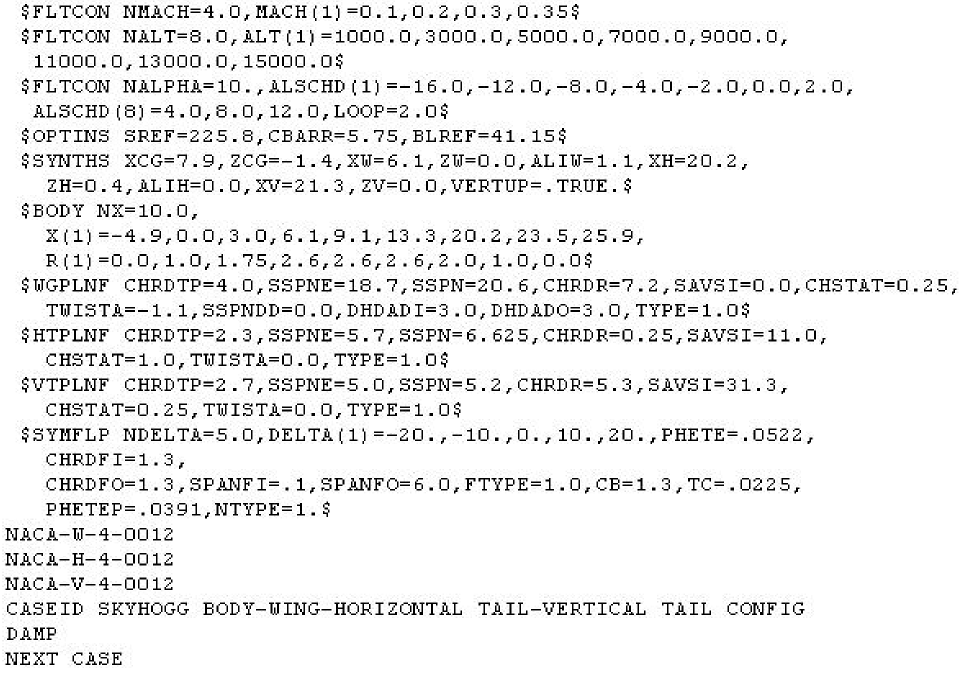
Figure 1. The light-weight four-seat monoplane to be designed[1].

III. Determining Vehicle Geometry

Once system level specifications are available, engineers need to determine an aircraft geometry that will result in aircraft performance that meets requirements. Aerodynamic stability and control coefficients and derivatives[2] are a set of numbers that are used in aircraft equations of motion for calculating aerodynamic forces and moments acting on the aircraft. These numbers are determined by aircraft geometry and directly affect aircraft performance. Experienced control engineers have a good understanding of what these numbers need to be in order to meet system level requirements. Therefore, engineers need a method that would provide values of aerodynamic stability and control coefficients and derivatives for a given aircraft geometry. Using this method engineers can determine how to change the aircraft geometry to achieve the desired aerodynamic characteristics and, therefore, aircraft performance.

Several methods exist for determining an aircraft’s aerodynamic characteristics. The most accurate method is to measure aerodynamic forces and moments acting on the aircraft during flight testing. This method is very expensive as it requires building a flight-worthy prototype and flying it. Another method is wind tunnel testing. This method is also expensive as it requires building a wind tunnel model of an aircraft and running a wind tunnel to measure aerodynamic forces and moments acting on the model. Both wind tunnel testing and flight testing must be run at some point in the development process. Ideally, by this point, engineers already have an aircraft geometry that results in performance that meets requirements, or almost meets requirements. This minimizes the number of iterations that have to be run through wind tunnel testing and flight testing, and therefore minimizes cost. To be able to determine reasonable aircraft geometry prior to wind tunnel testing and flight testing, engineers use methods for analytical prediction of aerodynamic characteristics.

Several analytical prediction methods exist[3-5]. One of better known analytical methods is Digital Datcom software developed by U.S. Air Force[6]. This public domain software takes an aircraft geometry described in a certain input format. As the sample Digital Datcom input file in Fig. 2 shows, this file defines geometric characteristics and characteristic dimensions of an aircraft’s fuselage, wings, horizontal, and vertical tail. A detailed description of the information that needs to be specified in Digital Datcom input files can be found in Digital Datcom manual.



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NACA-H-4-0012
NACA-V-4-0012
CASEID SKYHOGG BODY-WING-HORIZONTAL TAIL-VERTICAL TAIL CONFIG
DAMP
NEXT CASE
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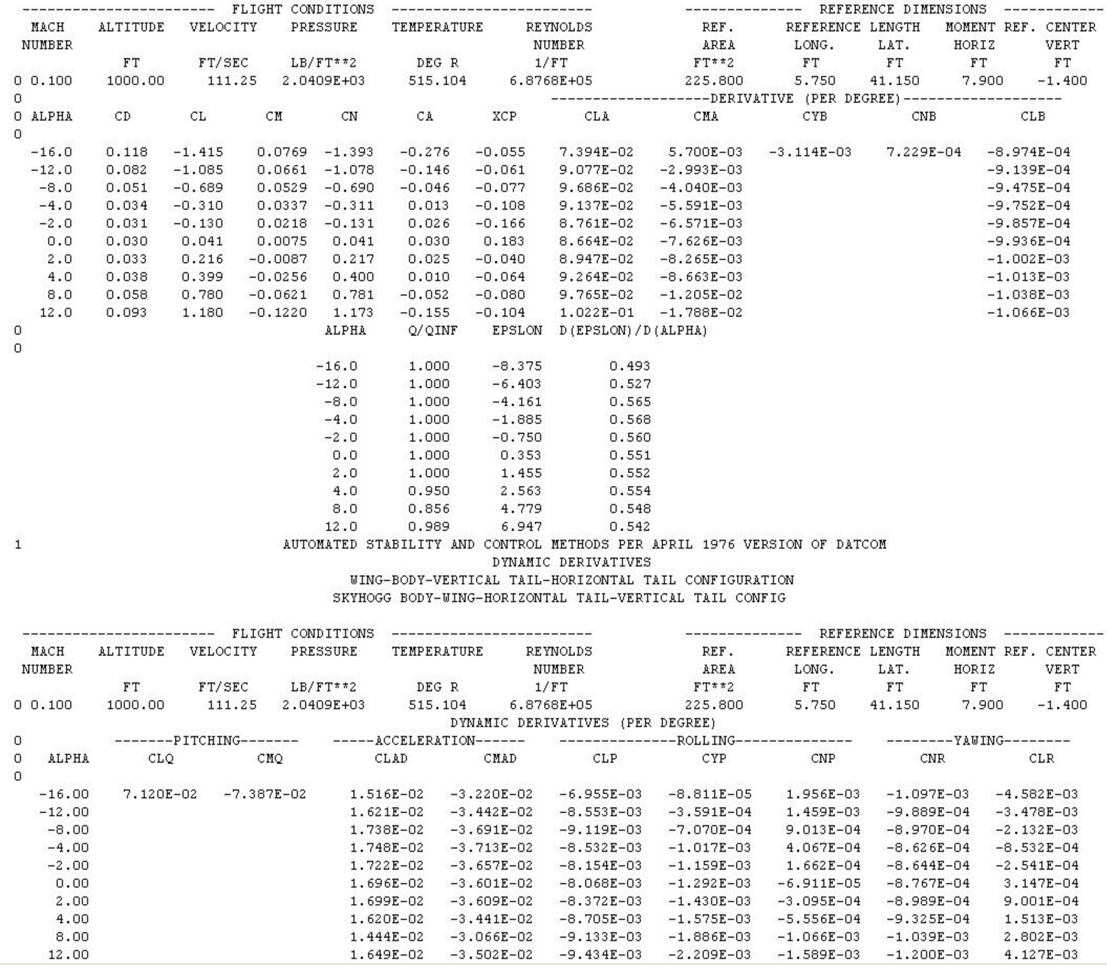
Figure 2. A Digital Datcom input file specifies aircraft geometry and flight conditions for the analysis.



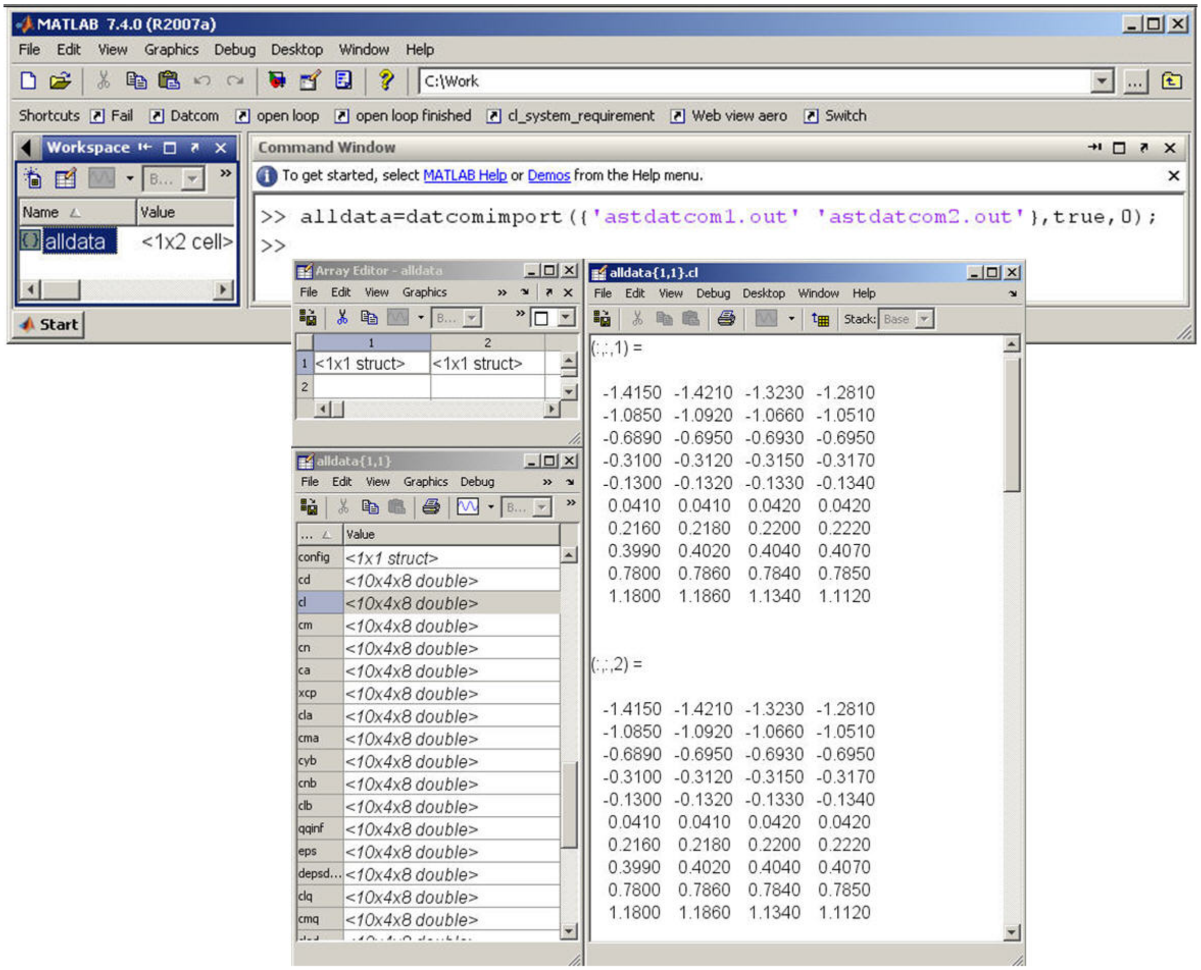
```
  -----------------------  FLIGHT CONDITIONS  ------------------------           --------------  REFERENCE DIMENSIONS  ------------
   MACH     ALTITUDE    VELOCITY     PRESSURE    TEMPERATURE      REYNOLDS             REF.      REFERENCE LENGTH    MOMENT REF. CENTER
  NUMBER                                                           NUMBER              AREA        LONG.      LAT.      HORIZ       VERT
               FT        FT/SEC      LB/FT**2       DEG R           1/FT               FT**2        FT         FT         FT         FT
 0 0.100     1000.00     111.25    2.0409E+03     515.104       6.8768E+05            225.800      5.750     41.150      7.900     -1.400
 0                                                                    -------------------DERIVATIVE (PER DEGREE)-------------------
 0 ALPHA      CD        CL        CM        CN        CA        XCP         CLA           CMA           CYB            CNB            CLB
 0
   -16.0     0.118    -1.415    0.0769   -1.393    -0.276    -0.055     7.394E-02     5.700E-03    -3.114E-03     7.229E-04     -8.974E-04
   -12.0     0.082    -1.085    0.0661   -1.078    -0.146    -0.061     9.077E-02    -2.993E-03                                  -9.139E-04
    -8.0     0.051    -0.689    0.0529   -0.690    -0.046    -0.077     9.686E-02    -4.040E-03                                  -9.475E-04
    -4.0     0.034    -0.310    0.0337   -0.311     0.013    -0.108     9.137E-02    -5.591E-03                                  -9.752E-04
    -2.0     0.031    -0.130    0.0218   -0.131     0.026    -0.166     8.761E-02    -6.571E-03                                  -9.857E-04
     0.0     0.030     0.041    0.0075    0.041     0.030     0.183     8.664E-02    -7.626E-03                                  -9.936E-04
     2.0     0.033     0.216   -0.0087    0.217     0.025    -0.040     8.947E-02    -8.265E-03                                  -1.002E-03
     4.0     0.038     0.399   -0.0256    0.400     0.010    -0.064     9.264E-02    -8.663E-03                                  -1.013E-03
     8.0     0.058     0.780   -0.0621    0.781    -0.052    -0.080     9.765E-02    -1.205E-02                                  -1.038E-03
    12.0     0.093     1.180   -0.1220    1.173    -0.155    -0.104     1.022E-01    -1.788E-02                                  -1.066E-03
 0                                        ALPHA     Q/QINF    EPSLON  D(EPSLON)/D(ALPHA)
 0
                                          -16.0      1.000    -8.375        0.493
                                          -12.0      1.000    -6.403        0.527
                                           -8.0      1.000    -4.161        0.565
                                           -4.0      1.000    -1.885        0.568
                                           -2.0      1.000    -0.750        0.560
                                            0.0      1.000     0.353        0.551
                                            2.0      1.000     1.455        0.552
                                            4.0      0.950     2.563        0.554
                                            8.0      0.856     4.779        0.548
                                           12.0      0.989     6.947        0.542
 1                                  AUTOMATED STABILITY AND CONTROL METHODS PER APRIL 1976 VERSION OF DATCOM
                                                                DYNAMIC DERIVATIVES
                                            WING-BODY-VERTICAL TAIL-HORIZONTAL TAIL CONFIGURATION
                                           SKYHOGG BODY-WING-HORIZONTAL TAIL-VERTICAL TAIL CONFIG

  -----------------------  FLIGHT CONDITIONS  ------------------------           --------------  REFERENCE DIMENSIONS  ------------
   MACH     ALTITUDE    VELOCITY     PRESSURE    TEMPERATURE      REYNOLDS             REF.      REFERENCE LENGTH    MOMENT REF. CENTER
  NUMBER                                                           NUMBER              AREA        LONG.      LAT.      HORIZ       VERT
               FT        FT/SEC      LB/FT**2       DEG R           1/FT               FT**2        FT         FT         FT         FT
 0 0.100     1000.00     111.25    2.0409E+03     515.104       6.8768E+05            225.800      5.750     41.150      7.900     -1.400
                                                         DYNAMIC DERIVATIVES (PER DEGREE)
 0            -------PITCHING-------     -----ACCELERATION------      --------------ROLLING--------------     --------YAWING--------
 0    ALPHA       CLQ          CMQ            CLAD          CMAD          CLP           CYP           CNP           CNR           CLR
 0
     -16.00    7.120E-02    -7.387E-02     1.516E-02    -3.220E-02    -6.955E-03    -8.811E-05     1.956E-03    -1.097E-03    -4.582E-03
     -12.00                                1.621E-02    -3.442E-02    -8.553E-03    -3.591E-04     1.459E-03    -9.889E-04    -3.478E-03
      -8.00                                1.738E-02    -3.691E-02    -9.119E-03    -7.070E-04     9.013E-04    -8.970E-04    -2.132E-03
      -4.00                                1.748E-02    -3.713E-02    -8.532E-03    -1.017E-03     4.067E-04    -8.626E-04    -8.532E-04
      -2.00                                1.722E-02    -3.657E-02    -8.154E-03    -1.159E-03     1.662E-04    -8.644E-04    -2.541E-04
       0.00                                1.696E-02    -3.601E-02    -8.068E-03    -1.292E-03    -6.911E-05    -8.767E-04     3.147E-04
       2.00                                1.699E-02    -3.609E-02    -8.372E-03    -1.430E-03    -3.095E-04    -8.989E-04     9.001E-04
       4.00                                1.620E-02    -3.441E-02    -8.705E-03    -1.575E-03    -5.556E-04    -9.325E-04     1.513E-03
       8.00                                1.444E-02    -3.066E-02    -9.133E-03    -1.886E-03    -1.066E-03    -1.039E-03     2.802E-03
      12.00                                1.649E-02    -3.502E-02    -9.434E-03    -2.209E-03    -1.589E-03    -1.200E-03     4.127E-03
```

Figure 3. A section of Digital Datcom output file shows some of the output results for the first flight condition.

The file shown in Fig. 2 also defines the flight conditions for which stability and control coefficients and derivatives are to be estimated. This file specifies that 320 flight conditions will be analyzed corresponding to four different values of Mach number, eight different values of altitude, and ten different values of angle of attack.

Once the input file is created, Digital Datcom can be run to produce the output file containing estimated stability and control coefficients and derivatives for the specified aircraft geometry and flight conditions. Figure 3 shows a section of Digital Datcom output file created for the input file shown in Fig. 2. The file shown in Fig. 3 is 3,180 lines long. This file is composed of 320 similar sections, each of them containing the values of the same stability and control coefficients and derivatives for each of the specified 320 flight conditions. After estimates of stability and control coefficients and derivatives are obtained, an engineer will want to have easy access to these numbers for analysis and for further use in modeling flight vehicle dynamics and control system design. As Fig. 3 shows the text format of Digital Datcom output file and its sheer size make it difficult to use for such an analysis.

MATLAB®[7] is a widely used commercial off-the-shelf software product that has extensive capabilities in the areas of data analysis, visualization, and reporting. Moreover, add-on products extend MATLAB capabilities in many areas - dynamic system simulation and control design being just two of them. Therefore, it would be highly desirable to have access to the Digital Datcom stability and control coefficients and derivatives in MATLAB. Aerospace Toolbox[8] provides this capability by importing Digital Datcom output files into MATLAB data structures. Figure 4 shows how the `datcomimport` function of Aerospace Toolbox imports two Digital Datcom output files, `astdatcom1.out` and `astdatcom2.out` into a 1-by-2 cell array of data structures in MATLAB. Each data structure in this cell array corresponds to one of the imported Digital Datcom output files and contains the values of all aerodynamic characteristics from the corresponding Digital Datcom output file, as shown in Fig 4. In this example, the lift coefficient, C_l variable in MATLAB workspace is a 10-by-4-by-8 array. The dimensions of the


MATLAB 7.4.0 (R2007a)
File Edit View Graphics Debug Desktop Window Help
C:\Work
Shortcuts Fail Datcom open loop open loop finished cl_system_requirement Web view aero Switch
Workspace
Command Window
To get started, select MATLAB Help or Demos from the Help menu.
Start
Array Editor - alldata
File Edit View Graphics
alldata{1,1}
File Edit View Graphics Debug
alldata{1,1}.cl
File Edit View Debug Desktop Window Help
Stack: Base

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	1	2
1	<1x1 struct>	<1x1 struct>
2		

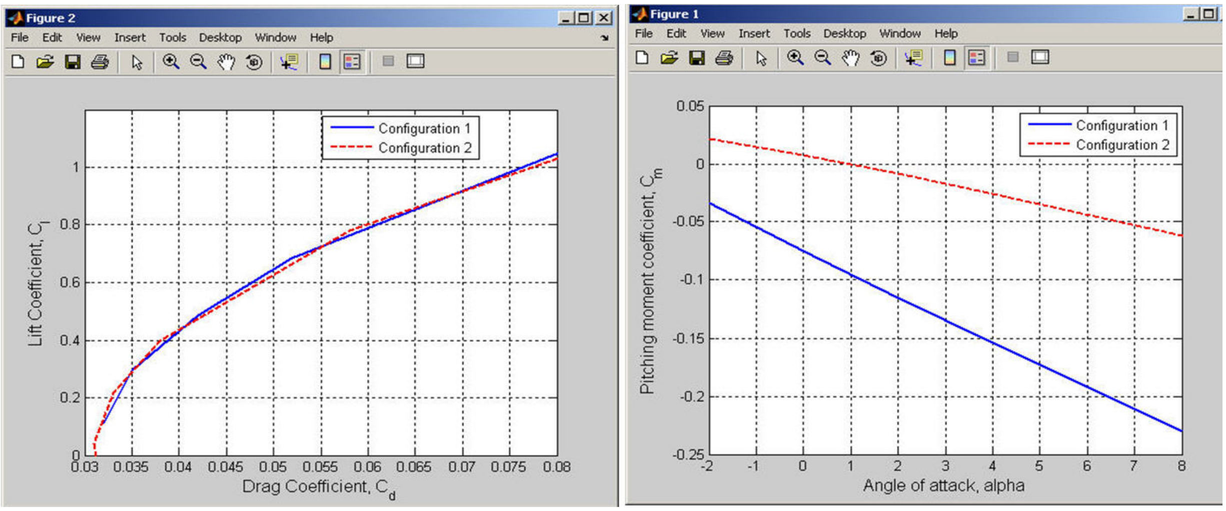
...	Value
config	<1x1 struct>
cd	<10x4x8 double>
cl	<10x4x8 double>
cm	<10x4x8 double>
cn	<10x4x8 double>
ca	<10x4x8 double>
xcp	<10x4x8 double>
cla	<10x4x8 double>
cma	<10x4x8 double>
cyb	<10x4x8 double>
cnb	<10x4x8 double>
clb	<10x4x8 double>
qqinf	<10x4x8 double>
eps	<10x4x8 double>
depsd...	<10x4x8 double>
clq	<10x4x8 double>
cmq	<10x4x8 double>

```
(:,:,1) =

 -1.4150  -1.4210  -1.3230  -1.2810
 -1.0850  -1.0920  -1.0660  -1.0510
 -0.6890  -0.6950  -0.6930  -0.6950
 -0.3100  -0.3120  -0.3150  -0.3170
 -0.1300  -0.1320  -0.1330  -0.1340
  0.0410   0.0410   0.0420   0.0420
  0.2160   0.2180   0.2200   0.2220
  0.3990   0.4020   0.4040   0.4070
  0.7800   0.7860   0.7840   0.7850
  1.1800   1.1860   1.1340   1.1120


(:,:,2) =

 -1.4150  -1.4210  -1.3230  -1.2810
 -1.0850  -1.0920  -1.0660  -1.0510
 -0.6890  -0.6950  -0.6930  -0.6950
 -0.3100  -0.3120  -0.3150  -0.3170
 -0.1300  -0.1320  -0.1330  -0.1340
  0.0410   0.0410   0.0420   0.0420
  0.2160   0.2180   0.2200   0.2220
  0.3990   0.4020   0.4040   0.4070
  0.7800   0.7860   0.7840   0.7850
  1.1800   1.1860   1.1340   1.1120
```

Figure 4. Several Digital Datcom output files can be imported into MATLAB simultaneously using Aerospace Toolbox.

array correspond to the number of flight conditions defined in the Digital Datcom input file: ten angles of attack, four Mach numbers, and eight altitudes.

With all the stability and control coefficients and derivatives available in MATLAB, various plots can be quickly constructed to evaluate the performance characteristics of the aircraft. For example, Fig. 5a shows a drag polar plot for two considered aircraft geometries corresponding to the two Digital Datcom output files imported into MATLAB. Figure 5b shows the values of pitching moment coefficient, C_m as a function of angle of attack for these two aircraft geometries. Both plots are for the flight condition of 0.1 Mach number and 5,000 feet altitude. These types of plots immediately convey useful information about the efficiency of the chosen geometry or about the effects of changes in the aircraft's geometry on its longitudinal static stability.



a) Drag polar plot. **b) Pitching moment coefficient.**

Figure 5. Digital Datcom coefficients can be used for preliminary configuration analysis in MATLAB.

IV. Creating an Open-Loop Plant Model

Availability of stability and control coefficients and derivatives in MATLAB simplifies preliminary analysis of these numbers. However, a control system has to be designed and closed-loop vehicle simulation has to be performed to understand whether the chosen vehicle geometry can lead to a vehicle design that will satisfy system level requirements. An open-loop plant model is required to start control system design. At least two approaches can be used to create the open-loop plant model.

With the first approach one would develop a linear state-space system describing the aircraft's linearized dynamics. Stability and control coefficients and derivatives imported from Digital Datcom can be used to calculate the coefficients of state-space matrices. The resulting linear model can then be used for control design tasks. The problem with this approach is that it does not provide a control engineer with a nonlinear aircraft model that could be used for checking control design across multiple flight conditions and for determining if the vehicle's performance satisfies system level requirements. Therefore, an alternative approach is proposed.

With the alternative approach, an open-loop plant model is constructed using full nonlinear equations of motion. The open-loop model developed this way can be linearized at a specific flight condition for control design, and can also be later used for nonlinear closed-loop simulation to determine if the chosen aircraft geometry and flight control design result in aircraft performance that meets system level requirements.

In the first step of this approach, an open loop model is constructed with equations of motion, based on Newton's second law. These equations of motion are solved by integrating input forces and moments to find aircraft's position and attitude. A convenient way to organize these calculations is through the use of Simulink®[9]. With this product an engineer can choose the appropriate blocks from the Simulink block library, place them into the model, and connect them. Aerospace Blockset[10] contains a library of blocks implementing equations of motions. A block from that library could be used as a starting point for the open-loop model. A library of blocks implementing six degrees-of-freedom (DOF) equations of motion is shown in Fig. 6. In the case of this article, a three-DOF (Body Axes) block was chosen and placed into a Simulink model for modeling the longitudinal dynamics of the aircraft.

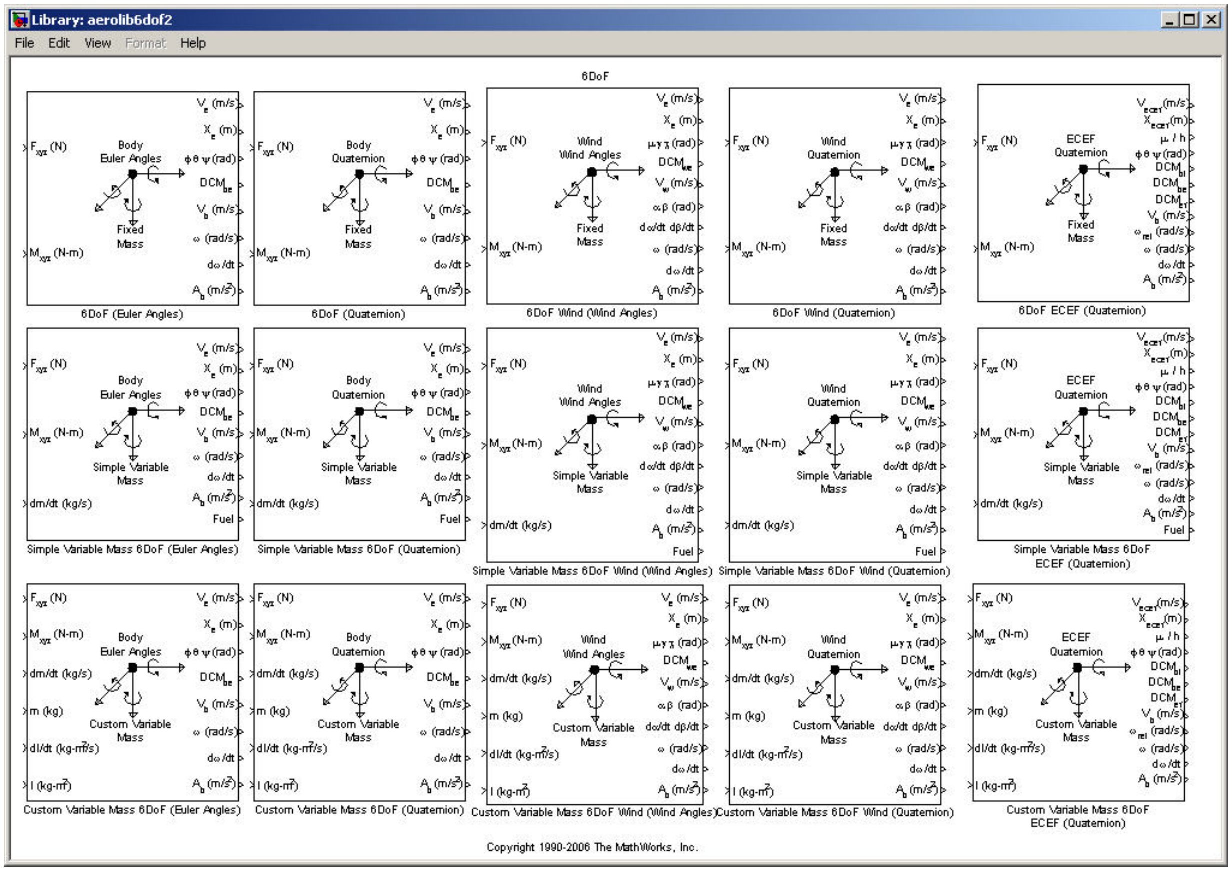

Library: aerolib6dof2
File Edit View Format Help
6DoF
6DoF (Euler Angles)
6DoF (Quaternion)
6DoF Wind (Wind Angles)
6DoF Wind (Quaternion)
6DoF ECEF (Quaternion)
Simple Variable Mass 6DoF (Euler Angles)
Simple Variable Mass 6DoF (Quaternion)
Simple Variable Mass 6DoF Wind (Wind Angles)
Simple Variable Mass 6DoF Wind (Quaternion)
Simple Variable Mass 6DoF ECEF (Quaternion)
Custom Variable Mass 6DoF (Euler Angles)
Custom Variable Mass 6DoF (Quaternion)
Custom Variable Mass 6DoF Wind (Wind Angles)
Custom Variable Mass 6DoF Wind (Quaternion)
Custom Variable Mass 6DoF ECEF (Quaternion)
Body Euler Angles
Body Quaternion
Wind Wind Angles
Wind Quaternion
ECEF Quaternion
Fixed Mass
Simple Variable Mass
Custom Variable Mass
F_xyz (N)
M_xyz (N-m)
dm/dt (kg/s)
m (kg)
dI/dt (kg-m²/s)
I (kg-m²)
V_e (m/s)
X_e (m)
φ θ ψ (rad)
DCM_be
V_b (m/s)
ω (rad/s)
dω/dt
A_b (m/s²)
Fuel
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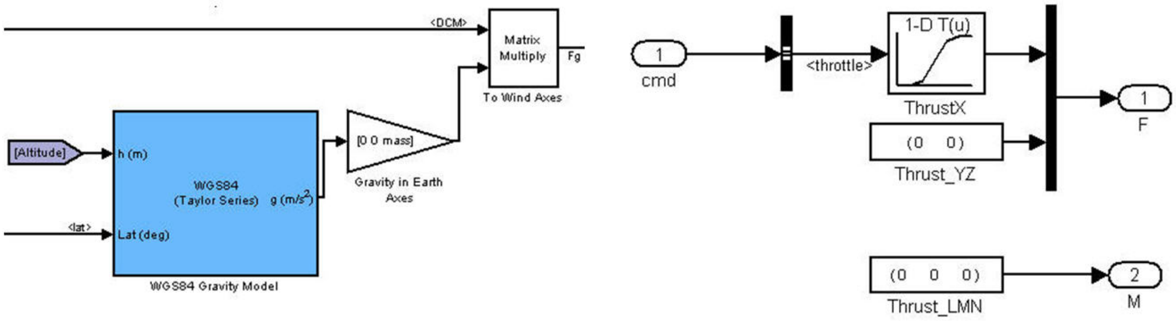
Figure 6. Equations of motion can be implemented with one of the blocks from the Aerospace Blockset Equations of Motion library.

This block can be replaced with a six-DOF equations of motion block at a later time when the dynamic model is further elaborated. Forces and moments that are inputs to the equations of motion come from several different sources: gravity, propulsion, and aerodynamics (aeroelastic effects are not considered in this article, but can be added later for higher fidelity simulation).

To calculate gravity forces and moments, a local gravity vector has to be multiplied by vehicle mass and converted to wind axes. For calculating propulsion forces and moments, a simple lookup table was used to calculate thrust as a function of throttle command, and the propulsive moment was assumed equal to zero. Calculation of gravity and propulsive forces and moments is shown in Fig. 7 (in this figure and all subsequent figures blocks from

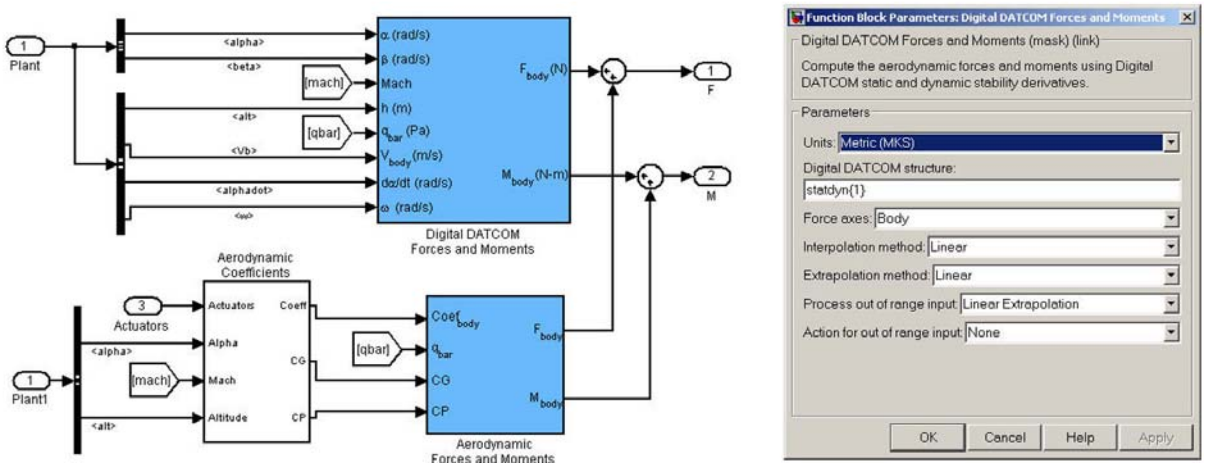


a) Calculation of gravity force.

b) Calculation of propulsive forces and moments.

Figure 7. Forces and moments acting on the aircraft include gravity force and propulsive forces and moments.

Aerospace Blockset are highlighted in blue). In accordance with Model-Based Design, these calculations can be further elaborated when a more precise dynamic model of the vehicle is required.



Function Block Parameters: Digital DATCOM Forces and Moments

Digital DATCOM Forces and Moments (mask) (link)

Compute the aerodynamic forces and moments using Digital DATCOM static and dynamic stability derivatives.

Parameters

Units: Metric (MKS)

Digital DATCOM structure:
statdyn{1}

Force axes: Body

Interpolation method: Linear

Extrapolation method: Linear

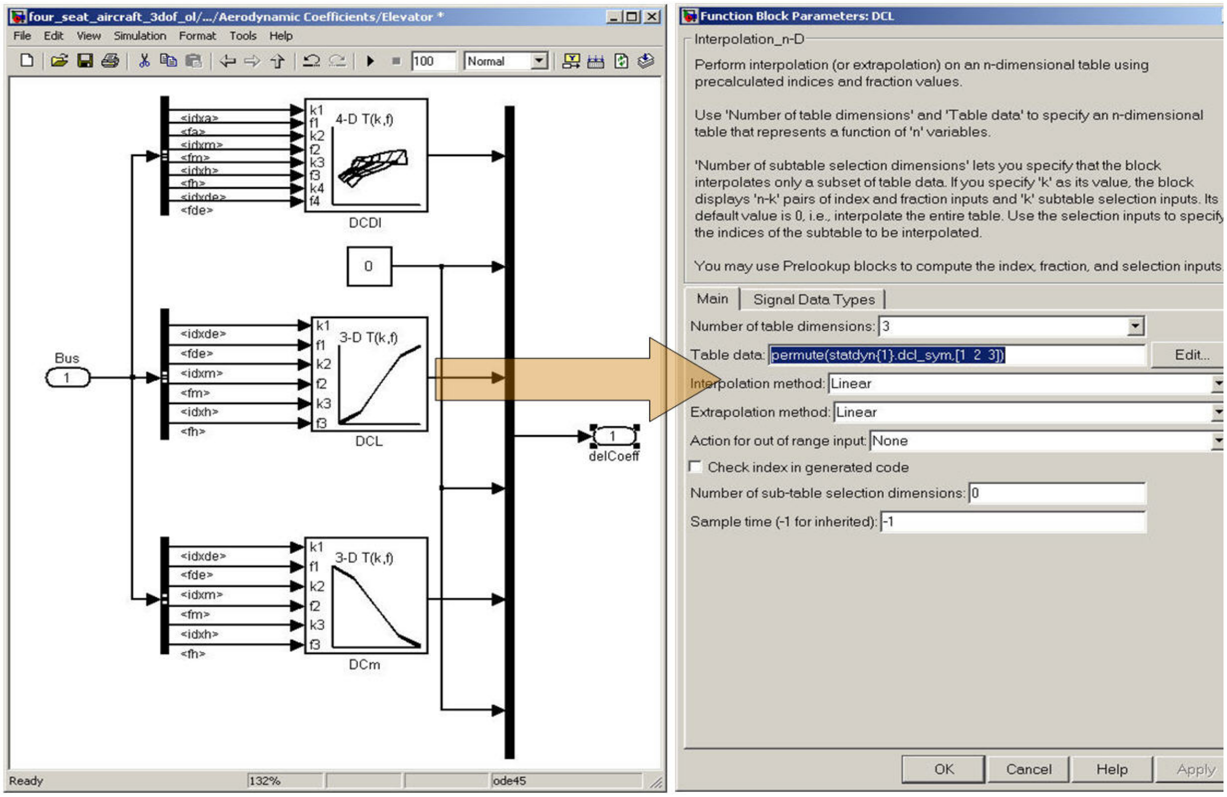
Process out of range input: Linear Extrapolation

Action for out of range input: None

a) Calculation of aerodynamic forces and moments.

b)User dialogue for Digital Datcom Forces and Moments block.

Figure 8. The Digital Datcom Forces and Moments block uses a structure with data imported from Digital Datcom to calculate aerodynamic forces and moments.



Function Block Parameters: DCL

Interpolation_n-D

Perform interpolation (or extrapolation) on an n-dimensional table using precalculated indices and fraction values.

Use 'Number of table dimensions' and 'Table data' to specify an n-dimensional table that represents a function of 'n' variables.

'Number of subtable selection dimensions' lets you specify that the block interpolates only a subset of table data. If you specify 'k' as its value, the block displays 'n-k' pairs of index and fraction inputs and 'k' subtable selection inputs. Its default value is 0, i.e., interpolate the entire table. Use the selection inputs to specif the indices of the subtable to be interpolated.

You may use Prelookup blocks to compute the index, fraction, and selection inputs.

Number of table dimensions: 3

Table data: permute(statdyn{1}.dcl_sym,[1 2 3]) Edit...

Interpolation method: Linear

Extrapolation method: Linear

Action for out of range input: None

□ Check index in generated code

Number of sub-table selection dimensions: 0

Sample time (-1 for inherited): -1

a) Calculation of aerodynamic coefficients for elevator forces and moments.

b) Coefficients are based on data imported from Digital Datcom.

Figure 9. Digital Datcom data is used to calculate aerodynamic forces and moments from control surface deflections.

Aerospace Blockset provides a Digital Datcom Forces and Moments block that calculates static and dynamic aerodynamic forces and moments acting on the aircraft using stability and control coefficients and derivatives imported from a Digital Datcom output file. In addition to the Digital Datcom Forces and Moments block, another calculation is needed to determine short-term aerodynamic forces and moments created by control surface deflections. Figure 8a shows how the Digital Datcom Forces and Moments block is used to calculate static and dynamic aerodynamic forces and moments.

Figure 8b shows the user dialog for the Digital Datcom Forces and Moments block. Figure 8a also shows the calculation of total aerodynamic forces and moments, which is achieved by adding static and dynamic aerodynamic forces and moments calculated by the Digital Datcom Forces and Moments block with forces and moments created by the aircraft's control surface deflections (calculated in Aerodynamic Forces and Moments subsystem in Fig. 8a). Figure 8b shows that the name of the MATLAB structure containing Digital Datcom stability and control coefficients and derivatives is specified in the user dialog for the Digital Datcom Forces and Moments block in the **Digital Datcom structure** field. Aerodynamic coefficients used for calculating forces and moments created by control surface deflections are also based on stability and control derivatives imported from Digital Datcom. For example, Fig. 9 shows the calculation of coefficients for determining aerodynamic forces and moments generated by elevator deflection. Once a Simulink model for the open- loop plant model has been setup, it can be quickly updated for different aircraft geometries by simply importing a new Digital Datcom output file containing the aerodynamic characteristics for the new geometry. The vehicle's mass and inertia properties may need to be updated as well.

The open-loop plant model to be used for control design should also include actuator models as well as sensor dynamics. Blocks from Aerospace Blockset were used for this purpose. Figure 10 shows a subsystem implementing

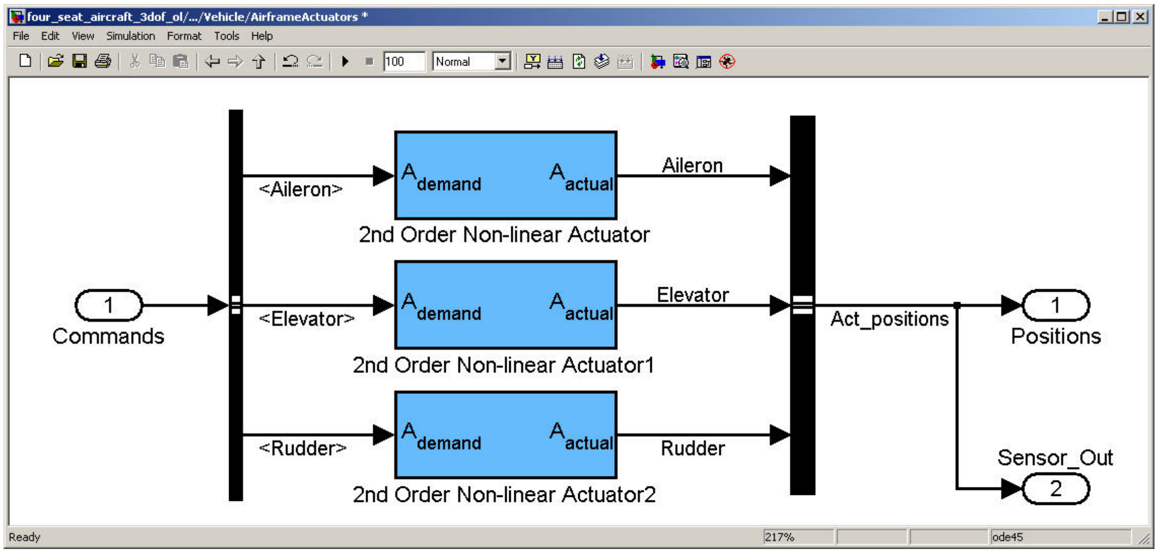
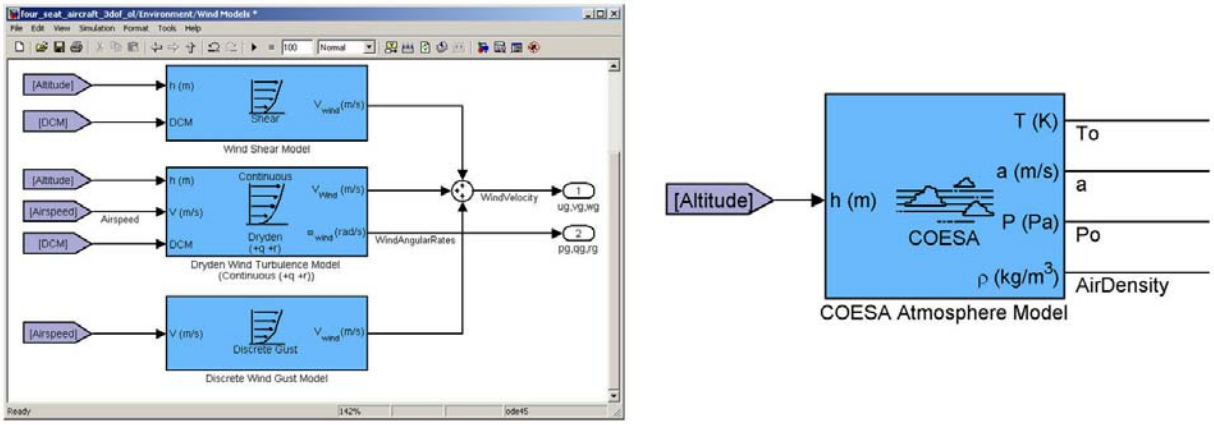

four_seat_aircraft_3dof_ol/.../Vehicle/AirframeActuators *
File Edit View Simulation Format Tools Help
100
Normal
1
Commands
<Aileron>
<Elevator>
<Rudder>
A_{demand}
A_{actual}
2nd Order Non-linear Actuator
2nd Order Non-linear Actuator1
2nd Order Non-linear Actuator2
Aileron
Elevator
Rudder
Act_positions
1
Positions
Sensor_Out
2
Ready
217%
ode45

Figure 10. Actuator dynamics were modeled with Aerospace Blockset blocks.



a) Wind turbulence model. **b) Model of the atmosphere.**

Figure 11. Model fidelity was increased by including environmental effects.

actuator dynamics.

Aerospace Blockset blocks were also used to increase the fidelity of the model by adding environmental effects. Specifically, wind turbulence models from Aerospace Blockset were used to calculate wind velocities as shown in Fig. 11a. The Committee on Extension to International Standard Atmosphere (COESA) model was used to model changes in atmospheric temperature, pressure, density, and local speed of sound as shown in Fig. 11b. These values were used for calculating Mach number and dynamic pressure values.

Finally, to keep calculations consistent, transformations from body axes to inertial axes, from wind axes to body axes, and from vehicle coordinates in the inertial coordinate system to vehicle latitude, longitude, and altitude had to be performed. All these operations were done using the appropriate block from Aerospace Blockset.

V. Designing Flight Control System

For the purposes of this article, a longitudinal flight controller for the aircraft was developed. With the open-loop nonlinear model created, the next steps are to select the control architecture and linearize the model for linear control design. Simulink® Control Design[11] made this convenient by providing the ability to apply the linear control design tools directly on the Simulink model by specifying the blocks in the model to tune and specifying closed loop input and output signals with linearization points. The first step is to modify the open-loop system with the control architecture to close the loop. This is done by inserting blocks into the model that represent flight control logic. In the discussed example, the longitudinal controller represents a two-loop setup, shown in Fig. 12. An inner loop uses the measurement of pitch angle, θ, and the outer loop uses the measurement of the aircraft's altitude. The structure of the longitudinal controller in Simulink is shown in Fig. 13. The output linearization point, measured altitude, is also shown in Fig. 13. The input linearization point is altitude command.

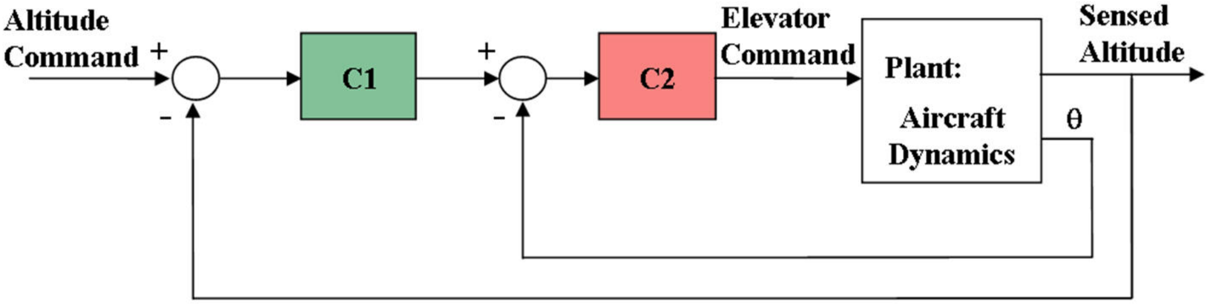
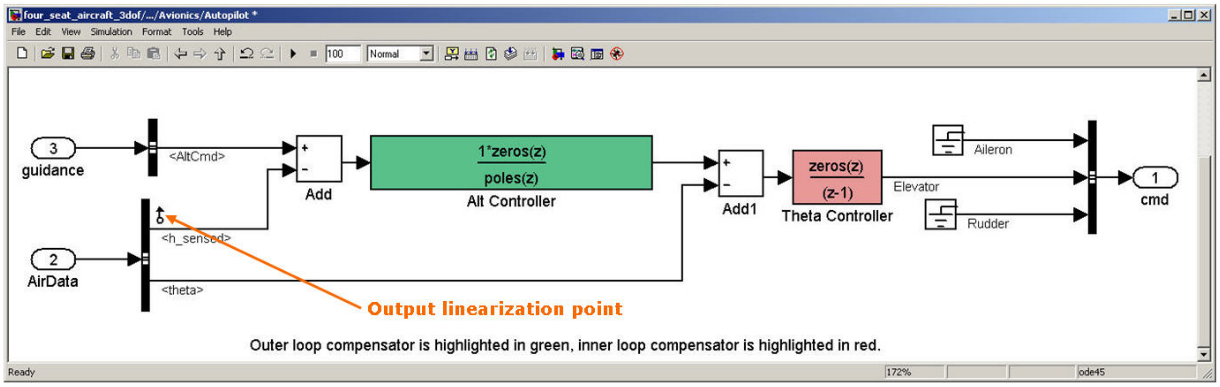


Figure 12. Longitudinal controller consists of an inner pitch loop and an outer altitude loop.

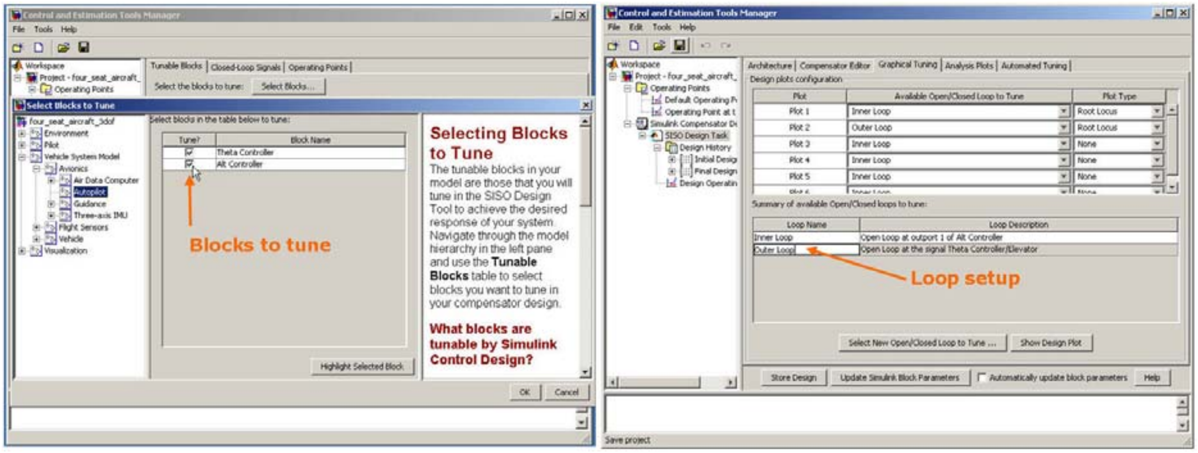

four_seat_aircraft_3dof/.../Avionics/Autopilot *

Output linearization point

Outer loop compensator is highlighted in green, inner loop compensator is highlighted in red.

Figure 13. Longitudinal controller in Simulink also consists of inner pitch loop and outer altitude loop.

With input and output linearization points specified and the controllers for both the inner loop and the outer loop specified as the blocks to tune, as shown in Fig. 14a, Simulink Control Design automatically linearizes the plant about the default operating point. A different operating point can be specified, as was done in this example, by specifying a certain simulation time. The state of the system at the specified time will be used as the operating point for linearization. In the specific example discussed here, the operating point was calculated at a simulation time of five seconds, when the system was in steady state. In addition, Simulink Control Design automatically defines feedback loops to be used in the design, as shown in Fig. 14b. The next step of the process was to specify design and analysis plots. In this case root locus charts were used for design and a step response plot was used for analysis.



Select blocks in the table below to tune:

Tune?	Block Name
☑	Theta Controller
☑	Alt Controller

Selecting Blocks to Tune

The tunable blocks in your model are those that you will tune in the SISO Design Tool to achieve the desired response of your system. Navigate through the model hierarchy in the left pane and use the **Tunable Blocks** table to select blocks you want to tune in your compensator design.

What blocks are tunable by Simulink Control Design?

Design plots configuration

Plot	Available Open/Closed Loop to Tune	Plot Type
Plot 1	Inner Loop	Root Locus
Plot 2	Outer Loop	Root Locus
Plot 3	Inner Loop	None
Plot 4	Inner Loop	None
Plot 5	Inner Loop	None
Plot 6	Inner Loop	None

Summary of available Open/Closed loops to tune:

Loop Name	Loop Description
Inner Loop	Open Loop at outport 1 of Alt Controller
Outer Loop	Open Loop at the signal Theta Controller/Elevator

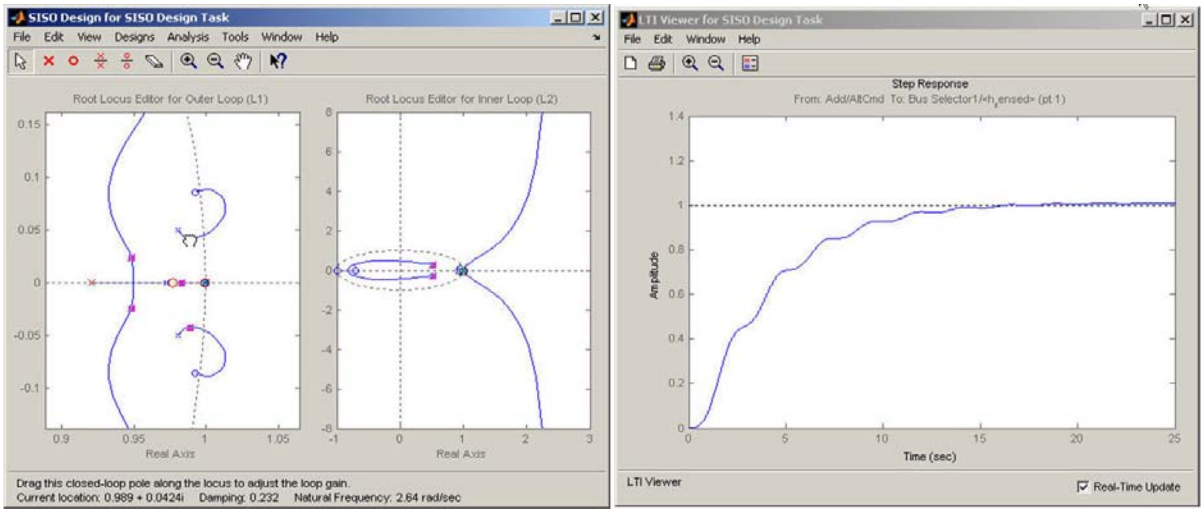
☐ Automatically update block parameters

a) Selecting blocks to tune.

b) Loop naming.

Figure 14. Simulink Control Design was used to select blocks to tune and to name the loops.

With Simulink Control Design setup completed, the tool could be used for interactive graphical tuning of the controller. Effects of changes in the controller's gains or pole and zero locations, as shown in Fig. 15a, can be immediately observed in the analysis plots as shown in Fig. 15b.


SISO Design for SISO Design Task
File Edit View Designs Analysis Tools Window Help
Root Locus Editor for Outer Loop (L1)
Root Locus Editor for Inner Loop (L2)
0.15
0.1
0.05
0
-0.05
-0.1
0.9
0.95
1
1.05
Real Axis
8
6
4
2
0
-2
-4
-6
-8
-1
0
1
2
3
Real Axis
LTI Viewer for SISO Design Task
File Edit Window Help
Step Response
From: Add/AltCmd To: Bus Selector1/<h_sensed> (pt 1)
Amplitude
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Time (sec)
LTI Viewer

Drag this closed-loop pole along the locus to adjust the loop gain.
Current location: 0.989 + 0.0424i   Damping: 0.232   Natural Frequency: 2.64 rad/sec

☑ Real-Time Update

a) Loop gains as well as pole and zero locations can be changed.

b) The step response updates as changes are made.

Figure 15. Controller was tuned interactively using graphical tuning.

Because the control system in the case of a longitudinal controller includes inner and outer loops, any changes to the inner loop compensator affect the outer loop dynamics, and any changes to the outer loop compensator influence inner loop dynamics. This is shown schematically in Fig. 12. This interdependency makes tuning of two control loops more difficult.

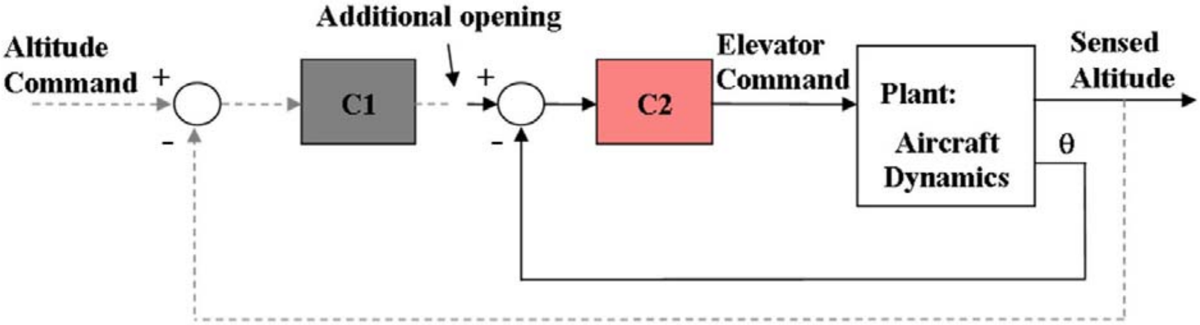
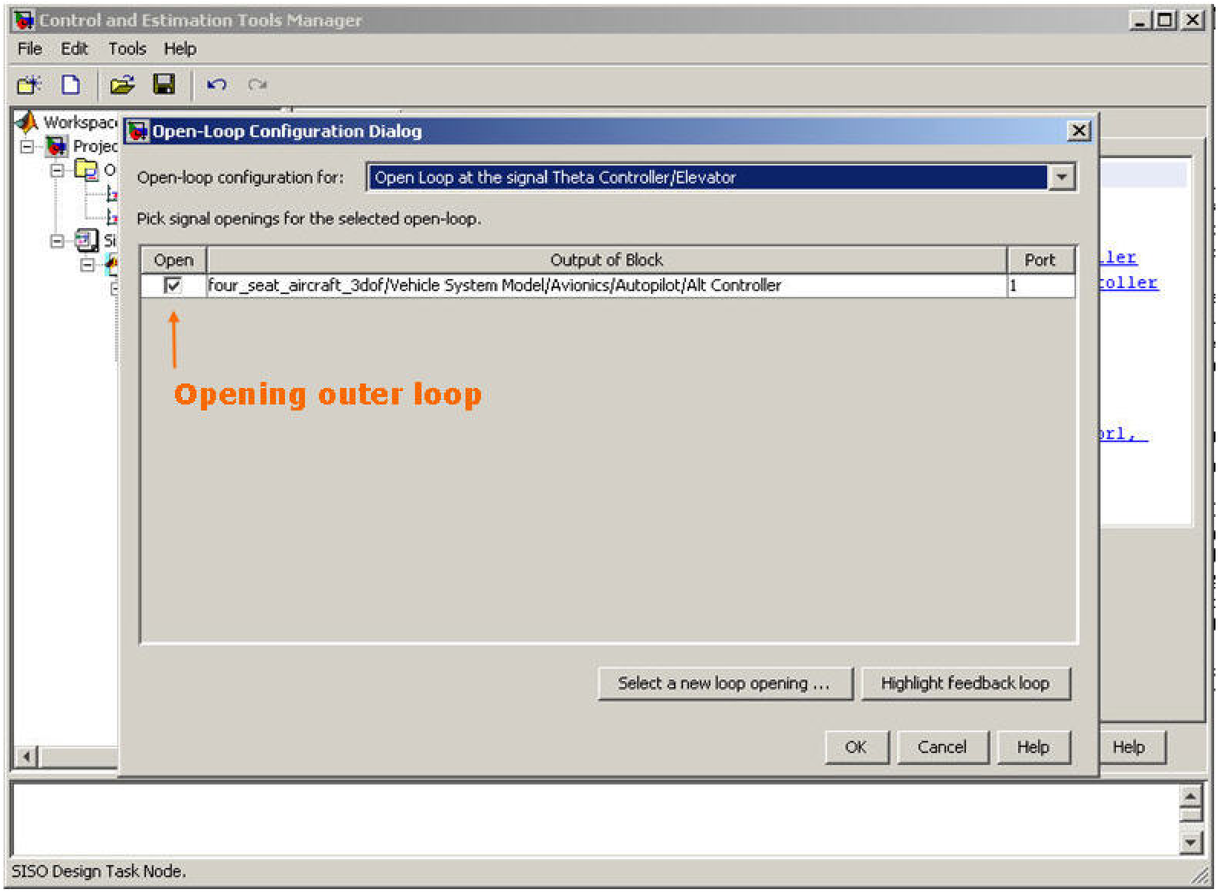


Figure 16. The outer loop was "broken" to simplify loop tuning.

To address this issue, we use a sequential loop closure technique which allows us to incrementally take into account the dynamics of the loops during the design process. With Simulink Control Design the inner loop is configured with an additional loop opening ("break") in the outer loop. This outer loop opening is shown schematically in Fig. 16, and the corresponding dialog to accomplish this in Simulink Control Design is shown in Fig. 17. With the outer loop open, the inner loop is isolated from the outer loop. Therefore, the inner loop compensator was designed first, and with that design in place, the outer loop compensator was designed next. The final designs for the inner and outer loop compensators are shown in Fig. 18. Both compensators were designed to


Control and Estimation Tools Manager
File Edit Tools Help
Workspac
Projec
Si
Open-Loop Configuration Dialog
Select a new loop opening ...
Highlight feedback loop
OK
Cancel
Help
Help
Opening outer loop

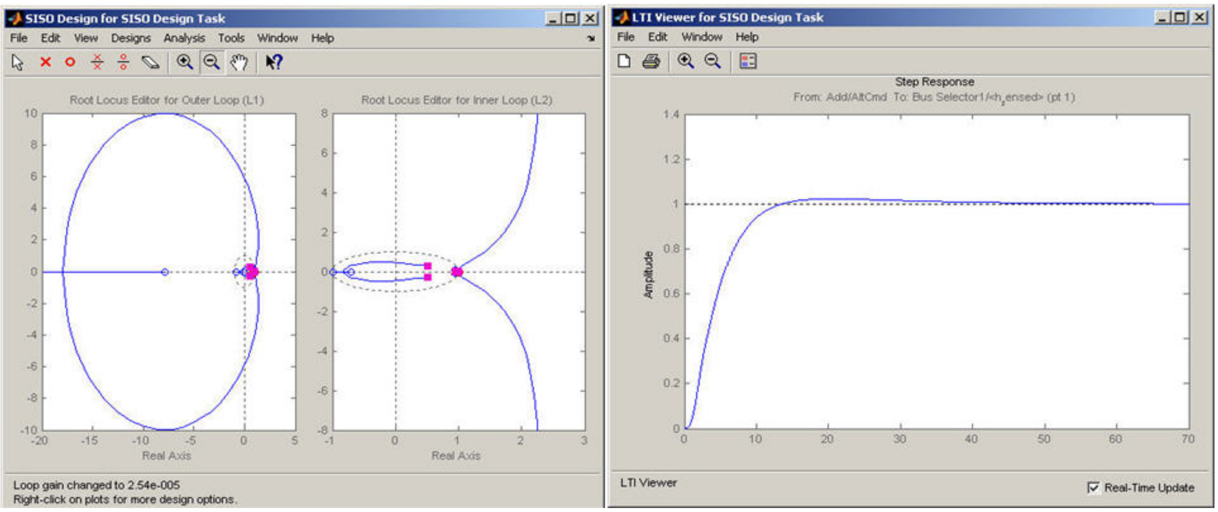
Open-loop configuration for: Open Loop at the signal Theta Controller/Elevator

Pick signal openings for the selected open-loop.

Open	Output of Block	Port
☑	four_seat_aircraft_3dof/Vehicle System Model/Avionics/Autopilot/Alt Controller	1

SISO Design Task Node.

Figure 17. Simulink Control Design was used to open the outer loop.


SISO Design for SISO Design Task
File Edit View Designs Analysis Tools Window Help
Root Locus Editor for Outer Loop (L1)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-20
-15
-10
-5
0
5
Real Axis
Root Locus Editor for Inner Loop (L2)
8
6
4
2
0
-2
-4
-6
-8
-1
0
1
2
3
Real Axis
LTI Viewer for SISO Design Task
File Edit Window Help
Step Response
From: Add/AltCmd To: Bus Selector1/<h_ensed> (pt 1)
Amplitude
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
LTI Viewer
☑ Real-Time Update

Loop gain changed to 2.54e-005
Right-click on plots for more design options.

Figure 18. Final compensator design.

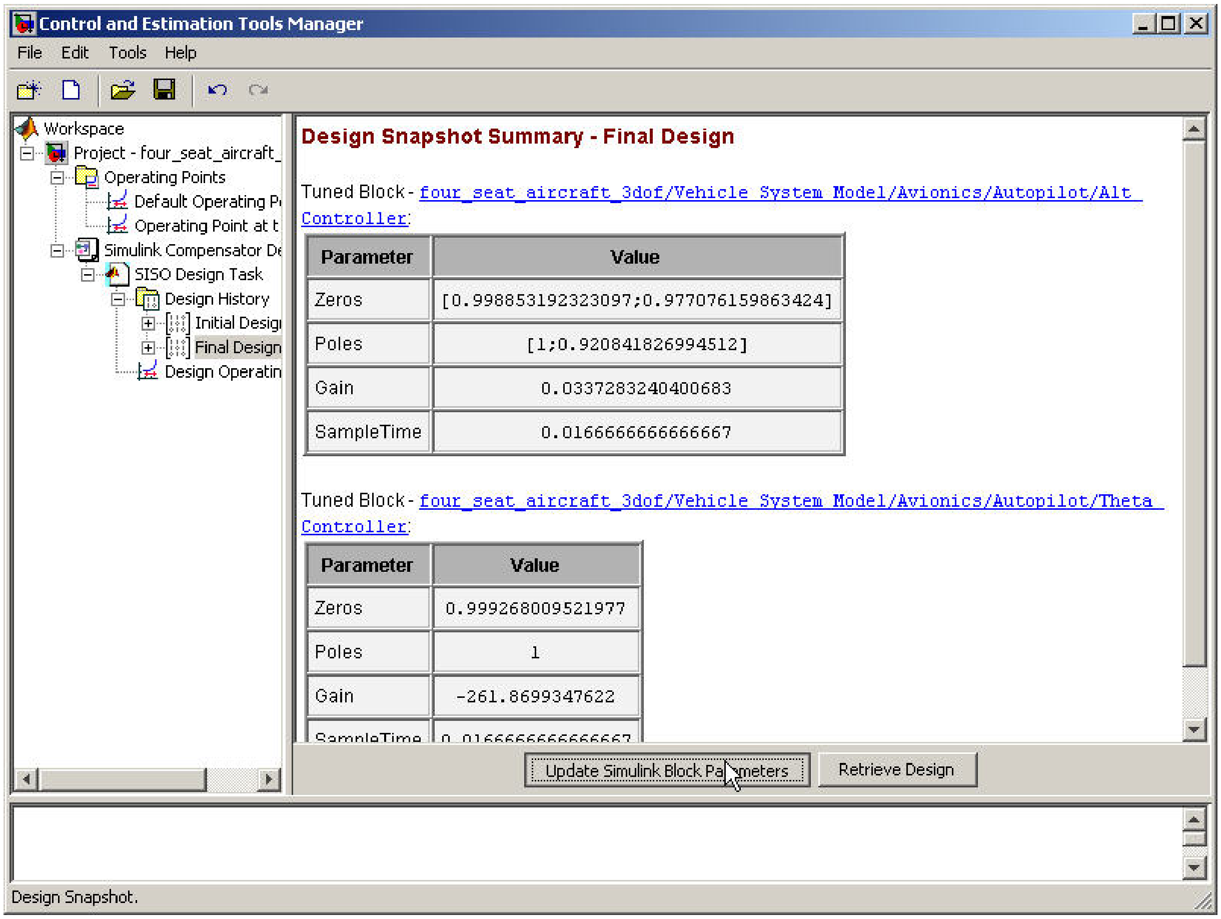
provide a satisfactory step response and to satisfy the frequency domain requirements of 9dB gain margin as well as 30 degrees phase margin for the inner loop and 65 degree phase margin for the outer loop.

As we only considered climb rate requirement at 2,000 meters for this article, the longitudinal flight controller was designed solely around the operating point corresponding to the trim condition at this altitude. To design a flight controller for the whole flight envelope, multiple operating points could be chosen corresponding to various flight conditions spanning the flight envelope, and multiple compensators could be designed, with one compensator for each operating point. Simulink Control Design supports this workflow.

A flight controller over the whole flight envelop could then be implemented by gain scheduling the designed compensators with flight conditions such as Mach number and altitude.

VI. Simulating Nonlinear Closed-Loop Dynamics

Once the flight controller has been designed, full nonlinear closed-loop simulation could be performed to verify compensator performance in a nonlinear model and to check if the aircraft design met system level requirements. Once the detailed open-loop plant model was developed, as descried in section IV, and the closed loop system with preliminary compensator design was set up, as described in section V, all that needed to be done was to update compensator coefficients in the appropriate Simulink blocks with the values from the final compensator design. Simulink Control Design enables easy updates of compensator coefficients with the **Update Simulink Blocks Parameters** button, as shown in Fig. 19.



Design Snapshot Summary - Final Design

Tuned Block - four_seat_aircraft_3dof/Vehicle System Model/Avionics/Autopilot/Alt Controller:

Parameter	Value
Zeros	[0.998853192323097;0.977076159863424]
Poles	[1;0.920841826994512]
Gain	0.0337283240400683
SampleTime	0.0166666666666667

Tuned Block - four_seat_aircraft_3dof/Vehicle System Model/Avionics/Autopilot/Theta Controller:

Parameter	Value
Zeros	0.999268009521977
Poles	1
Gain	-261.8699347622
SampleTime	0.0166666666666667

Figure 19. Simulink model was updated with compensator values designed with Simulink Control Design.

Closed-loop simulation was run by commanding a change of altitude from 2,000 meters to 2,050 meters starting at 5 seconds of simulation time. The altitude command and altitude response are shown in Fig. 20, which demonstrates that the longitudinal flight controller provides a stable response. It can also be seen that the measured altitude reaches 2,050 meters fewer than 20 seconds after the requested change in altitude. Therefore, the aircraft's

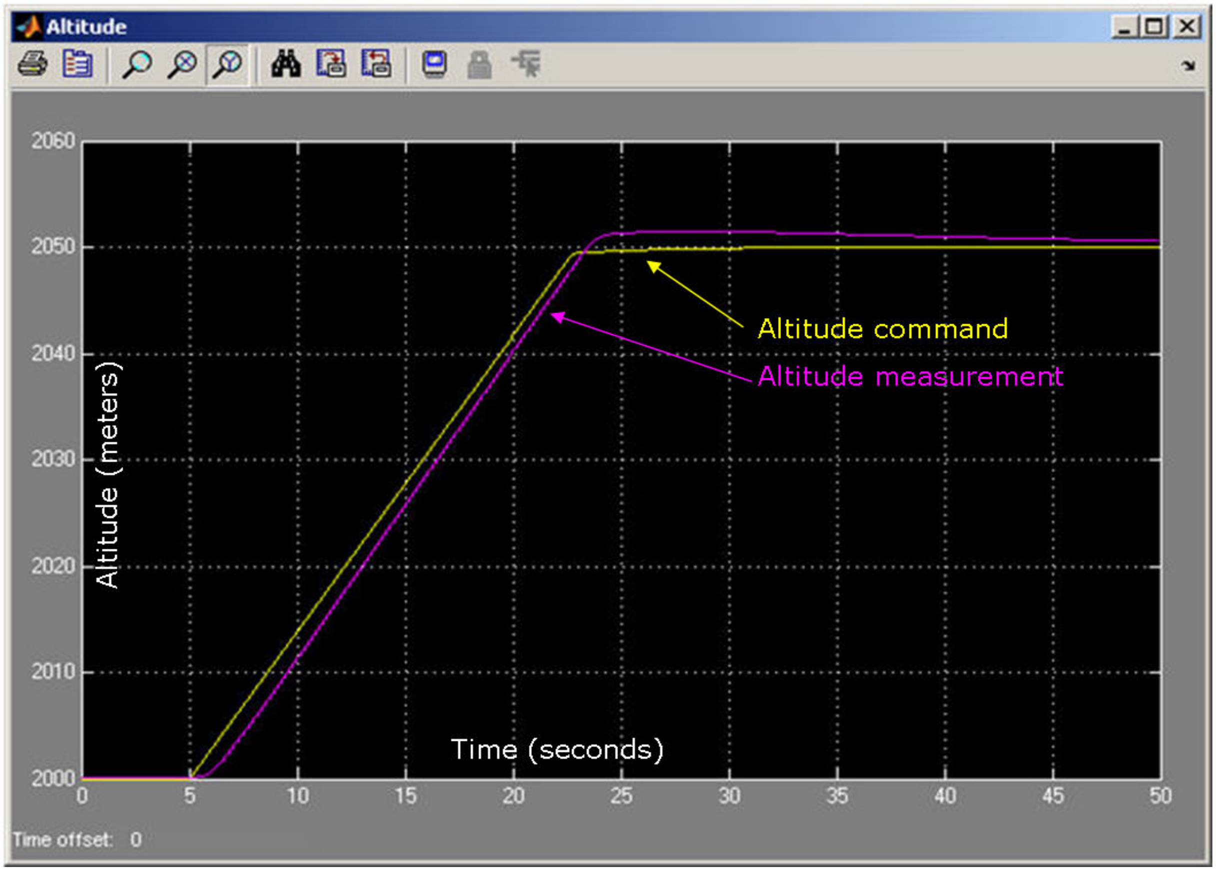
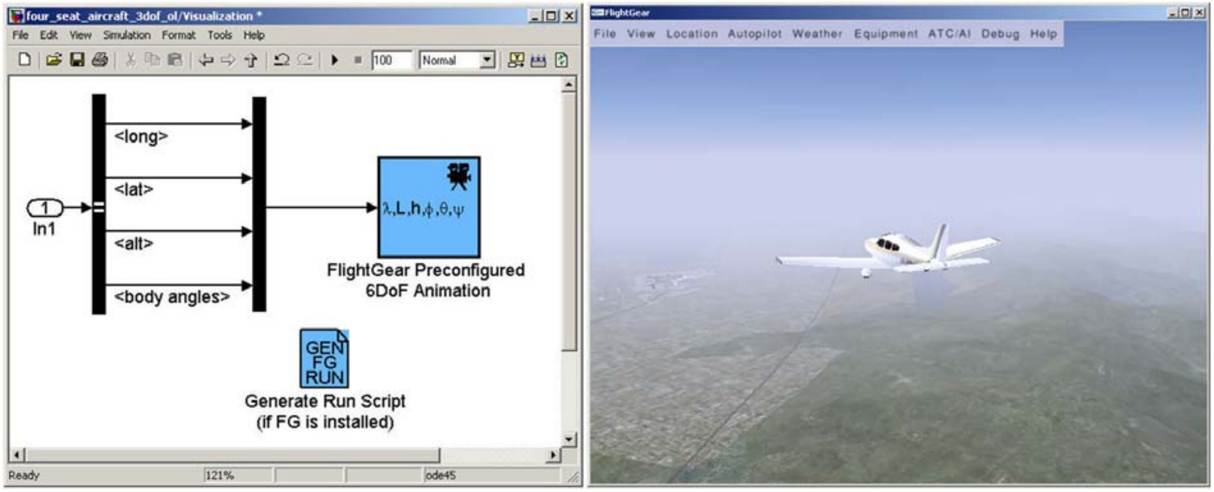


Figure 20. Altitude command and response of the final compensator design.

rate of climb at this particular flight condition is greater than 2 meters/second. This satisfies the original system level requirement for climb rate.

In addition to plots like the one shown in Fig. 20, visualization can be used to help understand aircraft performance. Aerospace Blockset contains blocks for interfacing to FlightGear flight simulator[12]. These blocks were placed into the closed-loop nonlinear model to visualize aircraft position and attitude with the corresponding values calculated by the closed-loop nonlinear model. Figure 21a shows the described blocks, and Fig. 21b shows the resulting visualization.



a) Aerospace Blockset blocks providing interface to FlightGear. **b) FlightGear visualization.**

Figure 21. Interface to FlightGear was used to visualize simulation results.

VII. Iterating over the Controller and Aircraft Design

In the somewhat simple example described in this article, the closed-loop system met system level requirements. More realistically, it can be expected that multiple design iterations will be needed. Further, different types of iterations could be needed.

The design of the controller could be iterated on. For example, if desired the climb rate was not achieved, a better control design could be tried to achieve a faster rise time. Closed-loop simulation could then be rerun to determine if the revised controller design meets system level requirements. It could, however, be determined that the best possible control design still results in a failure to meet system level requirements for a given aircraft configuration. Therefore, iteration on the aircraft's geometric configuration might be needed as well.

In the considered example, if the climb rate requirement was not met, designers could investigate a different wing shape or a larger wing area to make the aircraft climb faster. The changes in geometry would naturally affect other areas of performance for the aircraft. These changes would have to be investigated to ensure that meeting one system level requirement does not result in violating other requirements.

The described design process does not eliminate the need for multiple design iterations. It does, however, provide a way to go thorough design iterations faster and more efficiently.

VIII. Conclusions

An aircraft design process using both free and commercial off-the-shelf software products has been proposed. Using an example of a new light-weight monoplane, it was shown how aircraft aerodynamic characteristics can be quickly estimated and analyzed. It was also shown how an open-loop aircraft model can be quickly created using pre-built blocks and using control and stability coefficients and derivatives derived from the aircraft's geometric configuration. It was shown how to linearize the plant and how to design a flight control system. It was shown how the open-loop plant model can be augmented with control logic to create a closed-loop nonlinear model which can be used for both control design and validation. The process of designing a flight control system using linear control design techniques for the closed-loop model was demonstrated. It was also shown how simulations of the nonlinear model can be used for checking the controller's performance and for determining if system level requirements have been met. The proposed design process allows for quick iterations through aircraft geometric configurations and control design. With this approach designers can create aircraft geometry that will meet system level requirements by using software tools rather than by building the actual prototypes. The simulation models developed with the proposed approach can be easily elaborated and updated with experimental data from wind tunnel testing or actual flight tests.

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