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# Modeling, Simulation, and Flight Test for Automatic Flight Control of the Condor Hybrid-Electric Remote Piloted Aircraft

Christopher Giacomo

**MODELING, SIMULATION, AND FLIGHT TEST FOR AUTOMATIC FLIGHT CONTROL OF THE CONDOR HYBRID-ELECTRIC REMOTE PILTOED AIRCRAFT**

THESIS

Christopher Giacomo, Lieutenant, USAF

AFIT/GSE/ENV/12-M04

**DEPARTMENT OF THE AIR FORCE**
**AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

**Wright-Patterson Air Force Base, Ohio**

AFIT/GSE/ENV/12-M04

# MODELING, SIMULATION, AND FLIGHT TEST FOR AUTOMATIC FLIGHT CONTROL OF THE CONDOR HYBRID-ELECTRIC REMOTE PILTOED AIRCRAFT

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Christopher Giacomo, BS

Lieutenant, USAF

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Approved:

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|---|---|
| ______________________________ | ________ |
| David R. Jacques, PhD (Chairman) | Date |
| ______________________________ | ________ |
| Frederick G. Harmon, Lt Col, USAF (Member) | Date |
| ______________________________ | ________ |
| Bradley S. Liebst, PhD (Member) | Date |

AFIT/GSE/ENV/12-M04


*Abstract*

This thesis describes the modeling and verification process for the stability and control analysis of the Condor hybrid-electric Remote-Piloted Aircraft (HE-RPA). Due to the high-aspect ratio, sailplane-like geometry of the aircraft, both longitudinal and lateral/directional aerodynamic moments and effects are investigated. The aircraft is modeled using both digital DATCOM as well as the JET5 Excel-based design tool. Static model data is used to create a detailed assessment of predictive flight characteristics and PID autopilot gains that are verified with autonomous flight test. PID gain values were determined using a six degree of freedom linear simulation with the Matlab/SIMULINK software. Flight testing revealed an over-prediction of the short period poles natural frequency, and a prediction to within 0.5% error of the long-period pole frequency. Flight test results show the tuned model PID gains produced a 21.7% and 44.1% reduction in the altitude and roll angle error, respectively. This research effort was successful in providing an analytic and simulation model for the hybrid-electric RPA, supporting first-ever flight test of parallel hybrid-electric propulsion system on a small RPA.

**Acknowledgments**

I would like to express my sincere appreciation to my faculty advisor, Dr. David Jacques, for the continuous support, guidance, and patience he provided that enabled my success in this endeavor. I would like to also thank Dr. Bradley Liebst for continuously dropping everything on his plate to help troubleshoot flawed parameters and providing invaluable mentorship. The Condor project would not have been possible without the extensive work of the other team members, Captain Michael Molesworth, Captain Jacob English, and Lieutenant Joseph Ausserer. They were responsible for every aspect of acquiring, building, and enabling the flight of the aircraft. The contractors at CESI, John McNees, Don Smith, and Rick Patton, who flight readied and flew the aircraft, and will probably forget more about S-RPAs than most of us will ever learn. I must thank my AFIT student family, who provide immeasurable support in the worst and best of times. Finally, to my wife, who keeps my head up, my wings level, and always reminds me to come back down to earth.

Christopher Giacomo

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MODELING, SIMULATION, AND FLIGHT TEST FOR AUTOMATIC FLIGHT CONTROL OF THE CONDOR HYBRID-ELECTRIC REMOTE PILTOED AIRCRAFT

# 1 Introduction

The effective use of Remote Piloted Aircraft (RPAs) for reconnaissance and surveillance requires a combination of good flight performance and low-observable capabilities. Of particular interest for the low-flying RPA is the necessary compromise between these characteristics necessitated by system design with conventional propulsion systems. The purpose of the Condor RPA is to develop a hybrid-electric proof of concept that mates the range and speed capabilities of a traditional Internal Combustion Engine (ICE) with the low-acoustic capabilities of an electric motor.

The Condor program consists of two aircraft, one with a conventional ICE, and the second with the full hybrid-electric engine. Each aircraft has a 12-foot wingspan, with wingtip extensions available to increase span to 15 feet for increased loiter performance. The fuselage and empennage sections are composed of composite fiberglass, with an aluminum-reinforced polystyrene main wing. The aircraft is in a high wing, conventional tail configuration, with tricycle landing gear.

To effectively test the mission-capable potential of the CONDOR Hybrid-Electric Remote Piloted Aircraft (HE-RPA), the airframes will utilize a Procerus Technologies Kestrel™ autopilot system, enabling the aircraft to climb, cruise, and loiter without pilot interaction. For the Kestrel to effectively control the Condor aircraft, the aircraft must be effectively modeled, and proper gains input into the Kestrel autopilot system.

The execution of this thesis was performed in cooperation with Ausserer, Engligh, and Molesworth, as part of the systems engineering proof of concept for an HE-RPA system (Ausserer, 2012; English and Molesworth, 2012). The completion of flight tests of the Condor AC2 aircraft would demonstrate the first successful flight of a parallel hybrid-electric configuration RPA. The Ausserer thesis encompasses the integration of commercial-off-the-shelf (COTS) components that make up the propulsive system (Ausserer, 2012). The project management and aircraft development process was executed by English and Molesworth, and also includes the aircraft evaluation for long-loiter, quiet operations (English and Molesworth, 2012).

## 1.1 Problem Statement

This research intends to model the Six Degree of Freedom (6-DOF) aircraft Equations of Motion (EOM) for the Condor aircraft, and effectively set the Kestrel autopilot gains based on the predicted EOMs. With a successful programming of the Kestrel autopilot, the Condor aircraft should be able to climb, cruise, and loiter over a designated target without pilot interaction. The aircraft must maintain the determined altitude, as well as demonstrate Level 1 handling qualities, as determined by the MIL-STD-1797A. Successful completion of this tuning process, in conjunction with the research and development by the other Condor team members, will enable the first ever flight of a parallel HE-RPA.

## 1.2 Scope and Assumptions

Due to the high aspect ratio of the Condor aircraft, it is necessary to investigate both the longitudinal and lateral-directional stability modes of the aircraft. For this reason, computational analysis will be compared to in-flight data for modal instability. All analysis assumes a steady, level flight condition, with no changes in pitch, roll, or throttle command. The aircraft modes of primary concern are the short period, Dutch roll, and spiral modes, as these are the most likely to cause significant flight performance problems. Flight test results will be used to further refine the Kestrel autopilot gains, in order to improve the aircraft handling qualities.

## 1.3 Research Objectives

The objectives of this research are two-fold. The first objective is to develop an accurate aircraft model and simulation. This model will be used to evaluate the predicted open-loop performance of the aircraft in both the longitudinal and lateral-directional dynamics. The predicted analysis for the base aircraft drives the determination of autopilot gains for the Kestrel system. Once the primary gains have been selected, the second objective of the research is to compare the in-flight data with predicted values for further tuning. This comparison will enable the fine-tuning of the aircraft gains to better predict future models as well as improve mission command and control of the Condor aircraft.

## 1.4 Outline

This thesis consists of background information, analytical processes, analysis and flight test results, and finally conclusions and recommendations. The background information section consists of a literature review of relevant research as well as an overview of mathematical and aeronautical principles and techniques that will be utilized in the development of the autopilot gain determination. The analytical process section discusses the determination of the 6-DOF aircraft model, as well as the process of setting PID gains by consecutive loop closures. The results section lays out the findings of the iterative process of gain determination throughout the flight testing. Finally, the conclusion section will analyze the results and discuss ramifications and future recommendations for continued study.

# 2 Background

## 2.1 Chapter Overview

The military demand for Small Remote-Piloted Aircraft (S-RPA) reconnaissance platforms has created a wealth of knowledge in the fields of modeling, stability and control. This section details the most important research, methods, models, and concepts for development of the Condor model.

## 2.2 Literature Review

Of the vast expanse of current RPA research, a surprisingly small niche can be directly related to the Condor, due to its glider-like configuration and wing loading. The theses most integral to the development of the Condor model are discussed below.

### 2.2.1 Procerus Kestrel© Development

The most significant factor in modeling the Condor aircraft is the integration with the Kestrel® autopilot system. The prototype Kestrel autopilot system was developed in 2004 by Reed Christiansen at Brigham Young University (Christiansen 2004). In this model, he utilizes Proportional-Integral-Derivative (PID) gain loops for the aircraft feedback in both the longitudinal and lateral modes (Stryker 2010). These simple loops were expanded upon by the addition of feed-forward parameters and additional control logic to allow for multiple tail configurations, as well as the fine-tuning capability for a wide range of small RPAs (Christiansen 2004). The Kestrel® throttle, longitudinal and lateral control designs can be seen below in Figure 1, Figure 2 and Figure 3.

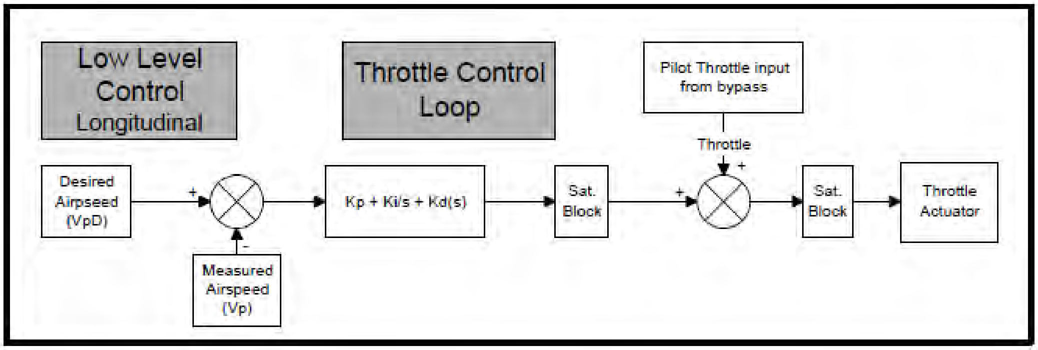



Figure 1: Kestrel Throttle Control (Christiansen, 2004)

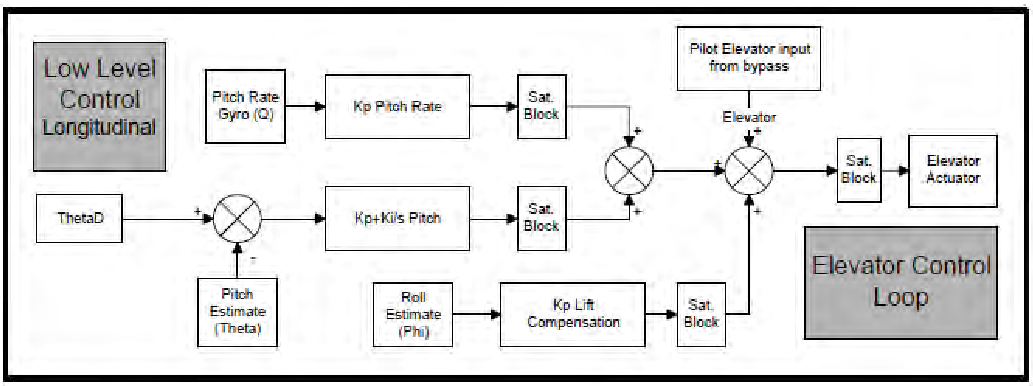



Figure 2: Kestrel Longitudinal Control (Christiansen, 2004)

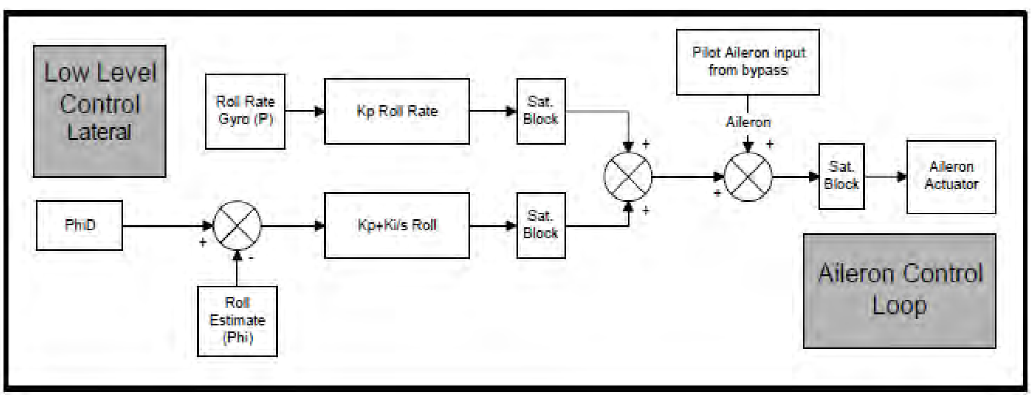



Figure 3: Kestrel Lateral Control (Christiansen, 2004)

### 2.2.2 USAFA JET5 Design Tool

The *ElectricJet Designer v5.55* aircraft design tool was created by Dr. Steven Brandt at the United States Air Force Academy, for use in prototype aircraft design (Brandt 2011). Although originally written in other programming languages, this now excel-based program is able to rapidly model and predict basic aircraft static and dynamic stability, as well as aircraft performance, drag polars, mission analysis, and weight calculations. The current iteration of the model used for this analysis has been adapted from the *Jet Designer v5*, focused on full-scale turbine-powered aircraft to predict flight characteristics for small, electric RPAs. Future references to the ElectricJet Designer will more simply refer it to Jet5. Use of the Jet5 software enables the user to input basic geometric, aerodynamic and propulsive data for an airframe, and receive back critical stability, performance, and weight calculations (Brandt, 2011). The use of Jet5 drastically reduces the time required to effectively predict the basic static and dynamic characteristics of S-RPA. The Results from the Condor Jet5 analysis proved far more accurate, and much simpler to work with than the Air Force standard program *Digital DATCOM.* The Jet5 Modeling tool references the McRuer (1973), Roskam (1979), Yechout (2003), and Brandt (2004) text as the basis for calculations.

### 2.2.3 SIG Rascal Program

The SIG Rascal was fully characterized by Captain Nidal Jodeh, USAF in his 2006 AFIT Thesis (Jodeh, 2006). The Jodeh research demonstrated effective determination of S-RPA Moment of Inertia (MOI) data by measurement of the period of oscillation when hung like a pendulum (Jodeh, 2006). The overall characterization of the

SIG platform was determined for use with the Piccolo® autopilot, but were transposed for use with the Kestrel® by S. Farrell in 2009 (Farrell 2009). The SIG Rascal is the closest comparative model available for demonstrating approximate flight characteristics of the Condor aircraft, and thus the tuned SIG gains developed by Jodeh, and Farrell, were adopted as the baseline gains for the Condor PID until the predictive gains could be proven (Farrell 2009; Jodeh, 2006).

**Figure 4: SIG Rascal 110 (Farrell, 2009)**

#### 2.2.4 AFIT OWL

Captain Andrew J Stryker, USAF, characterized the AFIT OWL MAV as part of his Master's thesis at the Air Force Institute of Technology (Stryker, 2010). Stryker's research provided a comprehensive explanation of the methods and difficulties associated with tuning the Kestrel® autopilot to a new airframe. From Stryker's recommendations, the determination was made to fully model the Condor aircraft prior to flight, rather than attempting in-flight PID tuning via the Zeigler-Nichols method (Stryker 2010). The Stryker AFIT OWL model was derived primarily from Jacques' A-4 Skyraider model, in conjunction with the McRuer and Nelson texts. (Jacques, 1995; McRuer, 1973; Nelson, 1998). The Jacques and Stryker models are both limited only to the longitudinal motion of the aircraft, due to the focus of their research being altitude-specific control (Jacques, 1995; Stryker, 2010). For this reason, the AFIT OWL model was only utilized as the basis for the longitudinal modeling and control of the Condor.

**Figure 5: AFIT OWL (Stryker, 2010)**

### 2.2.5 Naval Postgraduate School SUAS Modeling.

The 2008 Naval Postgraduate School (NPS) RPA modeling thesis by Chua Choon Seong provides a wealth of comparative data on current RPA systems. Choon Seong analyzed the SIG Rascal, Silver Fox, P10B Pioneer, Bluebird, and FROG aircraft in order to demonstrate the variance of aircraft stability parameters depending on the methods of calculation and geometric differences (Choon Seong 2008). The resulting data from his research provides arguably the most comprehensive collection of S-RPA stability parameter data available, and was absolutely vital in the evaluation and validation of the calculated values throughout the Condor modeling process.

### 2.2.6 Nelson Text

Robert C Nelson's *Flight Stability and Automatic Control* serves as a detailed yet succinct resource for calculating most basic aircraft stability parameters. Basic aircraft dynamic modes and automated control are likewise discussed, in conjunction with many "back of the envelope" methods for model verification and estimation (Nelson, 1998). The reputable traditional aircraft models discussed in Nelson's text were used to develop the Condor lateral/directional model. Aerodynamic data and the state-space model from the Navion aircraft were used extensively as a benchmark for comparative analysis and high-level verification for the initial Condor models (Nelson, 1998).

## 2.3 Aircraft Description

### 2.3.1 Missions

The primary mission of Aircraft #1 (AC1) is to demonstrate the flight characteristics of the 30 lb, 12-foot flight configuration, and to validate the numerical model for autopilot tuning. Analysis of the 15-foot wingspan is also investigated, but to a lesser extent than AC1, due to the decreased importance of flight endurance as a program objective. AC1 is then used to fine-tune the Kestrel© autopilot gains at the predicted weight. Once sufficient confidence in the aircraft stability has been achieved, AC1 will be adapted to maximize flight duration and minimize the acoustic signature.

Aircraft #2 (AC2) is the full Hybrid-Electric (HE) engine configuration. The Mission of AC2 is to analyze the potential for use of HE systems in UAV aircraft, both from mission longevity, efficiency, and acoustic standpoints. All non-propulsion variables, such as center of gravity and weight configurations for AC2 are almost identical to that of AC1, allowing a direct transfer of the mathematical model and Kestrel PID gains.

### 2.3.2 Design

The Condor aircraft was designed and constructed by CL Max Engineering, a Colorado-based UAV design firm. The aircraft is designed for a 30 lb flying weight and 12 foot wingspan, with 1.5 foot wingtip extensions available if desired. This weight and high-aspect ratio configuration was chosen for the sailplane-like characteristics of low speed, long-endurance and low acoustic flights. Both airframes are designed and weighted to the specification of the full HE engine configuration, despite Aircraft #1 being driven by a standard Internal Combustion Engine (ICE). The basic aircraft parameters are shown in Table 1, along with a view of the AC1 prototype shown in Figure 6.

**Table 1: Aircraft Configuration**

| System | Description |
|---|---|
| Engine | – 35cc Honda ICE (AC1) or 25cc Honda ICE and Electric (AC2) |
| Aircraft Weight | – 30lbs (optimal) 50lbs (maximum) |
| Wings | – 12 ft wingspan with extensions to 15ft<br>– Eppler 210 airfoil with 1 ft chord<br>– Wing Area 12ft$^2$ or 15 ft$^2$ |
| Fuselage | – Tapered 6”x4” fiberglass-covered foam layup.<br>– Length 4.83 ft (including engine) |
| Tail configuration | – Low-cruciform tail<br>– NACA 0009 airfoil with 9in chord, 25% control surface<br>– Horizontal Stabilizers 18in span<br>– Vertical Stabilizer 15in span |
| Landing Gear | – Convention configuration with optional drop-away main gear<br>– Steerable tail-wheel electronically linked to rudder control |
| Aircraft Controllers | – Futaba R6008HS and Procerus Technologies Kestrel© v2.4 |
| Ground Control Station | – Procerus Technologies Virtual Cockpit v2.0 and Futaba Controller |
| Predicted Airspeeds (at 30 lbs) | – $V_{s0}$ = 24 mph<br>– $V_{TO}$ = 20 mph<br>– $V_{NE}$ = 80 mph<br>– $V_A$ = 65 mph |

**Figure 6: Condor S-RPA in AC1 Configuration**

## 2.4 Definitions and Convention

### 2.4.1 Body Axis Convention

Because the focus of stability and control is on the aircraft reactions to external moments and forces, the relative position of the aircraft is insignificant in the analysis. For this reason, the Body-Axis reference frame is chosen for analysis. The Body-Axis reference frame is based at the Center of Gravity (cg). The coordinate system consists of orthogonal *X, Y,* and *Z* axes, where the *X* axis travels from the nose to tail of the aircraft, the *Y* axis along the span of the wings, and the *Z* axis vertically. Rotations about these axes are measured in the angles *L*(roll angle), *M* (pitch angle) and *N* (yaw angle). The corresponding velocities along these axes are *u, v,* and *w*, and the moments about the axes are *p, q,* and *r*, respectively. A depiction of the right-hand body axis coordinate frame can be seen below in Figure 7.

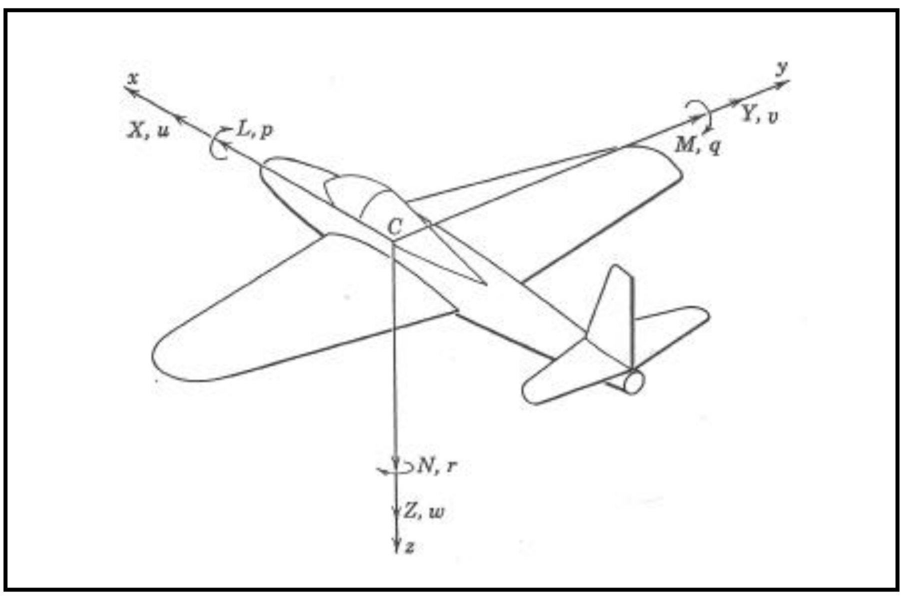



**Figure 7: Body-Fixed Reference Frame**

### 2.4.2 Wind Axes and Euler Angles

The wind axes for the aircraft are relative to the body reference frame, and consist of the angle of attack and angle of sideslip values α and β, respectively. When it is necessary to relate the body reference frame to the earth or another frame, a set of angles between the two frames are described by the *Euler Angles*. Table 2 shows the Society of Flight Test Engineers definitions for the Euler Angles.

**Table 2: Euler Angle Definitions (Gardner, 2001)**

| Angle | Description |
|---|---|
| Ψ | Yaw angle: The angle between the projection of the vehicle x axis on the horizon plane and the reference x axis. If a North-East-Down (NED) frame is used, ψ is the heading angle |
| Θ | Pitch angle: The angle in the vertical plane between the body x axis and the horizon |
| Φ | Bank angle: The angle between the body y axis and the horizontal reference plane as measured in the y –z plane. Also known as the Roll angle. |

### 2.4.3 Moments and Accelerations

Mathematical modeling of aircraft flight dynamics is made possible by the expression of the aircraft movement in terms of the linear and rotational accelerations about the 6 degrees of freedom on the body reference frame. Each of these accelerations is generally expressed as acceleration about or along an axis. Using this symbology, acceleration of the aircraft along the $x$ axis due to the change in velocity ($u$) is written as $X_u$. Table 3 below shows the 6-degree of freedom accelerations used for longitudinal stability, and Table 4 the lateral/directional accelerations for conventional aircraft. (Stryker 2010). Derivations and approximations for these variables can be found in Nelson (1998), McRuer (1973), Yechout et.al (2003), and most notably Roskam (1979).

**Table 3: Aircraft Longitudinal Definitions (Nelson, 1998 p.123)**

| Variable | Description |
|---|---|
| $X_u$ | *x* acceleration due to change in *u* |
| $X_w$ | *x* acceleration due to change in *w* |
| $Z_u$ | *z* acceleration due to change in *u* |
| $Z_w$ | *z* acceleration due to change in *w* |
| $Z_{\dot{w}}$ | *z* acceleration due to change in *w velocity* |
| $Z_{\propto}$ | *z* acceleration due to change in *α* |
| $Z_{\dot{\propto}}$ | *z* acceleration due to change in *α velocity* |
| $Z_Q$ | *z* acceleration due to change in *w velocity* |
| $Z_{\delta e}$ | *z* acceleration due to change in elevator angle |
| $M_u$ | Pitch moment due to change in *u* |
| $M_w$ | Pitch moment due to change in *w* |
| $M_{\dot{w}}$ | Pitch moment due to change in *w velocity* |
| $M_{\propto}$ | Pitch moment due to change in *α* |
| $M_{\dot{\propto}}$ | Pitch moment due to change in *α velocity* |
| $M_Q$ | Pitch moment due to change in Q |
| $M_{\delta e}$ | Pitch moment due to change in elevator angle |

**Table 4: Aircraft Lateral/Directional Derivatives**

| Variable | Description |
|---|---|
| $Y_\beta$ | Pitch acceleration due to change in *v* |
| $N_\beta$ | Pitch acceleration due to change in roll |
| $L_\beta$ | Pitch acceleration due to change in yaw |
| $Y_p$ | Roll acceleration due to change in *v* |
| $N_p$ | Roll acceleration due to change in roll |
| $L_p$ | Roll acceleration due to change in yaw |
| $Y_r$ | *z* acceleration due to change in *α* |
| $N_r$ | *z* acceleration due to change in *α velocity* |
| $L_r$ | *z* acceleration due to change in *w velocity* |
| $Y_{\delta a}$ | *z* acceleration due to change in elevator angle |
| $N_{\delta a}$ | Pitch moment due to change in *u* |
| $L_{\delta a}$ | Pitch moment due to change in *w* |
| $Y_{\delta r}$ | Pitch moment due to change in *w velocity* |
| $N_{\delta r}$ | Pitch moment due to change in *α* |
| $L_{\delta r}$ | Pitch moment due to change in *α velocity* |

## 2.5 Airframe Stability

The first major division in aircraft stability analysis is between the static and dynamic stability of the aircraft. Yechout (2003) describes static stability as the "initial tendency of an aircraft to develop aerodynamic forces or moments that are in the direction to return the aircraft to the steady state position" following a perturbation from the steady state (p.173). The important differentiation that must be made between static and dynamic stability is that static stability is only the initial and thus time-independent stability. In contrast, dynamic stability is the time response analysis of an aircraft's ability to return to the steady state. This is shown pictorially below in Figure 8.

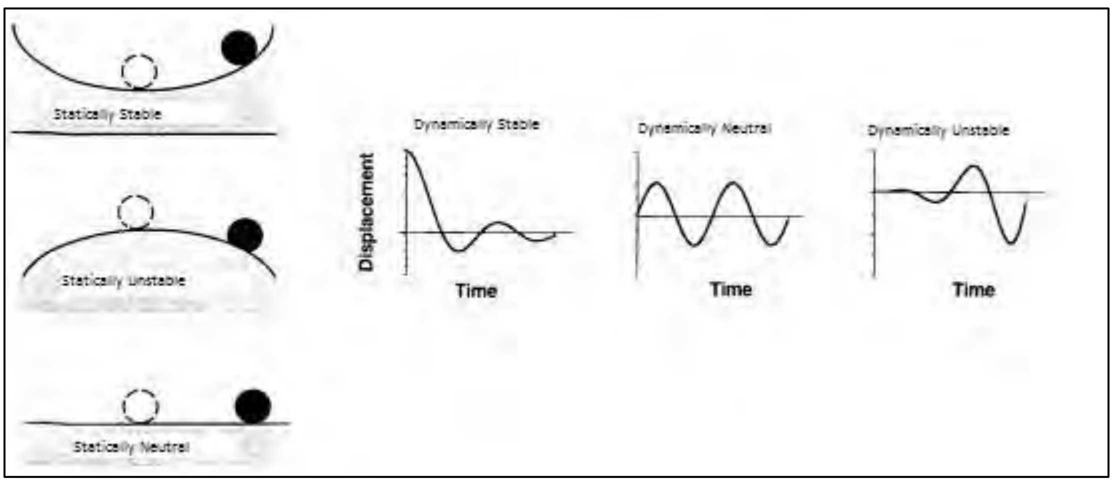



**Figure 8: Static and Dynamic Stability (Nelson, 2008 p.39)**

### 2.5.1 Static Stability Analysis

The static stability for conventional aircraft is most dependent upon the relative positions of the aircraft center of pressure and center of gravity. In order for an aircraft to be statically stable, the center of gravity must be forward of the center of pressure

(Yechout, 2003). Likewise, the aerodynamic moments caused by the control surfaces following a perturbation must generally cause a restoring moment. For this to be achieved, the stability derivatives in Table 3 and Table 4 must take the appropriate sign.

To further refine the static stability of the aircraft, a balance must be reached between each aircraft force and moment. This is achieved by utilizing the USAFA/Brandt JET5 software, capable of not only modeling the aircraft layout and weight configuration, but the balance between longitudinal and lateral/directional derivatives. A screenshot of the Condor model in Jet5 is shown in Figure 9. For specific information on static stability derivatives, Yechout Chapters 5-6 and Nelson Chapter 2 both provide comprehensive explanations (Yechout, 2003), (Nelson, 1998).

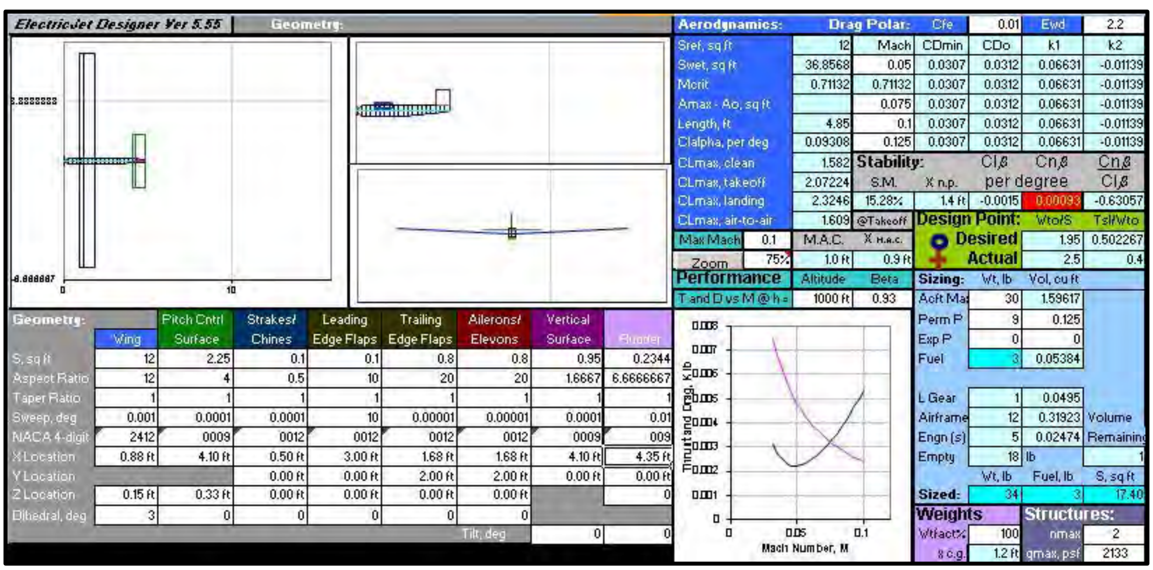


**Figure 9: USAFA/Brandt Jet5 Aircraft Modeling Program**

### 2.5.1 Dynamic Aircraft Stability Modes

Of primary concern for dynamic stability of conventional aircraft are the oscillatory longitudinal and lateral modes. For longitudinal analysis, this can be found in the short period and long period, or Phugoid modes. In lateral-directional analysis, there is usually only the Dutch roll mode, as the roll and spiral modes are generally non-oscillatory (Nelson, 1998). The critical information regarding the behavior of these modes can be deduced by focusing on the poles of the transfer function shown in Equation 2.4. When factored into this specific format, the natural frequencies of the short period ($\boldsymbol{\omega_{sp}}$) and Phugoid ($\boldsymbol{\omega_p}$), as well as the corresponding damping ratios $\boldsymbol{\zeta_{sp}}$ and $\boldsymbol{\zeta_p}$ are easily calculated. This is similarly true for the lateral-directional Dutch Roll mode. By evaluating the frequency and damping of each mode, a basic assessment of the open-loop dynamic stability can be made (Yechout 2003). Approximations for the Short Period and Phugoid natural frequencies can be found by using Equations 1 and 2 (Stryker 2010).

$$\boldsymbol{\omega_{sp} \sim \frac{u_0 S\bar{c}}{\sqrt{I_y m}}} \tag{1}$$

$$\boldsymbol{\omega_p \sim \sqrt{\frac{Z_w g}{u_0}}} \tag{2}$$

### 2.5.2 State-Space Representation

The most common method of developing and analyzing an aircraft model is by utilizing state-space representations **(**Stevens 2003). The basic aircraft linear state-space model is comprised of the plant matrix ***A*,** input matrix ***B*,** filter matrix ***C*** and disturbance matrix ***D*,** as well as the state vector ***x*,** input vector ***u*** and output vector ***y*.** For the simplified model being used in the Condor analysis, the ***D*** matrix and the associated gusts or disturbances are neglected. This ultimately simplifies the state-space representation for the input-output relationship of the Condor simulations to Equations 3 and 4. In order to express this relationship in a frequency-observable layout, Equation 5 is used to convert the state space equations into transfer function format. By then selecting a single input and output from the *u* and *y* vectors, the specific response to a particular type of input can be parsed. This input-output relationship is shown in Equation 6 and is formatted to allow easy depiction of the specific frequencies and damping factors associated with the position of the poles and zeroes corresponding to that particular relationship (Ogata, 2001).

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \tag{3}$$

$$\mathbf{y} = \mathbf{Cx} \tag{4}$$

$$\mathbf{y(s)} = \mathbf{C(sI - A)^{-1}B \cdot u(s)} \tag{5}$$

$$\frac{\mathbf{y(s)}}{\mathbf{u(s)}} = \frac{\mathbf{(s+z_1)(s+z_2)}}{\mathbf{(s^2+2\omega_{sp}\zeta_{sp}+\omega_{sp}^2)(s^2+2\omega_p\zeta_p+\omega_p^2)}} \tag{6}$$

The validated state-space models used in the Condor analysis are shown below in Equations 7 and 8. These models were created by Roskam, refined by Jacques for use with his dissertation on aircraft terrain following, and adapted to SUAS systems in Stryker's 2010 thesis on the AFIT OWL stability and Control (Roskam, 1979; Jacques, 1995; Stryker 2010). This state-space representation is able to encompass the set of five coupled equations of longitudinal motion for the aircraft. For example, the first row of

Equation 7 demonstrates that the rate of change in the forward velocity is equal to the scaled sum of the current horizontal velocity, vertical velocity, and flight path angle at that moment in time. This formatting allows for the simultaneous solving and simulation of the system of equations, as well as the ability to visually determine effects on the aircraft input-output relationship through stability parameter adjustment.

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{Q} \\ \Delta\dot{\theta} \\ \Delta\dot{h} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g & 0 \\ Z_u & Z_w & u_0 & 0 & 0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_Q + M_{\dot{w}}u_0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & u_0 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta Q \\ \Delta\theta \\ \Delta h \end{bmatrix} + \begin{bmatrix} X_{\delta e} & X_{\delta T} \\ Z_{\delta e} & Z_{\delta T} \\ M_{\delta e} + M_{\dot{w}}Z_{\delta e} & M_{\delta T} + M_{\dot{w}}Z_{\delta T} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta e \\ \delta T \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} \Delta\dot{\beta} \\ \Delta\dot{p} \\ \Delta\dot{r} \\ \Delta\dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{Y_\beta}{u_0} & \frac{Y_p}{u_0} & -(1 - \frac{Y_r}{u_0}) & \frac{g}{u_0} \\ L_\beta & L_p & L_r & 0 \\ N_\beta & N_p & N_r & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\beta \\ \Delta p \\ \Delta r \\ \Delta\varphi \end{bmatrix} + \begin{bmatrix} 0 & Y_{\delta r} \\ L_{\delta a} & L_{\delta r} \\ N_{\delta a} & N_{\delta r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta a \\ \delta r \end{bmatrix} \tag{8}$$

## 2.6 Kestrel Autopilot Tuning

In order to utilize feedback control, the Kestrel autopilot system uses three levels of controlling action. Level 1 loops control basic aircraft stabilization. They consist of the aircraft angles and rates, such as the pitching rate, yaw angles, and throttle position.

Level 2 loops allow for the autopilot to perform more advanced tasks, such as following headings and maintaining altitudes. Finally, the feed-forward parameters allow for trimming the aircraft to specific flight conditions, and smoothing out the autopilot commands by placing limitation on servo rates and positions (Stryker 2010). Furthermore, the Kestrel system is capable of flying in a "manual mode" where only level 1 1oops are enabled, allowing the pilot to fly with a stability augmentation system, while still maintaining directional control. The level 1 and level 2 control loops can be seen in Figure 10, with the level 1 loops shown as the two innermost feedback loops.

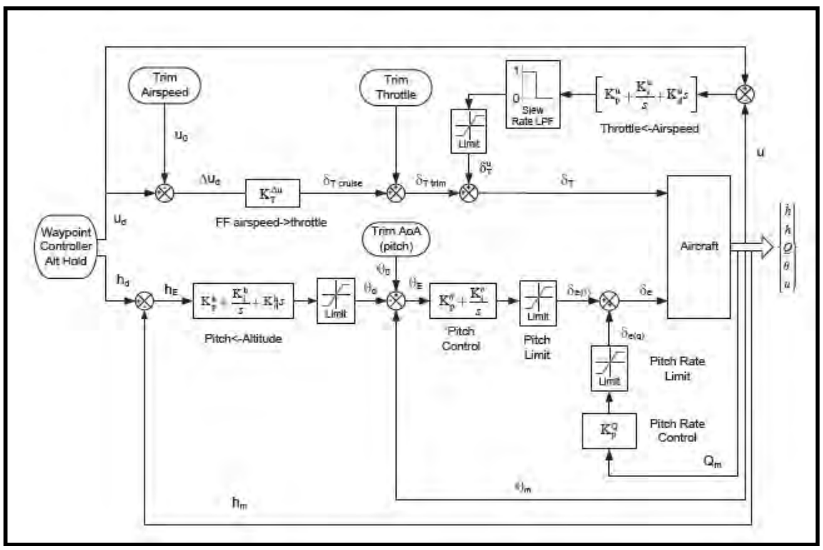



**Figure 10: Kestrel Level 1 and 2 Feedback Loops**

### 2.6.1 Longitudinal Control

Longitudinal control for the Kestrel is composed of two levels of control feedback loops that must be tuned for effective control. The pitch and pitch rate loops comprise the level 1, and the altitude and airspeed hold are the level 2 loops. Proper tuning of these loops can be accomplished using simulated or actual pitch perturbations. The difficulties with tuning the longitudinal parameters arise when shifts in the center of gravity due to cargo loading change the aircraft longitudinal moment of inertia. For this reason, weight and location limits for fuel and cargo capacity are critical for effective autonomous flight.

### 2.6.2 Lateral/Directional Control

The Kestrel lateral/directional control consists of the roll, roll rate, and yaw rate level 1 loops and the heading level 2 loop. Due to the significant aerodynamic coupling for large wingspan aircraft such as the Condor, determining efficient PID values for the lateral aircraft control is considerably more difficult than it is for the longitudinal modes. In contrast, the longitudinal stability analysis can often be completed by a test flight of the aircraft to determine effective PID values. The additional coupling of the longitudinal modes dictate that an approximation of the lateral values should be made through simulation prior to flight testing.

## 2.7 Flight Test Organization

Due to the fact that the Condor is a custom-build airframe, no prior testing for safety or performance measures have been conducted. Thus determination of its flight characteristics must follow a set of safe, pre-determined procedures. The procedures used in the analysis of the Condor flights are derived from those used by Stryker (2010), and Jodeh (2006), and utilize techniques discussed in Nelson (1998), Yechout (2003), and Roskam (1979).

### 2.7.1 Flight Test Objectives

The most critical flight test data for this project is aircraft telemetry that facilitates validation of the predictive PID values. Correct PID values enable the aircraft to fly in an efficient, stable configuration, to include autonomous flight. To accomplish this it is important to first determine the open-loop characteristics, such as pertinent airspeeds and modal characteristics. It is then possible to update the mathematical aircraft model to predict more accurate PID gains prior to the in-flight tuning process. The third level of test objective is the performance level. These objectives consist of determining the operational capabilities of the aircraft, such as loiter time, climb performance, and acoustic signature levels.

### 2.7.2 Test Range Requirements

Due to current FAA regulations, corporations and government organizations are limited to restricted airspace for testing of autonomous vehicles. For this reason, the Condor aircraft are tested at Camp Atterbury in Edinburgh, Indiana. This location allows for undisturbed flights of greater than two hours, with a mitigated risk of personal or property damage in the event of an accident. The flight test range at Camp Atterbury is shown below in Figure 11.

**Figure 11: Camp Atterbury Flight Test Range**

## 2.8 Chapter Conclusion

This brief background discussion detailed the background research, and processes necessary for effective modeling, tuning, and flight testing of the base and hybrid-electric Condor Aircraft. The utilization of the Procerus Technologies Kestrel autopilot significantly simplifies control the model and flight testing, provided that an effective mathematical model can be determined.

# 3 Methodology

## 3.1 Chapter Overview

The process for determining a suitable mathematical model for the Condor is very iterative in nature, based upon the high degree of accuracy needed for the autopilot to effectively operate. Based on the loiter mission for the Condor, a significantly greater effort was spent ensuring the longitudinal stability and ability to maintain and track altitudes. The major goals of the modeling process included the following.

- Based on geometric and historic data, determine static stability derivatives
- Develop longitudinal and lateral control loops to simulate Kestrel control
- Using successive loop closures, determine flying PID gains
- Verify flightworthiness of aircraft in both configurations
- Flight Test AC1
- Refine model to reflect flight test results
- Explain the necessary changes to the model
- Adapt model to accommodate differences in AC2

This process was made significantly more difficult due to the lack of engineering designs and aircraft data from the manufacturer. As a result, all calculations started with basic aircraft geometry and physically measured values.

## 3.2 Aircraft Static Modeling

Three different modeling software packages were used to predict the basic aircraft stability parameters. While it was not the original intent, difficulties with the initial approaches to the aircraft modeling process necessitated finding software that could effectively and expediently model the aircraft.

### 3.2.1 The CLMax Xplane Model

The first model of the Condor aircraft was developed by the manufacturer, CLMax Technologies, in accordance with the AFIT specifications. The design was driven by the parameters discussed in Harmon's work on optimization of an aircraft design for use with an HE system (Harmon et al, 2006). In order to physically model the aircraft, CLMax chose to model in CAD, and then transpose the design into the computer flight simulator Xplane®. Xplane® utilizes the blade element theory to predict actual flight characteristics. Unfortunately, any information beyond the basic geometric model, which was deemed under-detailed, was claimed as proprietary. Using the model that was provided, and converting from the left-handed coordinate system, the team was able to determine the three Moments of Inertia (MOI) calculations from the CLMax Xplane® model. These MOI values can be found in Table 6. Limitations in the software available, as well as the reliability of the model, forced the use of other models for further static and dynamic stability determination.

### 3.2.2 USAF Open Digital DATCOM

Digital DATCOM is a FORTRAN-based software package developed as a digitized version of the Air Force's DATCOM aircraft design manual. DATCOM encompasses all of the expected design parameters for a conventional aircraft, and is the primary tool utilized in the DOD for aircraft digital modeling. Unfortunately, Digital DATCOM is written in FORTRAN, an older programming language that has not been updated to a more modern code. OpenAE, an open-source variant of Digital DATCOM, utilizes a user-friendly Graphical User Interface (GUI), making the data interface much simpler. The OpenAE program is able to convert simple graphical user options and variables into the desired FORTRAN code, and then run the code as well.

Using OpenAE involves constructing the aircraft using the known geometric data, center of gravity, and any airfoil or engine information available. Figure 12 below shows a sample screen from the OpenAE GUI. The standard output file for the Digital DATCOM is a series of text files encompassing all requested stability derivatives, processes, and MOI data.

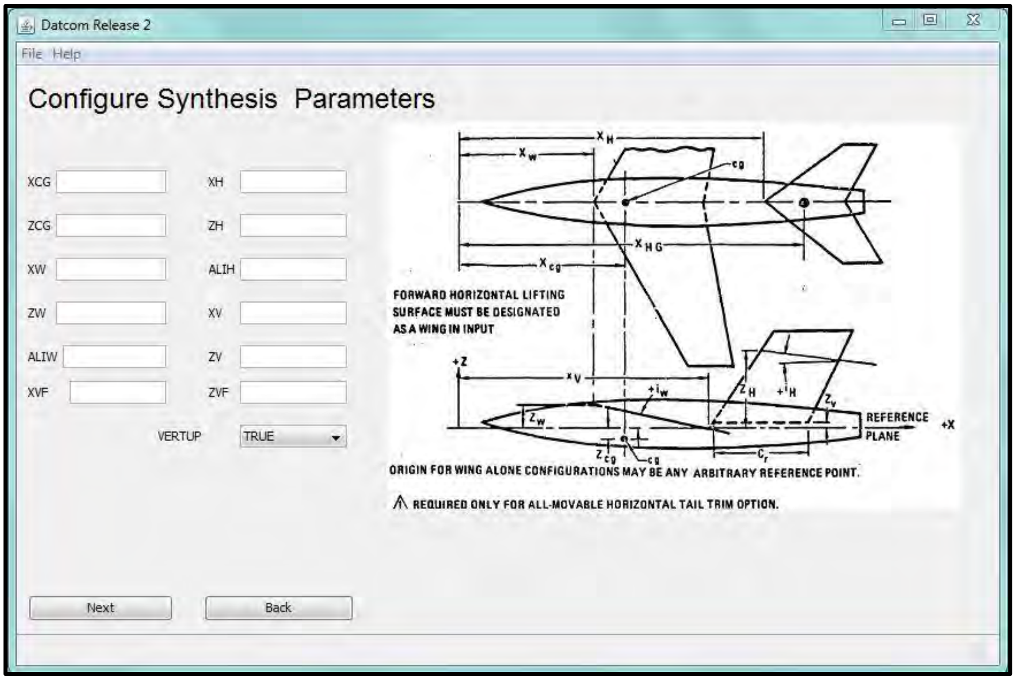



**Figure 12: OpenAE DATCOM Screenshot**

Several significant shortcomings were immediately apparent from the initial data output from the DATCOM. First is the inability of Digital DATCOM to model rectangular cross-sectional surfaces, such as fuselages and wing sections. As a result, the 12-foot configuration of AC1 was modeled using an oval fuselage cross-section, thus reducing the fuselage effect on stability and control. Secondly, and most importantly, Digital DATCOM is unable to model a closed fuselage, as well as prop effects. As a result, the output data from DATCOM, shown below in Figure 13, yields unrealistic predictions for the aircraft rolling and yawing stability derivatives ($C_{Y\beta}$, $C_{N\beta}$, and $C_{L\beta}$) , and under-predicted lift and over-predicted drag calculations ($C_L$ and $C_D$, respectively).

```
1                           AUTOMATED STABILITY AND CONTROL METHODS PER APRIL 1976 VERSION OF DATCOM
                                        CHARACTERISTICS AT ANGLE OF ATTACK AND IN SIDESLIP
                                       WING-BODY-VERTICAL TAIL-HORIZONTAL TAIL CONFIGURATION
                             PROPELLER POWER EFFECTS INCLUDED IN THE LONGITUDINAL STABILITY RESULTS
                                                            TEST

 -----------------------  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 0.050    1200.00      55.59   2.0260E+03     514.391     3.4195E+05            12.000       1.000    12.000     1.265     -0.050
0                                                               -------------------DERIVATIVE (PER DEGREE)-------------------
0 ALPHA     CD       CL       CM       CN       CA       XCP       CLA          CMA           CYB           CNB            CLB
0
    0.0    0.028    0.540    0.0306   0.540    0.028    0.057    1.232E-02          NaN   -3.939E-03   -3.270E-02    -1.741E-03
0                                     ALPHA    Q/QINF    EPSLON  D(EPSLON)/D(ALPHA)
0
                                       0.0      1.000     0.951        0.000
0*** VEHICLE WEIGHT =      30.00 LB.
0*** LEVEL FLIGHT LIFT COEFFICIENT = 0.70510
1         THE FOLLOWING IS A LIST OF ALL INPUT CARDS FOR THIS CASE.
0
1 END OF JOB.
```

**Figure 13: Digital DATCOM Stability Output**

The prop and engine modeling problem only became apparent with the use of Embry Riddle University's DATCOM 3-d Viewer, which uses the DATCOM geometric data to form a Matlab three-dimensional image of the aircraft (Greiner, 2008).The ERAU Matlab® code can be found in Appendix C. The Condor in the 12-foot AC1 configuration output file is shown in Figure 14 below. Despite repeated attempts to correct the errors in simulation, the aforementioned problems continued to cause detrimental effects on the outputs, and the use of DATCOM-based software was abandoned.

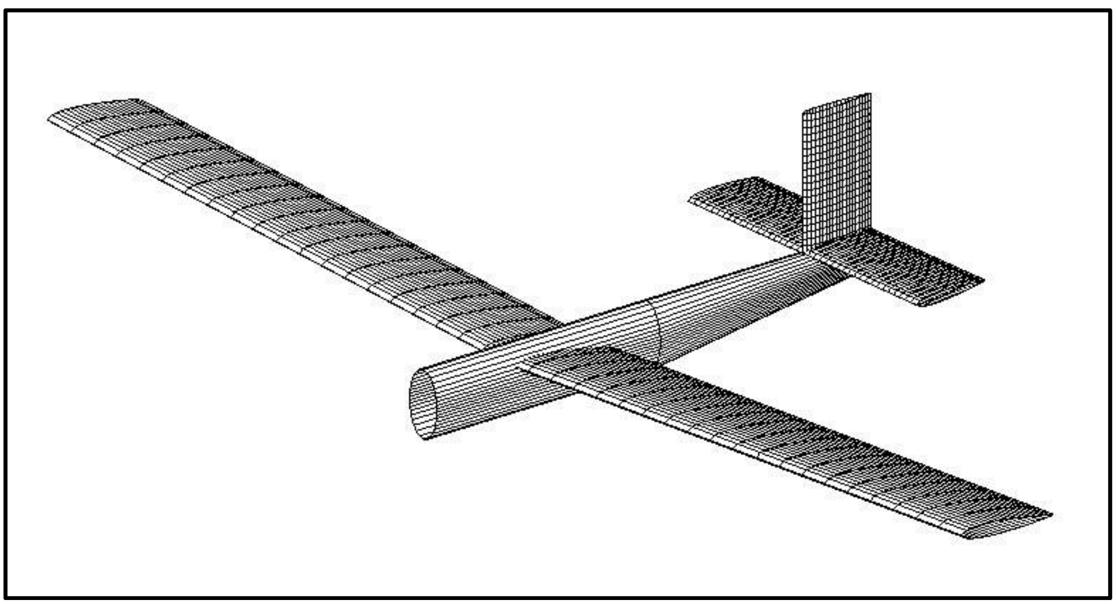


**Figure 14: Embry-Riddle 3-D View of Condor AC1 DATCOM Model**

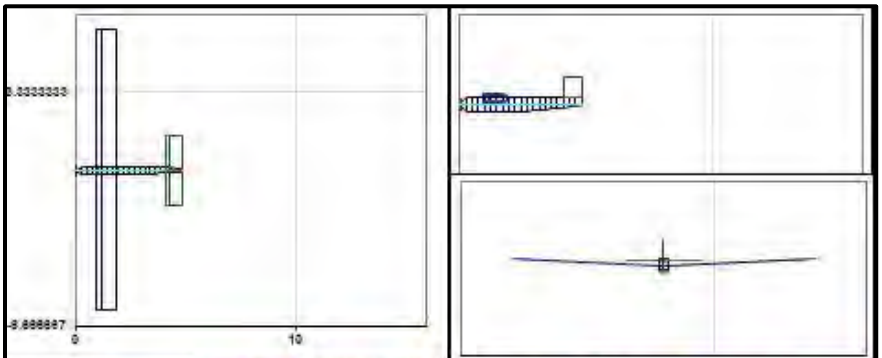
### 3.2.3 USAFA Jet5 Aircraft Design Tool

Use of the Jet5 design tool allows for the basic modeling and weight distribution needed to determine the fundamental stability derivatives. Because the Jet5 software is a composition of multiple texts in one Microsoft Excel spreadsheet, the accuracy of the results are highly dependent upon the fidelity applied to creating the model. Thus for a highly-accurate aircraft model, significant attention must be paid to ensuring the accuracy of the input parameters.

**Geometry**

In order to start on the correct scale of aircraft, Dr. Brandt of the US Air Force Academy provided the latest Electric RPA version of the Jet5 software shell. The pre-scaled nature of the software shell allowed minimal necessary change to scaling parameters such as Reynolds Number effects, which would have been required if adapting the code from the full *Jet Designer* software. The two most limiting factors in utilizing the Jet5 software were the adaptation of an ICE as the engine, and the definition of the base airfoil. Due to the modeling limitations of Jet5, the NACA 2412 airfoil was used in place of the Eppler 210. This substitution causes little change in the static or dynamic model of the aircraft, as the moments caused by the airfoil shape are negligibly different. There are slight performance differences between the two that will be discussed later.

The ability to define multiple geometric configurations allows Jet5 to more accurately depict the fuselage section, resulting in a highly accurate scale model of the physical aircraft fuselage.  Likewise, Jet5 assumes a closed surface at the engine face, thus negating the two major flaws in the Digital DATCOM tests. The geometric design page for the 12 foot ACI configuration is shown below in Figure 15. The resulting secondary geometric wing and control surface data output is shown in Figure 16.




| Geometry: | Wing | Pitch Cntrl Surface | Strakes/ Chines | Leading Edge Flaps | Trailing Edge Flaps | Ailerons/ Elevons | Vertical Surface | Rudder |
|---|---|---|---|---|---|---|---|---|
| S, sq ft | 12 | 2.25 | 0.1 | 0.1 | 0.8 | 0.8 | 0.95 | 0.2344 |
| Aspect Ratio | 12 | 4 | 0.5 | 10 | 20 | 20 | 1.6667 | 6.66667 |
| Taper Ratio | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Sweep, deg | 0.001 | 0.0001 | 0.0001 | 10 | 0.00001 | 0.00001 | 0.0001 | 0.01 |
| NACA 4-digi | 2412 | 0009 | 0012 | 0012 | 0012 | 0012 | 0009 | 009 |
| X Location | 0.88 ft | 4.10 ft | 0.50 ft | 3.00 ft | 1.68 ft | 1.68 ft | 4.10 ft | 4.35 ft |
| Y Location | | | 0.00 ft | 0.00 ft | 2.00 ft | 2.00 ft | 0.00 ft | 0.00 ft |
| Z Location | 0.15 ft | 0.33 ft | 0.00 ft | 0.00 ft | 0.00 ft | 0.00 ft | | 0 |
| Dihedral, deg | 3 | 0 | 0 | 0 | 0 | 0 | | |
| | | | | | | Tilt, deg | 0 | 0 |

**Figure 15: Jet5 Design of 12 Foot Span AC1 Configuration**

| Wing | | | Horizontal Tail | | | Vertical Tail | | |
|---|---|---|---|---|---|---|---|---|
| $b =$ | 12.000 | ft | $b_{HS} =$ | 3.000 | ft | $b_{VS} =$ | 1.258 | in |
| $c_r =$ | 1.000 | ft | $c_{rHS} =$ | 0.750 | ft | $c_{rVS} =$ | 0.755 | in |
| $c_t =$ | 1.000 | ft | $c_{tHS} =$ | 0.750 | ft | $c_{tVS} =$ | 0.755 | in |
| $x =$ | 0.880 | ft | $x_{HS} =$ | 4.100 | ft | $x_{VS} =$ | 4.100 | in |
| $z =$ | 0.150 | ft | $z_{HS} =$ | 0.333 | ft | | | |
| $\Lambda_{le} =$ | 0.001 | deg | $\Lambda_{leHS} =$ | 0.000 | deg | $\Lambda_{leVS} =$ | 30.000 | deg |
| $\Gamma =$ | 3.000 | deg | $\Gamma_{HS} =$ | 0.000 | deg | | | |
| $\lambda =$ | 1 | | $\lambda_{HS} =$ | 1 | | $\lambda_{VS} =$ | 1 | |
| $S =$ | 12.0000 | $ft^2$ | $S_{HS} =$ | 2.2500 | $ft^2$ | $S_{VS} =$ | 0.9500 | $ft^2$ |
| $AR =$ | 12.0000 | | $AR_{HS} =$ | 4.0000 | | $AR_{VS} =$ | 3.3334 | |
| $MAC =$ | 1.0000 | ft | $MAC_{HS} =$ | 0.7500 | ft | $MAC_{VS} =$ | 0.7550 | ft |
| $xbar_{acW} =$ | 1.1301 | ft | $xbar_{acHS} =$ | 4.2875 | | $xbar_{acVS} =$ | 4.6520 | |
| $x_{acW} =$ | 1.1301 | ft | $x_{acHS} =$ | 4.2875 | ft | $x_{acVS} =$ | 4.6520 | ft |
| $xbar_{cgW} =$ | 1.3801 | | $xbar_{cgHS} =$ | 4.4750 | | $xbar_{cgVS} =$ | 4.8407 | |
| $y_{acW} =$ | 3.0000 | ft | $y_{acHS} =$ | 0.7500 | ft | $y_{acVS} =$ | 0.0000 | ft |
| $z_{acW} =$ | 0.1570 | ft | $z_{acHS} =$ | 0.0000 | ft | $z_{acVS} =$ | 0.0000 | ft |
| $x_{cgW} =$ | 1.3801 | ft | $x_{cgHS} =$ | 4.4750 | ft | $x_{cgVS} =$ | 4.8407 | ft |
| $y_{cgW} =$ | 2.9959 | ft | $y_{cgHS} =$ | 0.7500 | ft | $y_{cgVS} =$ | 0.0000 | ft |
| $z_{cgW} =$ | 0.1570 | ft | $z_{cgHS} =$ | 0.0000 | ft | $z_{cgVS} =$ | 0.0000 | ft |
| $e =$ | 0.9236 | | $e =$ | 0.8090 | | $e =$ | 0.7532 | |
| $C_{L\alpha W} =$ | 5.3227 | $rad^{-1}$ | $C_{L\alpha HS} =$ | 3.8832 | $rad^{-1}$ | $C_{L\alpha VS} =$ | 3.4973 | $rad^{-1}$ |
| $e_o =$ | 0.38602491 | $e_o = 4.61(1-0.045AR^{0.68})(\cos\Lambda_{LE})^{0.15} - 3.1$ | | | | | | |
| $K_w =$ | 0.0687 | | $K_{HS} =$ | 0.0984 | | | | |

**Figure 16: Condor Geometric Data for Wings and Control Surfaces**

**Weight**

Once the basic geometry is defined, the vehicle weight distribution and center of gravity must be entered into the "Weight" tab. The critical area of interest from the Jet5 "Weight" Tab is shown below in Figure 17. The "permanent payload" referenced below is the ballasted weight in AC1, used to simulate the additional weight of electronics, motor, and additional batteries that are necessary for the Hybrid Electric System. The individual component weights can be found in Joseph Ausserer's *Integration, Testing, and Validation of a Small Hybrid-Electric Remotely Piloted Aircraft* (Ausserer, 2012). For the requirements of Jet5, the combined component packages are assumed to be one mass, with a constant center of gravity, and focused directly under the wing section, at roughly 1.5 feet from the nose of the aircraft.

| Item | Weight lb | Xcg ft | Moment ft lb | | |
|---|---|---|---|---|---|
| Wing | 10.07348 | 1.280052 | 12.89458 | | |
| Fuselage | 1.449389 | 2.416667 | 3.50269 | | |
| Pitch Cntrl | 0.5265 | 4.400001 | 2.316601 | | |
| Vert | 0.2223 | 4.401991 | 0.978563 | | |
| Nacelles | -0.04536 | -0.062 | 0.002812 | | |
| Strakes | 0.0234 | 0.517889 | 0.012119 | | |
| Engine | 4.9 | -0.327 | -1.6023 | | Weight Fraction |
| Gear | 1.1583 | 1.394748 | 1.615537 | | Model Used |
| Perm Payload | 9 | 1.5 | 13.5 | | 0.033 |
| Exp Payload1 | 0 | 0 | 0 | | |
| Exp Payload2 | 0 | 0 | 0 | | 0.1 |
| Fuel1 | 0.897331 | 1.5 | 1.345997 | | 0.1625 |
| Fuel2 | 0.897331 | 1.5 | 1.345997 | | 0.17 |
| Fuel3 | 0.897331 | 1.5 | 1.345997 | | |
| Total@Takeoff | 30 | 1.241953 | 37.25859 | 0.15279546 | |
| | | xcg takeoff | | S.M. | |
| Total for Lndg | 27.30801 | 1.216515 | 33.2206 | 0.178233454 | |
| | | xcg landing | | S.M. | |

**Figure 17: Jet5 "Weight" Tab for 12-Foot AC1 Configuration**

**Engine**

Defining the Condor power plant required hard-coding of predictive thrust values and component weights to properly model the aircraft. This is because the current release of Jet5 is tailored to an electric-only ducted-fan style RPA model. The correction to adapt the original JET5 to electric configuration mandated the scaling of the turbojet configuration to an R/C scale aircraft and replacing fuel with a constant battery weight. As a result, the electric ducted fan "turbojet" is modeled as a small square block with the dimensions of the AC1 35cc Honda ICE. Hard-coding of thrust and fuel burn values into the Jet5 program voids the accuracy of mission duration and range-type predictions, but allows a much simpler approach to calculating basic performance airspeeds and flight capabilities. Equation 9 below shows the approximation used to convert a horsepower rated engine, in this case rated at 1.3 SHP for the Honda 35cc ICE, into propeller-generated thrust (Ausserer, 2012). The low-subsonic flight regime of the Condor allows for the propeller efficiency factor, $\eta_P$, to be approximated at 0.9. The thrust-specific fuel consumption can then be calculated by referencing the engine fuel burn rate, and is shown in Equation 10. The final hardcoded inputs into the Jet5 software engine data are shown in Figure 18.

$$\boldsymbol{T_A = SHP_{SL}\frac{\rho}{\rho_{SL}}\frac{\eta_P}{V}} \qquad \textbf{(9)}$$

$$\boldsymbol{TSFC = \frac{\dot{W}_f}{T}} \qquad \textbf{(10)}$$

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Engine(s): # | 1 | Mil | Max | | mdot | | Diameter | |
| Static | Thrust ea | 12 | 12 | lb | 0.11 | lbm/s | 0.50 ft | 0.25 ft |
| Sea Level | TSFC | 0.12 | 0.12 | per hr | dX | dY | dZ | h |
| Fuselage: | Length | Max Width | Max Height | Inlet(s): | -0.13 ft | 0.00 ft | 0.00 ft | 0.25 ft |
| Regenerate | 4.83 ft | 0.35 ft | 0.63 ft | Compr Fac | -0.12 ft | 0.00 ft | 0.00 ft | 0.50 ft |

**Figure 18: Jet5 AC1 Engine Model**

### Stability and Control

The completion of the basic modeling of the Condor geometry and engine data allows for a first look at the static stability and controllability analysis. Utilizing a variety of equations found in Roskam (1979), Raymer (1999), and Brandt et al (2004), Jet5 is able to output the first detailed predictions of some vital static stability derivatives, shown in Figure 19.

| Calculations for Design Output | | | | | |
|---|---|---|---|---|---|
| Takeoff Wt = | 30.0000 | lb | | 0.0300 | lb |
| Landing Wt = | 27.3080 | lb | | 0.0273 | lb |
| $C_{L\alpha}$ = | 6.0508 | rad$^{-1}$ | | 0.10561 | per deg |
| $xbar_{np}$ = | 1.3947 | | $X_{np}$ = | 1.3947 | ft |
| $xbar_{cg\_Lndg}$ = | 1.2165 | | $X_{cg\_Lndg}$ = | 1.2165 | ft |
| $SM_{\_Lndg}$ = | 0.1782 | | | | |
| $xbar_{cgTakeoff}$ = | 1.2420 | | $X_{cgTakeoff}$ = | 1.2420 | ft |
| SM = | 0.1528 | | | | |
| $z_{cg}$ = | 0.0000 | | | | |
| $C_{N\beta VS}$ = | 0.07868 | rad$^{-1}$ | | 0.00137 | deg$^{-1}$ |
| $C_{N\beta WDihed}$ = | -0.00014 | rad$^{-1}$ | | 0.00000 | deg$^{-1}$ |
| $C_{N\beta HSDihed}$ = | 0.00000 | rad$^{-1}$ | | 0.00000 | deg$^{-1}$ |
| $C_{N\beta fus}$ = | -0.02544 | rad$^{-1}$ | | -0.00044 | deg$^{-1}$ |
| $C_{N\beta}$ = | 0.05310 | rad$^{-1}$ | | 0.00093 | deg$^{-1}$ |
| $C_{l\beta dihedral}$ = | -0.06967 | rad$^{-1}$ | | -0.00122 | deg$^{-1}$ |
| $C_{l\beta VS}$ = | -0.01452 | rad$^{-1}$ | | -0.00025 | deg$^{-1}$ |
| $C_{l\beta sweep}$ = | -0.00002 | rad$^{-1}$ | | 0.00000 | deg$^{-1}$ |
| $C_{l\beta dihedHS}$ = | 0.00000 | rad$^{-1}$ | | 0.00000 | deg$^{-1}$ |
| $C_{l\beta}$ = | -0.08421 | rad$^{-1}$ | | -0.00147 | deg$^{-1}$ |
| $C_{N\beta}/C_{l\beta}$ = | -0.6306 | | | | |
| $C_{m\alpha}$ = | -1.6219 | rad$^{-1}$ | | -0.02831 | deg$^{-1}$ |
| $C_{m\alpha}$ = | -0.9245 | rad$^{-1}$ | | -0.01614 | deg$^{-1}$ |
| $C_L$ = | 1.3099 | | | | |
| $C_{LNorm}$ = | 1.7295 | | | | |
| $L_W$ = | 26.3402 | lb | | | |
| $C_{LWing}$ = | 1.2635 | | | | |
| $C_{LWingNorm}$ = | 1.2652 | | | | |
| $L_{HS}$ = | 0.9678 | lb | | | |
| $C_{L\_HS}$ = | 35.6536 | | | | |
| $C_{L\_HSNorm}$ = | 2.4759 | | | | |
| $\alpha$ = | 0.2377 | rad | | 13.620 | deg |
| $\alpha_{0L}$ = | -0.0481 | rad | | -2.757 | deg |
| $\alpha_{HS}$ = | 0.6376 | rad | | 36.532 | deg |
| $i_H$ = | 0.3999 | rad | | 22.912 | deg |

**Figure 19: Jet Condor Stability Data**

The most critical values for continuation of the project without design changes are the static margin, $C_{N\beta}$, $C_{l\beta}$, and the ratio between them, $\frac{C_{n\beta}}{C_{l\beta}}$. The static margin alludes to the longitudinal stability, and is based upon the distance between the center of gravity and aerodynamic center. $C_{N\beta}$ is an indicator of the aircraft's natural ability to weathercock out of a sideslip, and $C_{l\beta}$ is an indicator of the aircraft's tendency and direction of roll when a sideslip occurs. The ratio $\frac{C_{n\beta}}{C_{l\beta}}$ is necessary to determine the overall aircraft response to a lateral-directional perturbation. A ratio less in magnitude than 1/3 will indicate an aircraft's tendency to "Dutch roll" or weave back and forth, much like a figure skater whereas a ratio greater in magnitude than 2/3 will indicate a tendency to enter a spiral mode (Brandt 2004). Figure 20 and Figure 21 display the Jet5 stability predictions for the aforementioned parameters for the initial 12 and 15-foot Condor Configurations.

| Stability: | | $Cl\beta$ | $Cn\beta$ | $\frac{Cn\beta}{Cl\beta}$ |
|---|---|---|---|---|
| S.M. | X n.p. | per degree | | |
| 15.31% | 1.4 ft | -0.001 | 0.00091 | -0.61974 |

**Figure 20: Jet5 Stability for 12 Foot Condor**

| Stability: | | $Cl\beta$ | $Cn\beta$ | $\frac{Cn\beta}{Cl\beta}$ |
|---|---|---|---|---|
| S.M. | X n.p. | per degree | | |
| 14.04% | 1.3 ft | -1E-03 | 0.00058 | -0.5849 |

**Figure 21: Jet5 Stability for 15 Foot Condor**

As the red highlighted areas indicate, the predicted weather-cocking stability parameter $C_{N\beta}$ values is lower than acceptable in both configurations. A $C_{N\beta}$ value of greater than 0.001 is necessary for traditional aircraft static stability in the yaw direction. The 12 foot configuration is within the probable error of the minimum value, and could be acceptable; however the 15 foot span would significantly suffer if left uncorrected. The simplest fix to this problem is to increase the size of the vertical stabilizer of the aircraft (Brandt 2004). Fortunately, the manufacturer provided interchangeable tail sections, and thus the 18 inch horizontal stabilizer from a spare aircraft can be used in place of the smaller vertical stabilizer. Figure 22 and Figure 23 show the corrected configurations for the 12 and 15 foot span. Although the 15 foot span configuration is still not within desired limits, the additional tail volume has brought it within an acceptable range of the target value. The Condor team determined that flight of the 15-foot configuration was a secondary objective of the project, and thus further design and fabrication of a larger tail for this configuration was unnecessary.

| Stability: | | $Cl\beta$ | $Cn\beta$ | $\frac{Cn\beta}{Cl\beta}$ |
|---|---|---|---|---|
| S.M. | X n.p. | per degree | | |
| 14.86% | 1.4 ft | -0.002 | 0.0012 | -0.77472 |

**Figure 22: Jet5 Corrected Stability for 12 Foot Condor**

| Stability: | | $Cl\beta$ | $Cn\beta$ | $\frac{Cn\beta}{Cl\beta}$ |
|---|---|---|---|---|
| S.M. | X n.p. | per degree | | |
| 13.65% | 1.3 ft | -0.001 | 0.00088 | -0.8093 |

**Figure 23: Jet5 Corrected Stability for 15 Foot Condor**

**Performance.**

The last major predictive contribution made by Jet5 was the output of numerous performance data points, necessary in determining critical aircraft airspeeds and performance expectations. Figure 24 below shows the Condor 12 foot configuration expected drag polar at 1000 feet Mean Sea Level (MSL). The airspeeds in Table 5 are determined using techniques found in *Introduction to Aeronautics: A Design Perspective* by Brant et al (2003). The lower airspeed values can be expected to decrease slightly in flight test, due to the differences in trailing edge surfaces between the Eppler 210 and NACA 2412 airfoils. Likewise, the maximum airspeed will most likely fluctuate from the predicted, due to differences between the Ausserer test results and the published Honda data on the 35cc ICE (Ausserer, 2012).

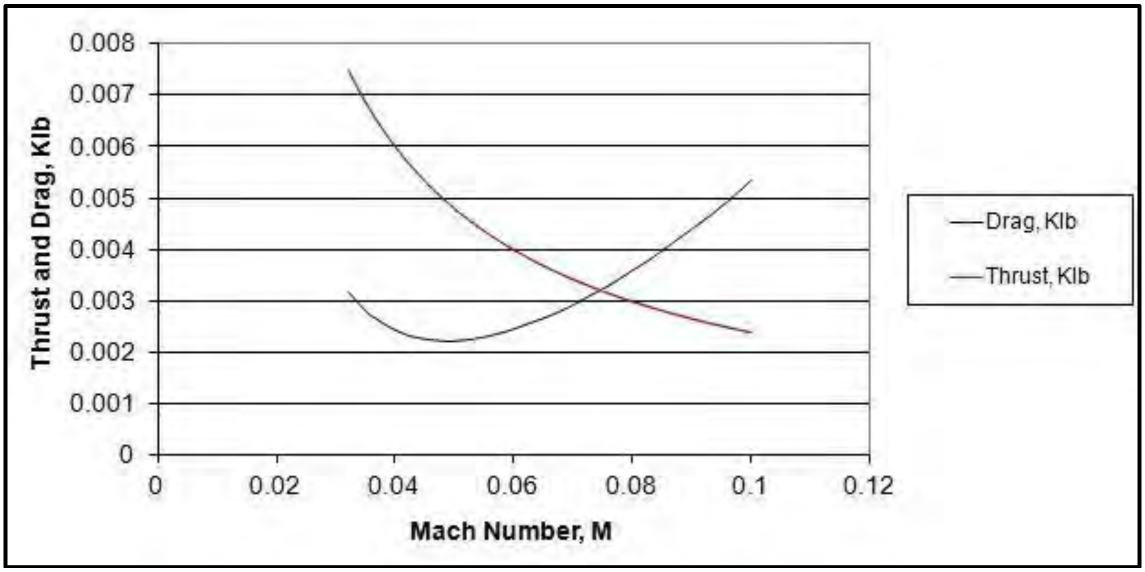



**Figure 24: Condor 12 Foot Wingspan Drag Polar**

**Table 5: Condor Predicted Airspeeds**

| Description | Airspeed |
|---|---|
| Stall Airspeed | 24.3 Mph (35.7 ft/s) |
| Takeoff Airspeed | 27.3 Mph (40.1 ft/s) |
| Max Endurance | 34.6 Mph (50.8 ft/s) |
| Max Range | 47.7 Mph (69.9 ft/s) |
| Max Level Speed | 63.0 Mph (92.3 ft/s) |

### 3.3 Moment of Inertia Analysis

The dynamic stability and tuning of the aircraft autopilot is highly dependent upon the accuracy of the Moment of Inertia calculations. In order to verify realistic values, two methods of calculation were used: The CL Max Xplane analysis and the Space Electronics MOI analysis, to be discussed subsequently. The results of these testes were then compared to similar scale aircraft from data found in Choon Seong's NPS research (Choon Seong, 2008).

### 3.3.1 CLMax Xplane Analysis.

The manufacturer of the Condor aircraft was able to provide an Xplane© model of the Condor that was accompanied by a set of MOI data. Because the aircraft was designed using a left-handed coordinate system, a re-labeling of axes was required to match the convention shown in Figure 7. Simply re-labeling the axes is mathematically acceptable, provided the restriction that only the moments, and not products of inertia are transformed to the right-handed reference frame. Additional data regarding the detail of calculation and modeling incorporated into the Xplane© model was considered proprietary, requiring additional MOI testing for verification of the provided results.

### 3.3.2 Space Electronics MOI Calculation.

Utilizing a *Space Electronics*$^{LLC}$ XR250 MOI device provided a much more precise measurement of AC1 MOIs. The XR250 is able to calculate object moments of inertia to an accuracy of ±0.002 lb-in$^2$. This accuracy, however was degraded by the setup required to handle the expansive size of the fully assembled AC1. The test stand shown in Figure 25 was created to effectively mount the Condor aircraft and allow it to rotate about the three primary flight axes for the XR250 calculation.


**Figure 25: MOI Device Aircraft Mount**

In order to determine the aircraft pitching MOI, the wings had to be removed, as the wingspan exceeded the height of the measuring device. This measure undoubtedly affected the calculation of the AC1 pitch MOI, but was necessary for achieving any potential reading. The associated error can be rationalized by the assumption that the majority of aircraft mass is not in the wing section, and is rotating at a minimal distance from the center of gravity, thus creating a minimal moment that has a nominal effect on the entire aircraft pitch MOI.

The rolling moment calculation was somewhat compromised by the aerodynamic dampening of the large wings arresting the oscillations prior to the completion of the XR250 calculation. Re-accomplishing the test failed to produce useable MOI data, but the period of oscillation for both wingspan configurations was recorded and calculated using the yawing moment for comparative analysis. Figure 26 illustrates the testing process for the AC1 yaw and roll MOI calculations.

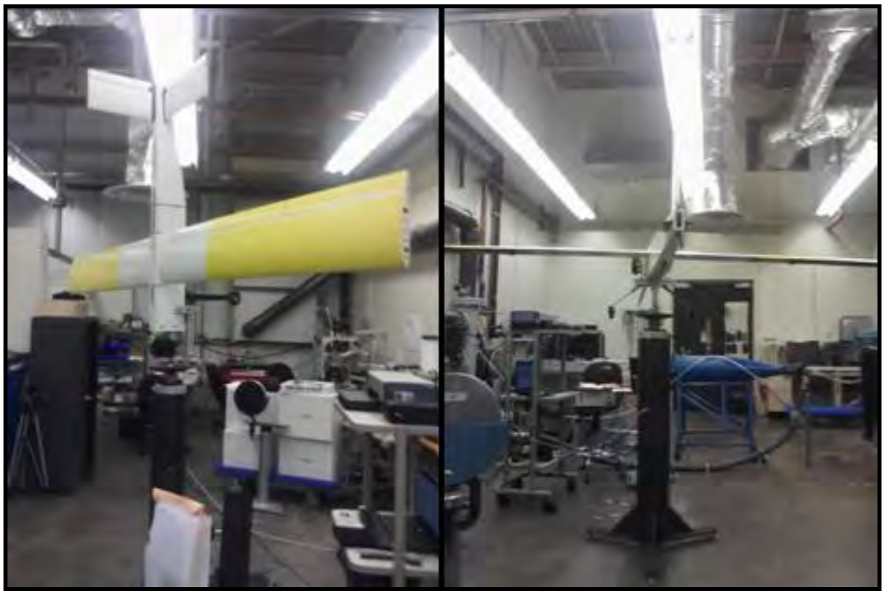


**Figure 26 Condor AC1 MOI Calculations**

### 3.3.3 Comparative Analysis

Utilizing data from Choon Seong and Jodeh's small RPA modeling research, a comparative table of MOI data for similar scaled aircraft is shown below in Table 6 (Choon Seong, 2008; Jodeh, 2006). The three NPS aircraft are all geometrically very different from the Condor, but serve as valuable datas point for the expected ratio of MOI data between different axes. Among the comparative aircraft, the AFIT SIG Rascal 110 is the closest aircraft geometrically. The results in Table 6 validate the accuracy in using the wingless configuration for the pitching moment calculations, as the 12-foot calculated Iyy MOI are very close to both the CLMax predictions as well as the SIG MOI values provided by Jodeh (2006).

**Table 6: Collective Small RPA MOI Data**

| Aircraft | Roll - Ixx (slug*ft$^2$) | Pitch - Iyy (slug*ft$^2$) | Yaw -Izz (slug*ft$^2$) |
|---|---|---|---|
| CLMax 12 foot Condor | 8.0778 | 1.124 | 9.091 |
| 12 foot Condor | 3.884 | 1.572 | 4.569 |
| 15 Foot Condor | 6.322 | 1.572 | 7.329 |
| NPS Frog | 12.538 | 8.408 | 18.585 |
| NPS Bluebird | 12.6113 | 13.201 | 19.986 |
| NPS PB10B | 33.1878 | 19.175 | 44.988 |
| AFIT SIG Rascal 110 | 1.9 | 1.55 | 1.7 |

## 3.4 Aircraft Model Development and Simulation

Dynamic modal analysis of the Condor aircraft requires the development of a base aircraft model, of the format shown in Equations 5 and 6. Because of the separable nature of lateral-directional and longitudinal control of the aircraft, it is both logical and preferable to individualize the control schemes. The longitudinal stability control consists of the elevator and throttle control, and the lateral-directional control consists of control over the rudder and aileron inputs.

### 3.4.1 Longitudinal Model.

The vast majority of modeling effort was focused on tuning the longitudinal model and control scheme to allow for adequate climb, cruise, and loiter capabilities. This modeling effort was composed of the model development, the Simulink® model, and the PID gain tuning.

**Model Development.**

Incorporating the basic model shown in Equation 5, with the adaptation of an altitude tracking state from the altitude deviation state used by Jacques, yields a full longitudinal control model of the Condor aircraft, shown below in Equation 11 and with the predictive values in Equation 12 (Jacques, 1995). The ***A*** and ***B*** matrices are populated with the calculated stability derivative values shown in Table 7, with further derivation and descriptions available in chapter 3 of the Nelson text (Nelson 2003).

$$\begin{bmatrix} \Delta\dot{w} \\ \Delta\dot{h} \\ \Delta\dot{Q} \\ \Delta\dot{\theta} \\ \Delta\dot{u} \end{bmatrix} = \begin{bmatrix} Z_w & 0 & u_0 & 0 & Z_u \\ -1 & 0 & 0 & u_0 & 0 \\ M_w + M_{\dot{w}} Z_w & 0 & M_Q + M_{\dot{w}} u_0 & 0 & M_u + M_{\dot{w}} Z_u \\ 0 & 0 & 1 & 0 & 0 \\ X_w & 0 & 0 & -g & X_u \end{bmatrix} \begin{bmatrix} \Delta w \\ \Delta h \\ \Delta Q \\ \Delta\theta \\ \Delta u \end{bmatrix} + \begin{bmatrix} \mathrm{Z}_{\mathrm{e}} & \mathrm{Z}_{\mathrm{T}} \\ 0 & 0 \\ \mathrm{M}_{\mathrm{e}} + \mathrm{M}_{\dot{w}} \mathrm{Z}_{\mathrm{e}} & \mathrm{M}_{\mathrm{T}} + \mathrm{M}_{\dot{w}} \mathrm{Z}_{\mathrm{T}} \\ 0 & 0 \\ 0 & 0 \\ \mathrm{X}_{\mathrm{e}} & \mathrm{X}_{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \delta e \\ \delta T \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} \Delta\dot{w} \\ \Delta\dot{h} \\ \Delta\dot{Q} \\ \Delta\dot{\theta} \\ \Delta\dot{u} \end{bmatrix} = \begin{bmatrix} -4.592 & 0 & 50.8 & 0 & -.374 \\ -1 & 0 & 0 & 50.8 & 0 \\ -.7248 & 0 & -2.627 & 0 & .0015 \\ 0 & 0 & 1 & 0 & 0 \\ -.039 & 0 & 0 & -32.2 & -.047 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta Q \\ \Delta\theta \\ \Delta h \end{bmatrix} + \begin{bmatrix} -35.661 & 0 \\ 0 & 0 \\ -66.11 & 0 \\ 0 & 0 \\ 0 & 0.15 \end{bmatrix} \begin{bmatrix} \delta e \\ \delta T \end{bmatrix} \tag{12}$$

**Table 7: Longitudinal Stability Derivatives**

| Parameter | Value | Unit |
|---|---|---|
| $CL_{\alpha}$ | 6.051 | per radian |
| $Cd_o$ | 0.0312 | |
| Q | 2.9775 | $lb/ft^2$ |
| $U_o$ | 50.8 | ft/sec |
| P | 0.002308 | $slug/ ft^3$ |
| S | 12 | $Ft^2$ |
| M | 0.931677 | Slugs |
| $Cl_u$ | 0.055862 | |
| $Cl_o$ | 0.22 | |
| $Cm_{\alpha}$ | -1.62 | per radian |
| $\bar{c}$ | 1 | Ft |
| $Cm_q$ | -11.7426 | |
| $Cm_u$ | 0 | |
| $Cd_{\alpha}$ | 0.271383 | Per Radian |
| $Cd_u$ | 0 | |
| $Z_u$ | -1.26772 | |
| $Z_w$ | -4.56891 | |
| $Cz_{\delta e}$ | -0.92989 | Per Degree |
| $Cm_{\delta e}$ | -2.93565 | Per Degree |
| $Cm_{\dot{\alpha}}$ | -3.91416 | Per Radian |
| $M\dot{w}$ | -0.01724 | |
| $X_{\delta T}$ | 0.25 | |

Open-loop analysis of this first model revealed that the aircraft exhibited unstable short period poles, and would thus be inherently unstable. This was caused by an error in the adaptation of Stryker's 2010 AFIT OWL model, where the value of the aircraft pitching moment due to an increase in airspeed, $M_u + M_{\dot{w}}Z_u$, was initially set to 0.15. Design differences between the AFIT OWL and the Condor, such as the pushing prop elevated above the center of gravity on the OWL, dictate that the pitching response of the OWL to an increase in airspeed will be significantly greater than that of the Condor.

For this reason, the value was decreased to a more reasonable 0.0015, yielding the open-loop pitch root locus found below in Figure 27. Of future interest from the open loop results are the nearly unstable Phugoid poles, located close to the imaginary axis. Although unstable Phugoid modes are not desirable, they are nearly always benign, and can be easily compensated for by pilots or feedback control systems (Stevens 2003).

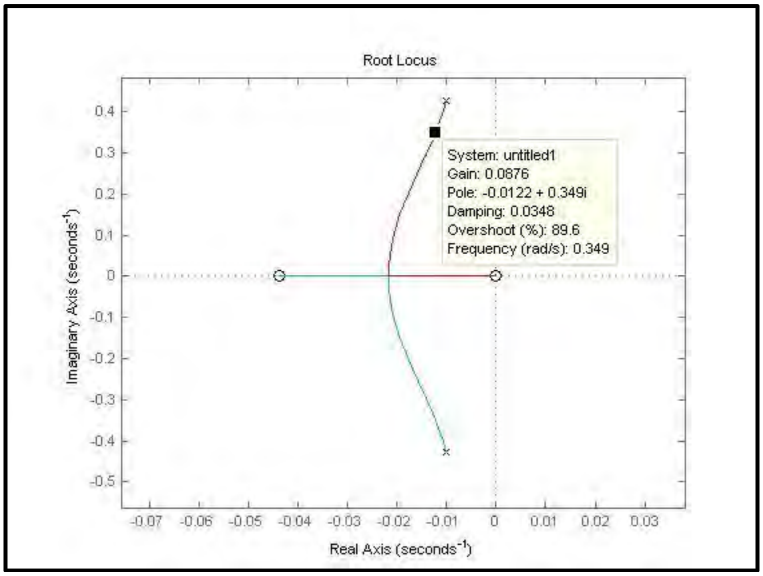



**Figure 27: Condor Open Loop Longitudinal Root Locus**

### Simulink Analysis.

Due to the proprietary nature of many of the control loops within the Kestrel® autopilot, an independent Simulink® model of the autopilot had to be constructed in order to effectively model the aircraft with specified gains. The Christiansen 2004 Brigham Young University Master's thesis "Design of an Autopilot for Small Unmanned Aerial Vehicles" serves as the foundation upon which the Kestrel® autopilot was built, and thus serves as a useable approximation of the current kestrel code (Christiansen, 2004). Christiansen utilized a longitudinal control flow block diagram shown in Figure 28.

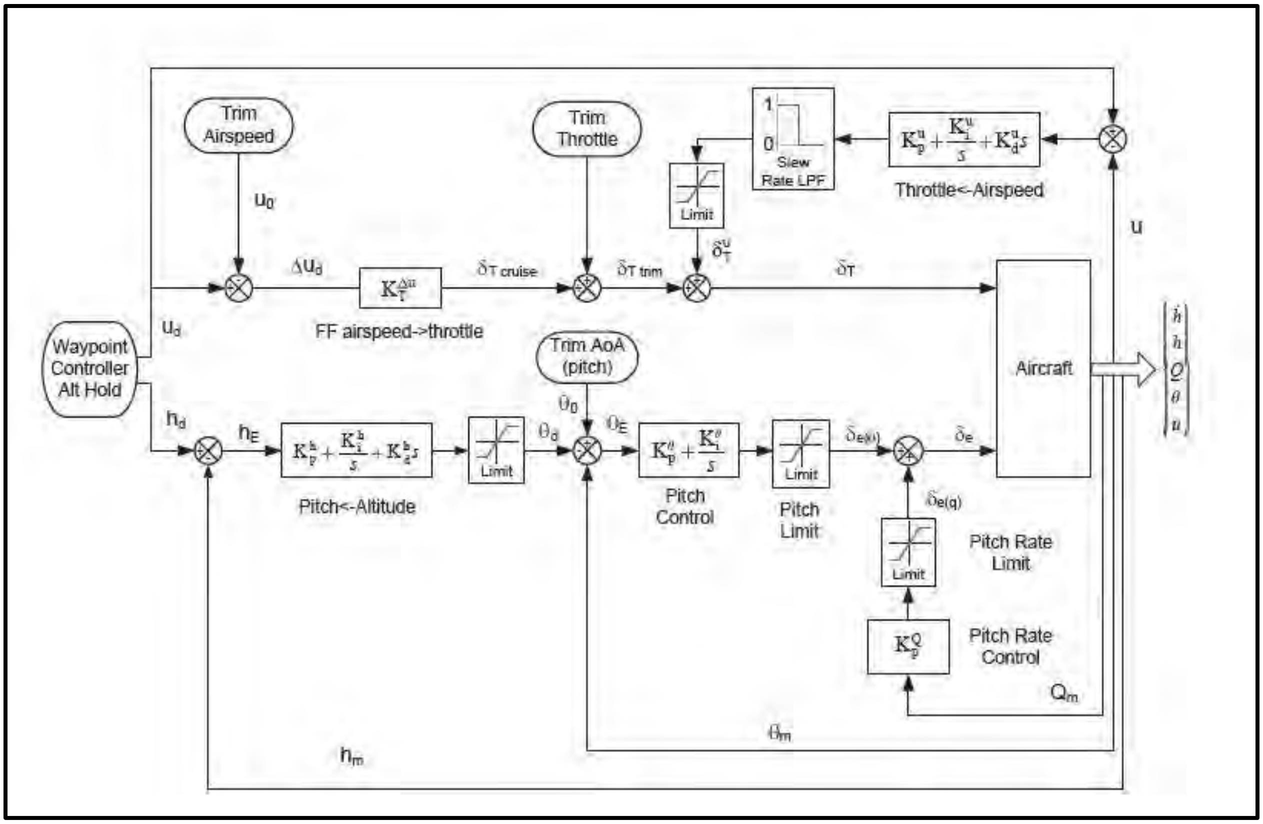



**Figure 28 Kestrel Longitudinal Control**

This model can be adapted easily utilizing the Matlab Simulink® toolbox. Because the focus of the modal analysis is the dynamic responses, utilizing the perturbation theory allows the elimination of many of the feed-forward values that Procerus Technologies has deemed proprietary and un-releasable in the Kestrel® code. Furthermore the addition of actuators and engine response models to the control model further increases its ability to accurately depict and predict aircraft controllability. By designing the actuators as inner feedback loops with independent rate and position saturations, the integrated error associated with the actuator is decreased, allowing for a more realistic actuator saturation. A fundamental aspect of the model that was initially overlooked during development was the perturbation-based nature of the linear model. This limitation was discovered as a result of the group's repeated inability to stabilize the aircraft model when the throttle loops were engaged. Because the model is only able to determine the next iteration of the aircraft flight path and dynamics, a designed throttle limit of 0 only allows the aircraft to maintain the current throttle setting, rather than decrease from its current state. The simple solution to this issue is to change the throttle setting limits from -25% to 75% throttle, allowing a full range of throttle control, yet adapting the model to overcome the software limitation. The resulting Simulink® longitudinal control model is shown in Figure 29.

Tuning the Proportional-Integral-Derivative (PID) control system in the model utilized a consecutive loop closure technique. The consecutive loop closure technique involves stabilizing the innermost loop to an impulse or step input, while leaving the remainder of the system open-loop. In order to quickly accomplish this, the manual switches shown in Figure 29 were used to open and close the loops as necessary. Upon determining a gain that will stabilize this first loop, in the longitudinal case the pitch rate, the next innermost loop is then closed and tuned, until all control gains have been tuned. With the inclusion of an integral gain on the middle loop, the expectation is that the aircraft will be able to track a specific pitch angle, and with the outermost loop, that it can track to a specific altitude. Due to the reliance of the outermost loops upon the inner loops, the consecutive loop closures technique is a very iterative process. Thus to accomplish the tuning with minimal iterations, a combination of root locus analysis and the Simulink® PID gain tuning analysis tool was used.

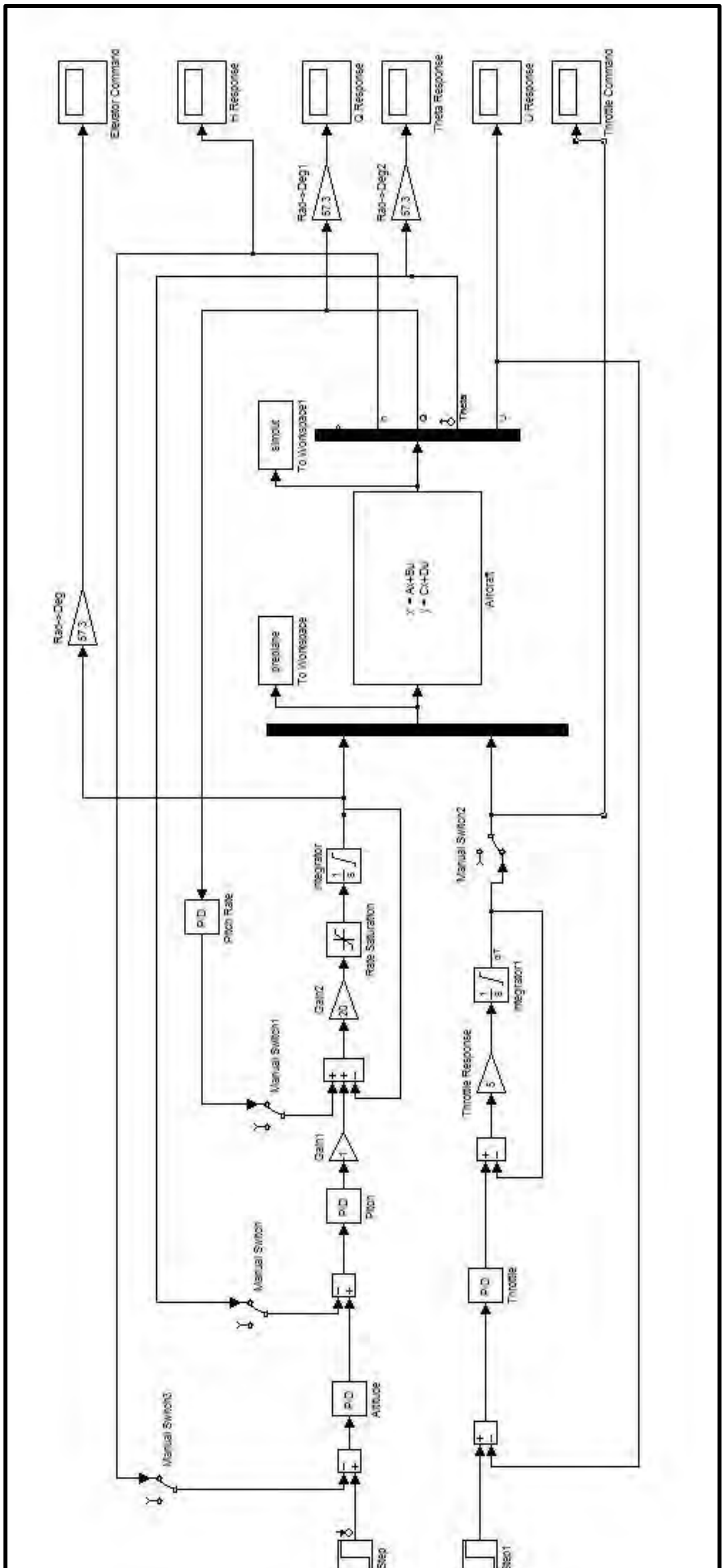



**Figure 29: Condor Longitudinal Simulink® Model**

Tuning of the innermost pitch rate loop resulted in the root locus shown in Figure 30. The proportional gain setting chosen allows for the short period poles to be ideally damped at roughly 0.707, with a predicted natural frequency of 8.21 radians/second (1.31 hz). The Phugoid poles can also be seen close to the origin in Figure 30, but at a much lower frequency and with far less damping than the short period poles.

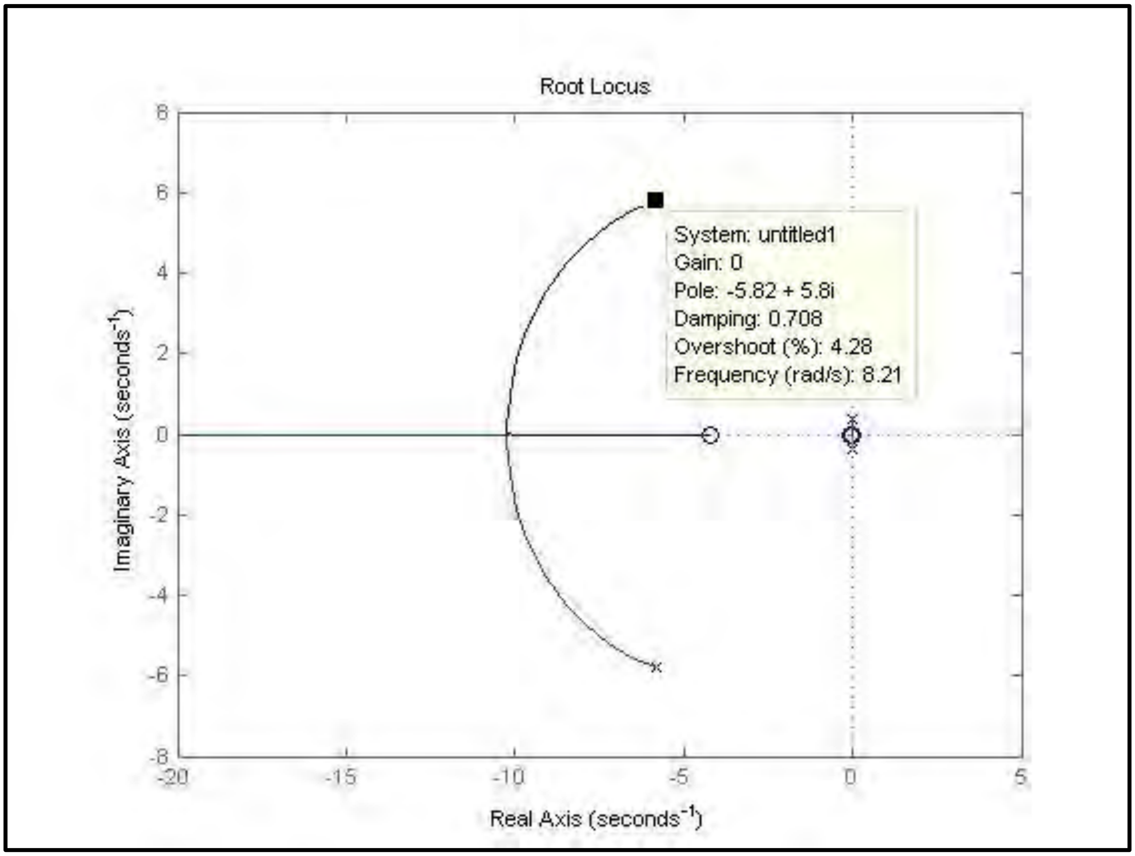



**Figure 30: Pitch Rate Closed Loop Root Locus**

The effects of the emphasis on the short period dampening and response can be seen clearly in the pitch rate step response plot of Figure 31. Although initial reactions to the step plot infer that the poles are clearly under-damped, the period of oscillations in the step response shows that the oscillatory behavior is being caused by the nearly unstable

Phugoid, or long-period oscillations, which are easily controlled with the outermost longitudinal control loops.

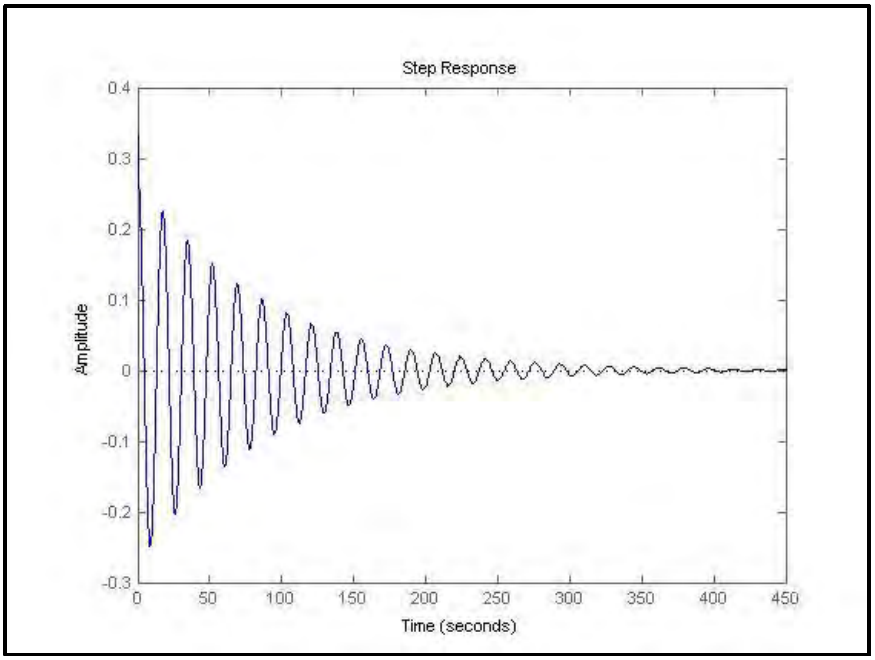



**Figure 31: Pitch Rate Response to Elevator Step Input**

Figure 32 shows the same step response plot in the first five seconds of response, where the short period response is shown to quickly respond and effectively dampen, while the Phugoid continues on in an under-damped harmonic motion. This response of the short period poles allows for sufficient confidence in the pitch-rate control to close the loop and move on to the pitch angle and altitude hold control loops.

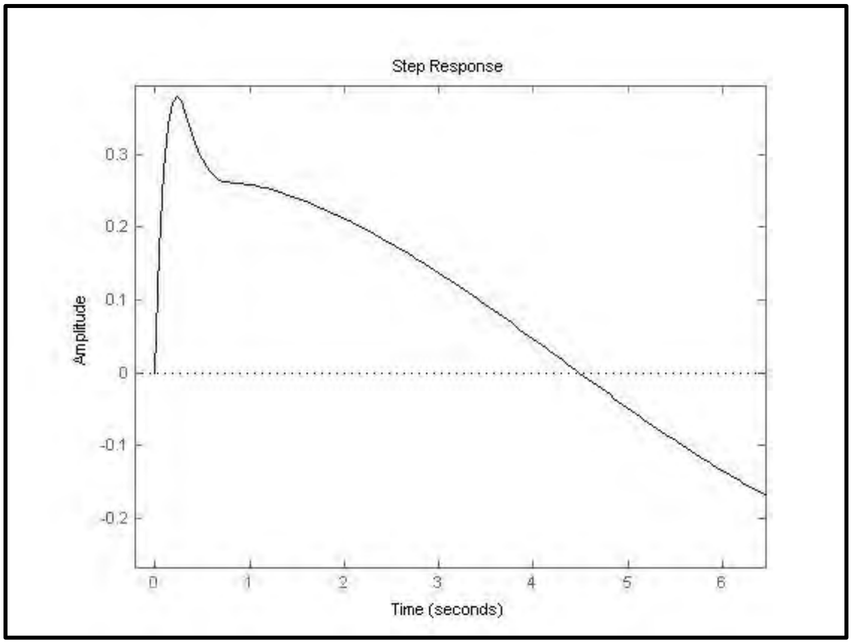



**Figure 32: Short Period Pitch Rate Response to Elevator Step Input**

Utilizing the Simulink® Control and Estimation Compensator Editor tool, the process of closing the two outer loops is significantly simplified. The Compensator Editor tool allows the user to simultaneously adjust the PID gains for both of the Pitch and Altitude hold controllers, while monitoring the desired output, in this case an altitude step of 100 feet. The compensator Editor can be seen in Figure 33, with the tuned step response following in Figure 34. After achieving a stable and correct steady state response to a 100 foot step command, the pitch proportional and integral gains were further adjusted to slow down the overall step response. The purpose of slowing the response is to ensure that the model provides enough of an error margin, since the model is not exact, the aircraft must remain stable for anticipated plant variations, even if this results in a slower response. Slowing the response too much can cause the autopilot to lag so far behind the aircraft that control actions will further propagate errors rather than correct them. Thus the objective of a 100 foot step in under 20 seconds, or a roughly 5ft/s climb rate was established as a minimum climb rate. This objective was easily met, as shown in Figure 34.

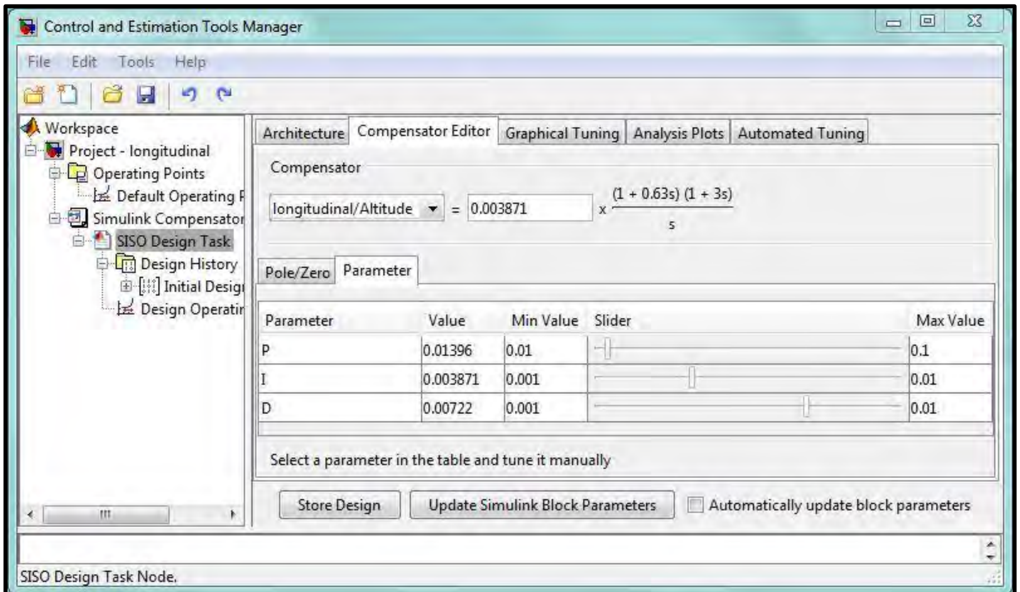



**Figure 33: Simulink® Compensator Editor**

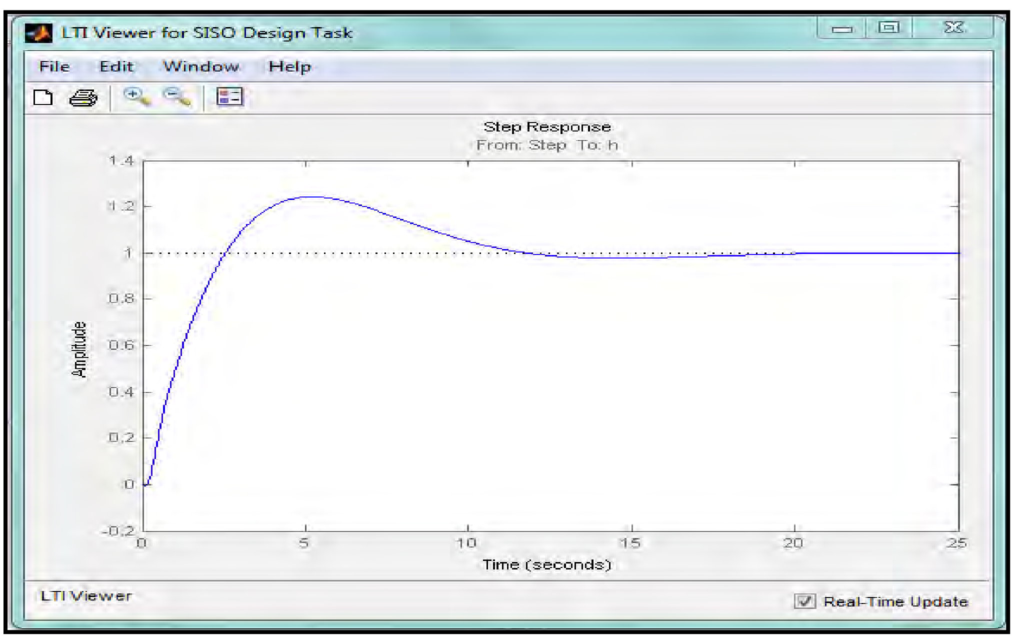



**Figure 34: 100 Foot Altitude Command Step Response**

### 3.4.2 Lateral/Directional Model

Development of the Lateral/Directional model encompasses the same procedures and techniques as the longitudinal model. The fundamental difference between the two processes is the incorporation of the aerodynamic coupling between the roll and yaw modes.

#### Model Development

The Lateral/Directional model development consisted of the generation of the lateral/directional parameters found in Table 4, as well as the refinement of the Nelson lateral/directional mathematical model in Equation 6. The addition of ailerons in the control scheme required alterations to the Stryker Owl model, which utilized the Kestrel® rudder-only control scheme. A simple alternative model was found in the Nelson and Stevens texts, which incorporates both ailerons and rudder, as well as the modeling of the aerodynamic coupling between them (Nelson, 1998;Stevens 2003). The resulting lateral/directional stability parameters are shown below in Table 8, and are used in conjunction with several of the universal parameters in Table 7 to form the Nelson mathematical model, shown in Equation 13 (Nelson 1998).

**Table 8: Lateral/Directional Stability Derivatives**

| Parameter | Value |
|---|---|
| $Cy_{\beta}$ | -0.31 |
| $Cy_{p}$ | 0 |
| $Cl_{p}$ | -0.415 |
| $Cy_{r}$ | 0 |
| $Cl_{r}$ | 0.08 |
| $Cy_{\delta a}$ | 0 |
| $Cn_{\delta a}$ | -0.0258 |
| $Cl_{\delta a}$ | 0.15 |
| $Cn_{\beta}$ | 0.0529 |
| $Cl_{\beta}$ | -0.1307 |
| $Cn_{p}$ | -0.04 |
| $Cn_{r}$ | -0.045 |
| $Cy_{\delta r}$ | 0.075 |
| $Cn_{\delta r}$ | -0.035 |
| $Cl_{\delta r}$ | 0.003 |

$$\begin{bmatrix}\Delta\dot{\beta}\\ \Delta\dot{p}\\ \Delta\dot{r}\\ \Delta\dot{\varphi}\end{bmatrix} = \begin{bmatrix}-0.234 & 0 & -0.977 & 0.634\\ -16.011 & -6.004 & 1.157 & 0\\ 4.964 & -0.443 & -0.499 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}\Delta\beta\\ \Delta p\\ \Delta r\\ \Delta\varphi\end{bmatrix} + \begin{bmatrix}0 & 2.876\\ 18.375 & 0.367\\ -2.421 & -3.284\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta a\\ \delta r\end{bmatrix} \quad \textbf{(13)}$$

Open-loop analysis of the lateral-directional stability shows that the aircraft model has inherent lateral stablity. This is apparent in Figure 35, where the oscillatory Dutch-roll mode poles and non-oscillatory spiral model pole are all located in the left-half plane. Of equal importance is the predicted damping ratio of the Dutch-roll root locus. Whereas the short period pitch poles were highly damped at roughly 0.8, the Dutch roll poles are shown with minimal natural dampening (ζ= 0.17) with infinite gain. Thus as the Jet5 static stability analysis alluded to, the aircraft will require tuning to correct for insufficient tail surface volume. This problem is further amplified by the addition of the 15-foot wingtip extensions.

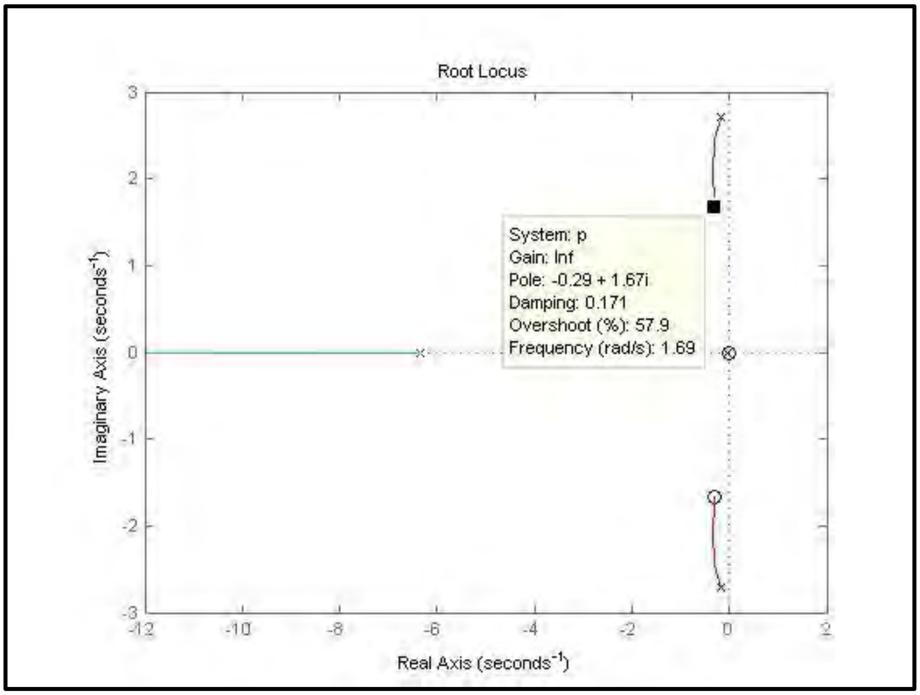



**Figure 35: Condor 12-foot Wingspan Lateral Root Locus**

### Simulink® Analysis

The current release of the Kestrel® autopilot code has the ability to stabilize and navigate multiple configurations of aircraft, including traditional, V-tail, and rudder-only lateral control arrangements. The lateral-directional control loop structure for traditional aircraft configurations is considered proprietary by Procerus Technologies, and thus had to be independently developed. The basis for the model was found in Stevens' *Aircraft Control and Simulation* (2003). Figure 36 below shows the Stevens combined lateral/directional model for a wing-leveling autopilot system.

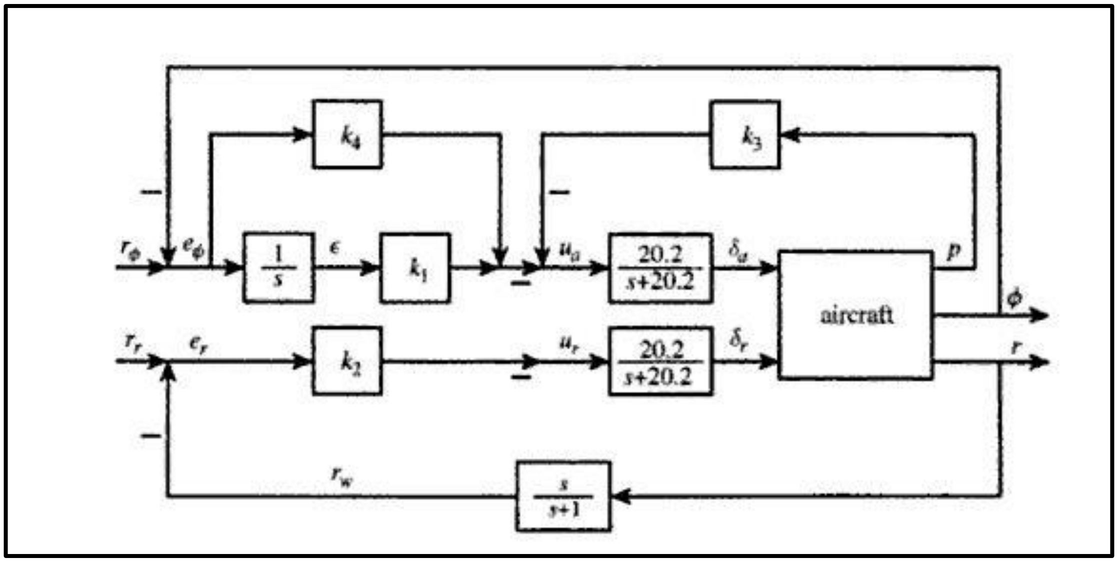



**Figure 36: Stevens Wing-Leveler Control system (Stevens 2003)**

Several modifications were required to further refine the Stevens model for practical use. The most important was the inclusion of actuator position and rate saturations. Saturations are generally detrimental to modeled stability, but essential for preserving the accuracy of the model for the real aircraft. Furthermore, the inclusion of manual switches allows for the independent analysis and tuning of the aileron controls and the rudder controls, without the coupled input effects of the non-monitored parameter, be it roll or yaw. Heading feedback control is not necessary as part of the model, as it is included as a feed-forward parameter, built into the internal Kestrel® code. The final Simulink® lateral/directional aircraft model used for the analysis of both the 12- and 15- foot Condor aircraft is shown below in Figure 37.

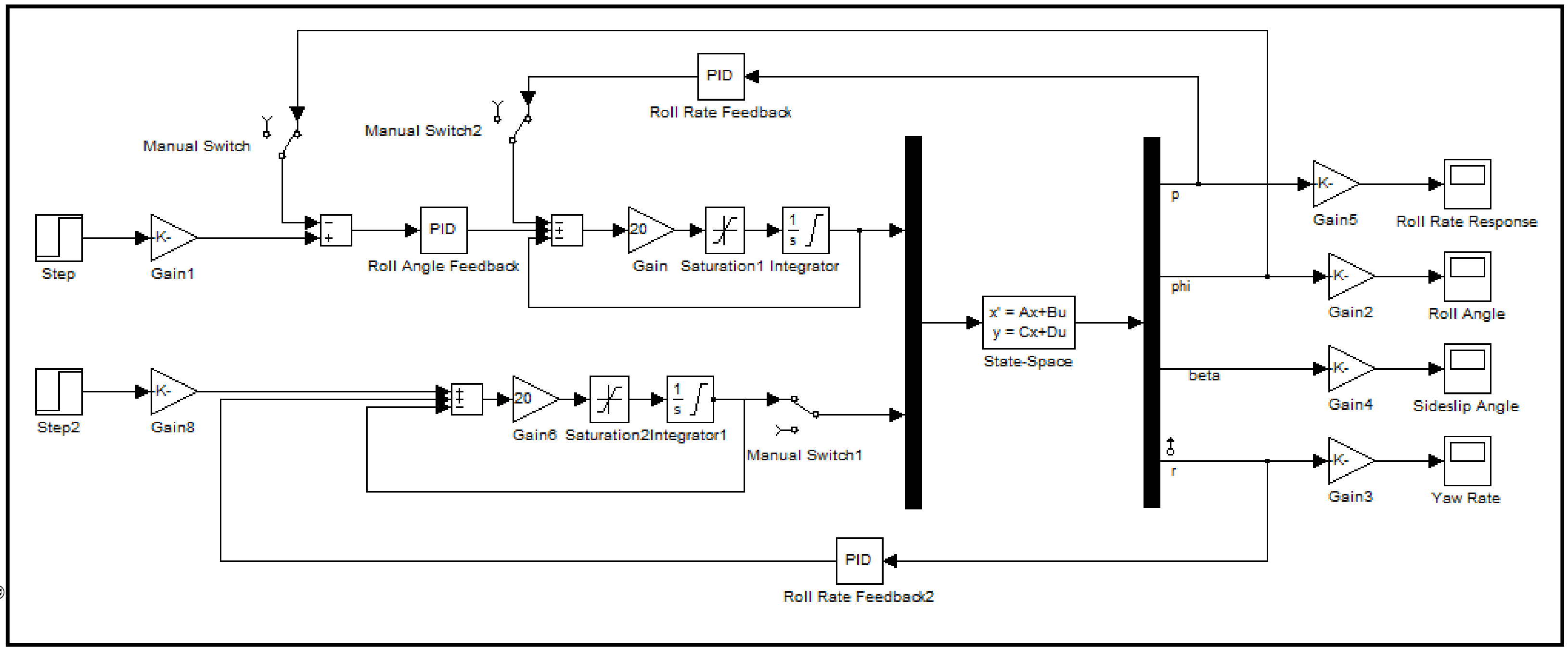



Figure 37: Condor Lateral/Directional Simulink® Model

The consecutive loop closure technique was performed to tune the lateral/directional model in the same manner that it was used to tune the longitudinal model. The roll rate and yaw rate loop gains were determined based on the root locus of Figure 35, and then the Simulink® controller design tool was used to tune the roll position controller. An increased emphasis on allowing a sufficient gain margin was adopted when tuning the roll and yaw rate loops, due to potential excitations caused by the aerodynamic coupling between the two. This was in effect useless, as tuning results indicated that the aircraft would operate with more lateral stability without the use of a rudder than with a tuned feedback loop. This result is completely counter-intuitive, and multiple attempts to adapt the model to improve results were unsuccessful. Figure 38 and Figure 39 show the roll response and sideslip angle response to a 15-degree roll command to the aircraft without rudder input.

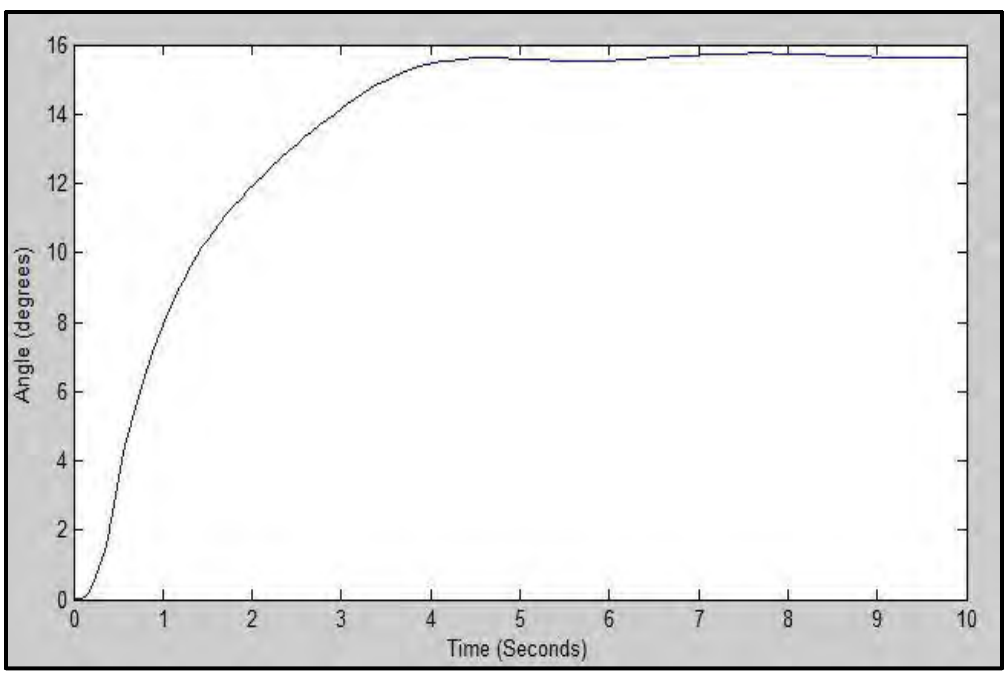



**Figure 38: 15-Degree Roll Input Roll Response**

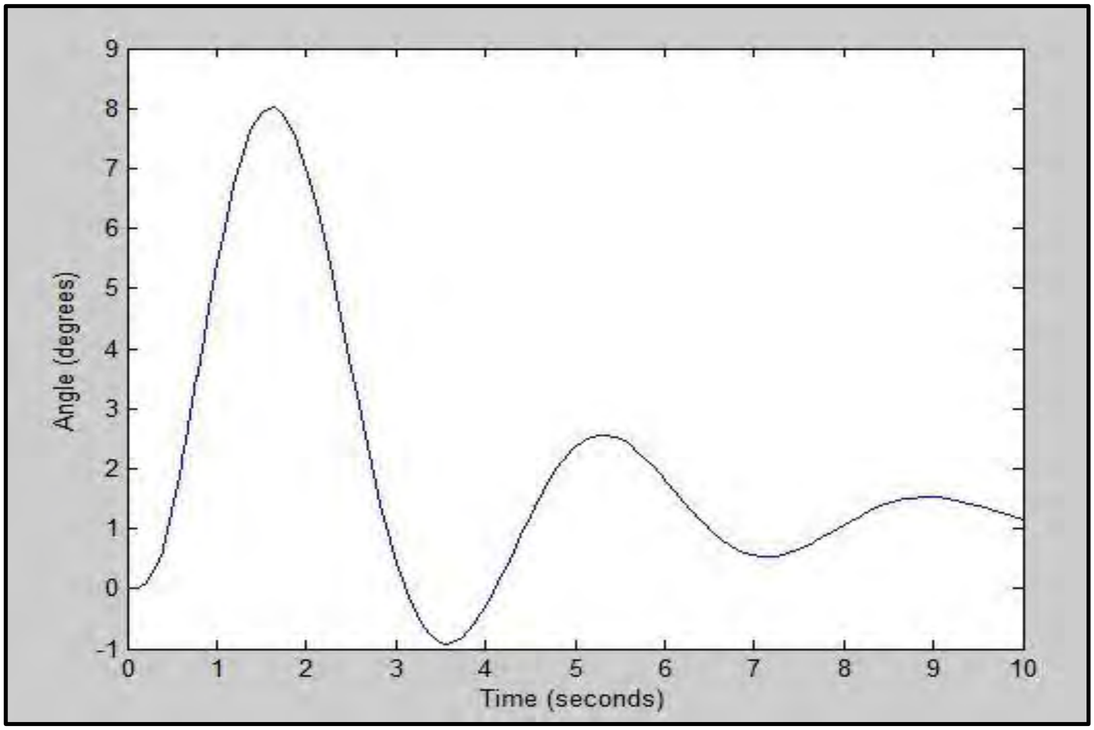



**Figure 39: 15 Degree Roll Input Sideslip Angle Response**

Although the output response above shows a significant sideslip of the aircraft following a commanded roll input, the steady-state response of both roll and yaw is stable, with a well damped roll response. Thus the tuned results above give enough confidence of stability in the lateral/directional modes using only roll feedback to satisfactorily assume a stable set of gains for initial flight testing.

## 3.5 Flight Test

Flight testing of the Condor aircraft involved of a series of grouped objectives, spanning over a planned flight test program of 5 flights per aircraft. The term "flight" indicates a set of objectives planned for a single aircraft launch; however, a flight could require several launches to accomplish all objectives reserved for that "flight." Several additional flights were made to meet secondary objectives after the initial stability and performance flights were complete. The flight test plans for all flight testing can be found in Appendix C.

### 3.5.1 Planned Testing Process

The five flight tests for each aircraft were designed to allow a conservative testing process, where the most important and least risk-prone objectives are accomplished prior to higher risk, lower importance objectives. This process is fully explained in English and Molesworth's *Concept Evaluation of a Remotely Piloted Aircraft Powered by a Hybrid-Electric Propulsion System* (English and Molesworth, 2012). The five planned flights for each aircraft were:

1. Remote Control only – Aircraft basic flight maneuvers, no stability augmentation, flown at minimal flight weight
2. Stability Augmentation – Tune rate control feedback loops for Stability Augmentation System (SAS)
3. Directional Control – Tune altitude and heading controls to allow full autonomous flight
4. Open Loop Testing – Disengage SAS, perform aircraft frequency response maneuvers to validate model
5. Performance flight – Full autonomous flight to measure altitude tracking, fuel burn rates, and acoustic signatures

### 3.5.2 AC1 Process Changes

Miscommunication with the contracted operators of the AC1 testing process induced several major adjustments in the proposed flight plan. The result of these miscommunications was AC1 being flown on flight #1 with faulty stability control enabled, stability parameters from the SIG Rascal aircraft, and an additional gain of 100 added to all servo outputs. Flight 1 telemetry shows this 35-second flight reached attitudes that exceeded 120 degrees of roll, 85 degrees of pitch, 35 degrees of yaw, and resulted in a crash landing that broke the empennage free of the fuselage at the hinge pins. Following the repair of the empennage pins and a re-briefing of the contractors, the flight schedule resumed its intended progression. The major deviation from the original plan is that AC1 was flown with the SIG Rascal gain settings, with the additional gain of 100 removed, until a stable autonomous mode was accomplished. Figure 40 below shows the repaired AC1 airframe on landing approach.

**Figure 40: AC1 In-Flight Photograph**

### 3.5.3 AC2 Process Changes

The intended process for flight testing of AC2 was far more focused on the limitations and performance of the HE system. The basic airframe was at that time considered stable through the AC1 flight test process, provided that AC2 could develop equivalent thrust to AC1. The limited data available from the flight testing of AC2 suggests that this was not the case, as AC2 was unable to successfully launch.

## 3.6 Data Reduction and Model Refinement

The stream of telemetry data at 20 data points per second produced a complete data set for Airframe and model analysis. The major aspects that were investigated and compared relative to the predictive model were the short and long period longitudinal oscillations, flight operating airspeeds, and the overall stability of the lateral/directional aircraft modes in flight. This information was determined from the airspeed, altitude and heading data, as well as the pitch, roll, and yaw rates found in the Kestrel telemetry stream.

### 3.6.1 Longitudinal Modal Analysis

The process of evaluating the longitudinal modes consists of forcing the aircraft to oscillate at or near the predicted natural frequency, and monitoring the resulting frequency of response. The methods of exciting the oscillatory modes are found in Appendix A.

### Phugoid Analysis

From the predictive model discussed in Section 3.4.1, the expected natural frequency of the Phugoid, or long period oscillations of the aircraft, are expected to occur at roughly 0.428 radian/second, or roughly 14.68 seconds per oscillatory cycle. Graphical analysis of Figure 41 below shows definitive peaks of an excited Phugoid mode following the initial excitation by a steady pull-up and release of the controls. Determination of the damped natural frequency from this data is found by calculating an average time between the first two major peaks of the oscillatory response. The Phugoid mode was excited effectively three times in succession, with an average natural frequency output of 14.6 cycles per second. This is a 0.55% difference from the predictive Phugoid frequency.

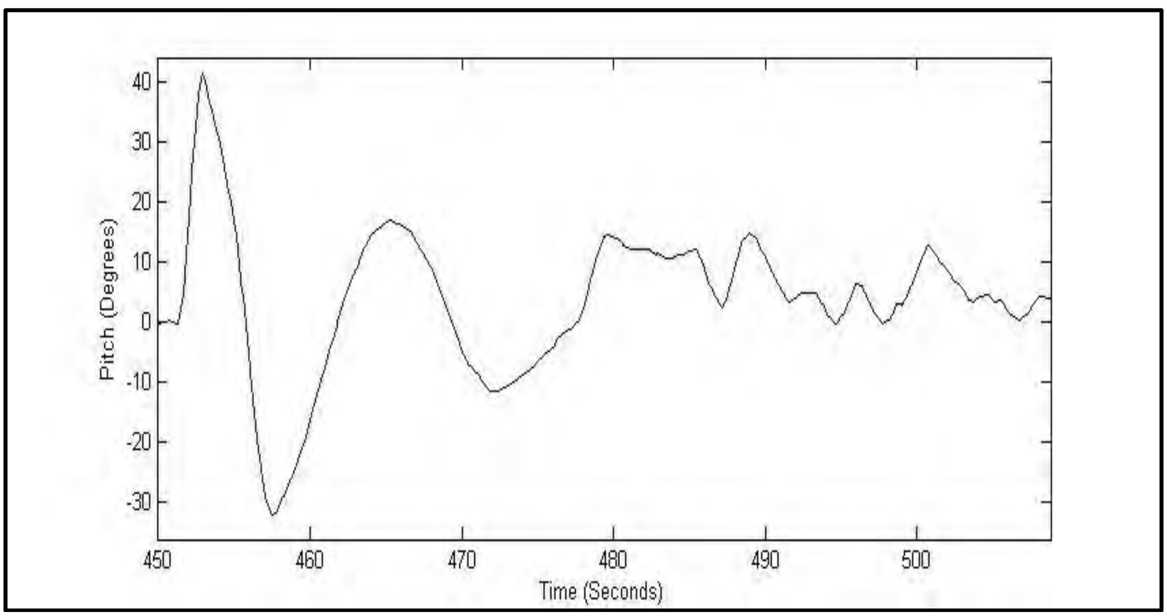



**Figure 41: Condor Phugoid Response**

### Short Period Analysis

Excitation of the Short Period oscillatory mode is accomplished by  a series of elevator “doublets” or continued forced oscillations of the elevator at the predicted frequency of approximately 7 radians/second, or 1.1 cycles of the elevator per second. The forcing of the aircraft can be seen in Figure 42 as the sharp repeated peaks from 235 to 255 seconds. The subsequent rounded peaks of the Short Period response are measured in the same manner as the Phugoid analysis, and averaged 3.5 seconds per cycle or 1.8 radians per second. This yields roughly a 75% error from the predictive values. Analysis of the forcing frequency shows that the pilot was able to correctly force the aircraft at the predictive frequency, yet the aircraft did not respond in the predicted manner.

The short period analysis test was completed a total of six times, with inconsistent results. Attempts to deduce the natural frequency by means of Fourier analysis of the flight were likewise inconclusive. Further testing was deemed unnecessary, as the test results were deemed valid, though the cause for inconsistent results remains unknown.

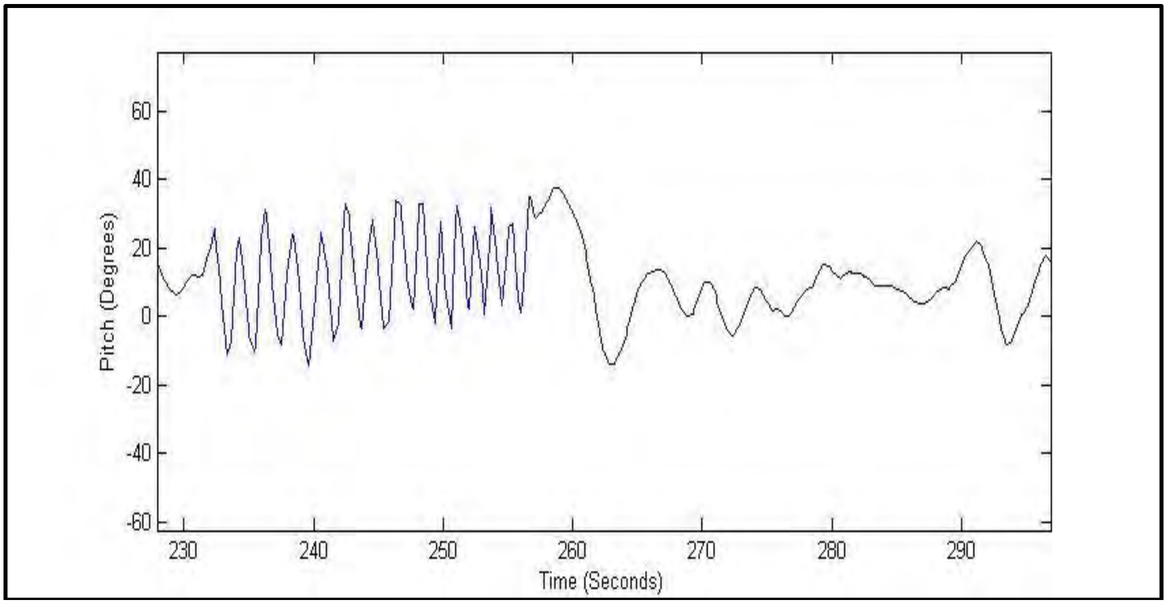



**Figure 42: Condor Short Period Response**

### 3.6.2 Operating Airspeed Analysis

Flight testing for the predicted airspeed values shown in Table 5 was accomplished in accordance with the flight test plan found in Appendix A. All airspeed values for AC1 were determined at an operating weight of 28 lbs, which is slightly lighter than the modeled weight, but not significant enough to cause drastic deviations. Further increases in vehicle weight, as is necessary for the test flights of AC2, will cause the resulting airspeed values to likewise increase proportionately. Aircraft stall speed was averaged over a series of seven tests, consisting of a idle throttle setting and slight up-elevator until the aircraft experienced buffeting and broke into the stall. This can be seen in Figure 43 below.

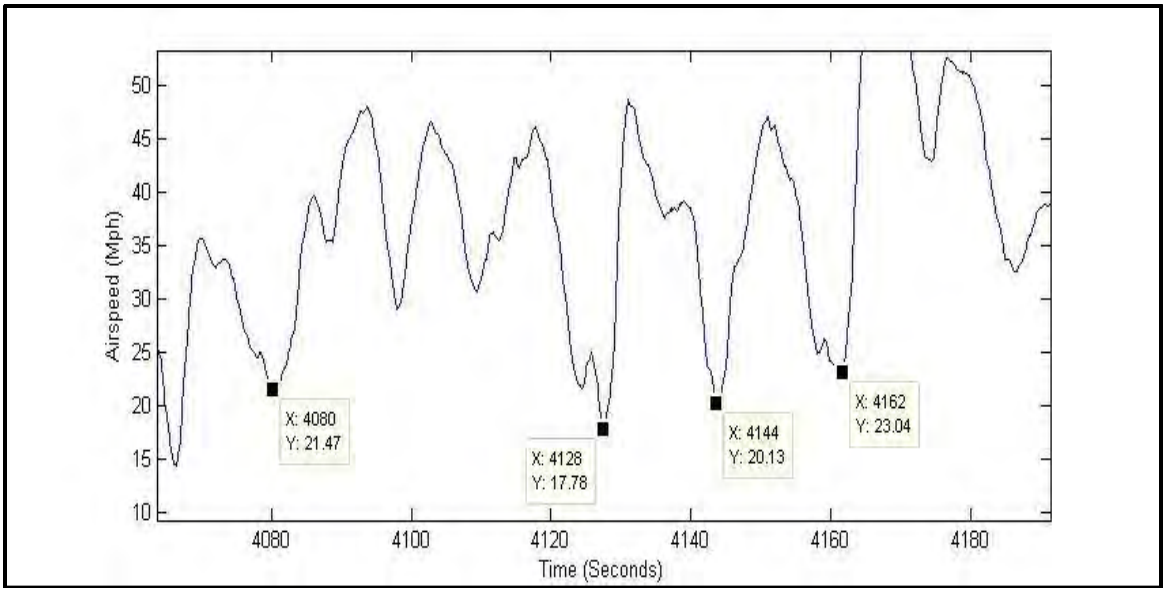



**Figure 43: Condor Stall Test Airspeed Data**

Takeoff airspeed was measured from the moment the Kestrel® autopilot recognized the aircraft in a flying state, and is an average of the individual airspeed reading for all aircraft takeoffs, including the variation of weight from 28 to 36 lbs. Takeoff airspeed varied from 24 to 29 mph, with an average increase in airspeed of 0.5 mph per lb of weight added. Wind conditions heavily affected the ability of the aircraft to effectively navigate at the predictive loiter airspeeds. The asserted "best" loiter airspeed corresponds to the minimum airspeed in which the aircraft could effectively loiter in a 10-15 mph wind environment, as demonstrated in flight test. All tested airspeed data results are shown in Table 9, with the most efficient cruise and loiter airspeeds not attainable from the data collected.

**Table 9: Condor AC1 Airspeeds**

| Description | Airspeed |
|---|---|
| Stall Airspeed | 21.6 Mph (31.7 ft/s) |
| Takeoff Airspeed | 26.3 Mph (40.1 ft/s) |
| Best Loiter | 47.5 Mph (69.7 ft/s) |

### 3.6.3 Lateral Stability Evaluation

The lateral/directional stability was not investigated as thoroughly as the longitudinal, because it was not considered to be a stressing factor for the operational concept evaluation. The spiral mode was evaluated as described in Appendix A, and no tendencies for instability were found. Evaluation of the Dutch-roll mode found the aircraft to be particularly susceptible to the Dutch-roll mode, as was predicted by both the static and dynamic mathematical models. The frequency of the Dutch-roll mode was significantly slower than predicted, but was forced at a lower frequency than intended. Data from Figure 44 below shows the forcing and response frequency of 2.44 radians per second. The predicted natural frequency was 6.34 radians per second.

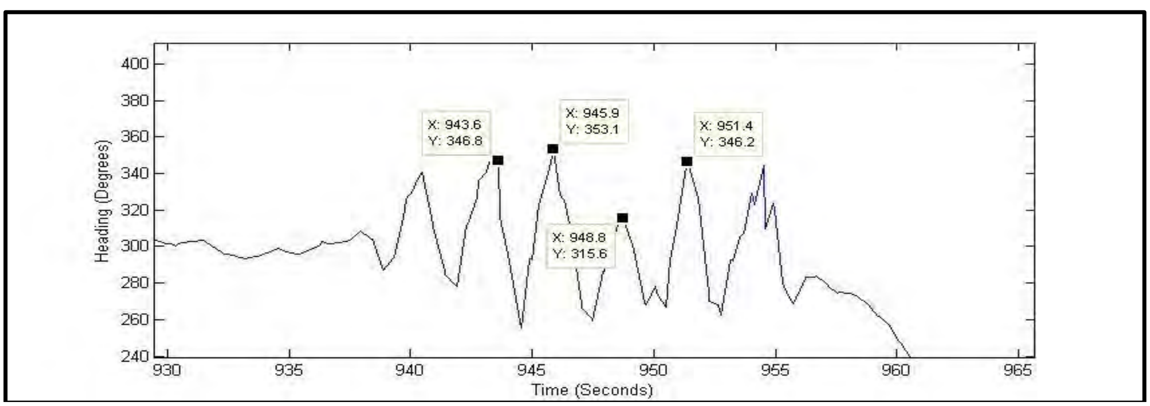



**Figure 44: Condor Dutch-Roll Results**

### 3.6.4 In-Flight Gain Tuning

The additional emphasis on aircraft test survivability following the crash on Flight #1 dictated the usage of the SIG Rascal PID gains developed by Nidal Jodeh, as they had been proven effective on a similarly-sized aircraft (Jodeh, 2006). In-flight aircraft telemetry provided streaming data, which enabled the ground crew to vary the PID gains on all aircraft settings to improve aircraft stability and handling. In flight adjustments to the SIG Rascal gains continuously approached those predicted in the Condor mathematical model throughout Flight #3, and were eventually changed out completely to the predictive gains for all subsequent flights, with significantly improved performance.

## 3.7 Aircraft Performance

Two major aspects of the aircraft proof of concept were additionally studied outside of the initial stability and control analysis on the Condor flight tests. The additional objectives were introduced after noting the very low fuel burn rates of the Honda 35cc engine. Due to the increased energy density of gasoline, it was suggested that efforts be made to reduce the acoustic signature of the aircraft, and additional fuel be added, in order to achieve long-loiter, near-silent operation without the use of a hybrid system. As a result, propellers with varying blade counts were investigated as an acoustic-reduction measure for the aircraft, as was accomplished on the Lockheed YO-3A “Quiet Star” in Vietnam (Army-Lockheed, 2004). As a general rule, for every additional blade added to an R/C propeller, the operator should decrease the span of the blade by an inch, and increase the pitch by an inch. Due to the limited range of pitch and span of multi-blade R/C scale propellers in the commercial marketplace, compromises were made regarding the proportional scaling of propellers. Results of the performance and acoustic tests are displayed and explained in *Concept Evaluation of a Remotely Piloted Aircraft Powered by a Hybrid-Electric Propulsion System* (English and Molesworth, 2012).

### 3.8 Chapter Conclusion

Development and refinement of the mathematical model for the Condor Aircraft was an iterative and multi-disciplinary endeavor. The development of the model, as can likewise be seen in the vast majority of the S-RPA research, is highly dependent upon the available resources necessary to determine the fundamental stability parameters. The lack of wind-tunnel testing and detailed modeling available for small RPA aircraft significantly increases the error induced into the model. This can, however, be compensated for by the juxtaposition of parameters between similar airframes, as was done on the small scale for unknown Condor values.

# 4 Results

## 4.1 Chapter Overview

The flight testing of the Condor aircraft validates the accuracy and validity of the static and dynamic models for use in Small Remote-Piloted Aircraft. Use of the Jet5 software tool to predict basic flight stability parameters led to the development of a useful mathematical model, providing for simple in-air stability tuning with very favorable results.

## 4.2 PID Tuning Results

Section 3.6.4 details the process by which the SIG Rascal gains were sequentially adapted to provide for a stable flight performance of AC1. The fundamental SIG gains are shown below in Table 10.

**Table 10: SIG Rascal PID Gains**

| Parameter | Description | Gain |
|---|---|---|
| $K_p^Q$ | Pitch Rate Proportional Gain | 0.2 |
| $K_p^\theta$ | Pitch Angle Proportional Gain | 1.1 |
| $K_I^\theta$ | Pitch Angle Integral Gain | .01 |
| $K_p^H$ | Altitude Proportional Gain | 0.02 |
| $K_I^H$ | Altitude Integral Gain | 0.002 |
| $K_D^H$ | Altitude Derivative Gain | 0.005 |
| $K_p^T$ | Throttle Proportional Gain | 2.0 |
| $K_I^T$ | Throttle Integral Gain | 1.0 |
| $K_D^T$ | Throttle Derivative Gain | 2.0 |
| $K_p^P$ | Roll Rate Proportional Gain | 0.03 |
| $K_P^\phi$ | Roll Angle Proportional Gain | 0.3 |
| $K_I^\phi$ | Roll Angle Integral Gain | 0.001 |
| $K_P^R$ | Yaw Rate Proportional Gain | 0.1 |

Throughout the process of flight testing, these gains were slowly adapted until they approached the predictive model gains. At this point, all fundamental longitudinal and lateral/directional gain values were changed to the predictive values shown below in Table 11. Further attempts to improve flight stability were insignificant in result, as the magnitude of in-flight fluctuations exceeded that of the control input responses.

**Table 11: Condor AC1 Final PID Gains**

| Parameter | Description | Gain Value |
|---|---|---|
| $K_p^Q$ | Pitch Rate Proportional Gain | 0.0664 |
| $K_p^\theta$ | Pitch Angle Proportional Gain | 0.490 |
| $K_I^\theta$ | Pitch Angle Integral Gain | 0.0416 |
| $K_p^H$ | Altitude Proportional Gain | 0.0140 |
| $K_I^H$ | Altitude Integral Gain | 0.004 |
| $K_D^H$ | Altitude Derivative Gain | 0.007 |
| $K_p^T$ | Throttle Proportional Gain | 10 |
| $K_I^T$ | Throttle Integral Gain | 1 |
| $K_D^T$ | Throttle Derivative Gain | 0.5 |
| $K_p^P$ | Roll Rate Proportional Gain | 0.3349 |
| $K_P^\phi$ | Roll Angle Proportional Gain | 0.4123 |
| $K_I^\phi$ | Roll Angle Integral Gain | 0.02 |
| $K_P^R$ | Yaw Rate Proportional Gain | 0.15 |

## 4.3 Simulated Model Performance

Despite the rather minor changes made to the PID gain values, a significant improvement in aircraft dynamic performance was achieved by adaptation of the modeled gains. A comparative parameter was developed to analyze the flight test periods where the SIG Rascal gains were in complete control of the aircraft, and when the tuned gains were in control. The deviation between the commanded control surface deflection and actual control surface deflection was calculated at each autonomous data point, and labeled the “model error.” This is demonstrated below in Figure 45.

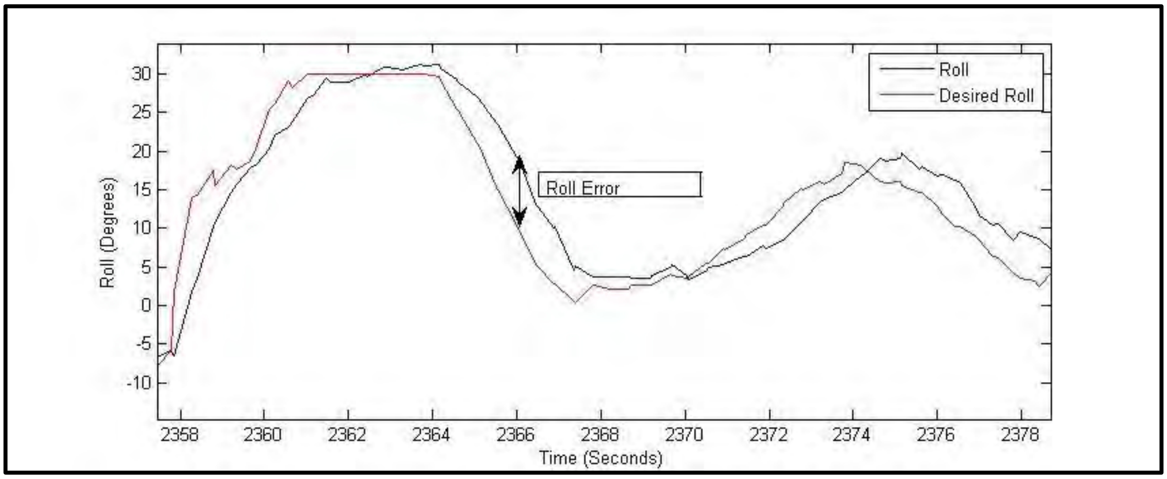



**Figure 45: Model Error Analysis**

Averaging the position model error for the two different sets of gains showed a significant improvement in roll and altitude errors when the predictive gains were entered. Table 12 lists the calculated average errors over several minutes of autonomous flight, as well as the percent reduction in error achieved by the tuned predictive gains.

**Table 12: PID Gain Model Error Comparison**

| | Roll Error (Deg) | Pitch Error (Deg) | Altitude Error (Ft) |
|---|---|---|---|
| SIG Rascal Gains | 3.106 | 0.820 | 7.251 |
| Tuned AC1 Gains | 1.734 | 0.782 | 5.678 |
| **% Improvement** | **44.08 %** | **4.64 %** | **21.69%** |

The significance of this error reduction is far more apparent in flight as it resulted in a reduction of the time delay between the commanded input and the actual aircraft response. A human pilot is expected to have a typical response time, from sensory to response, of roughly 0.25 seconds (Stevens, 2003). This response time, however, is for a manned aircraft pilot, which is far faster than the average response time of a remote pilot. The average time delay between the commanded response and the actual response in Figure 45 far supersedes the human standard, at 0.16 seconds. The combination of the improved control response and fast response time allowed the tuned Condor aircraft to fly in a far more stable manner than while under pilot control, or with the SIG rascal gains.

## 4.4 Open-Loop Characterization and Model Adaptation

The differences previously noted in the offset of the short period response were investigated extensively. Initial hypotheses pointed to miscalculations in either the aircraft pitching Moment of Inertia, or pitching moment coefficients. Specifically, the coefficients $C_{M\alpha}$ and $C_{Mq}$, the moments due to angle of attack change and pitch rate. The aircraft pitching Moment of Inertia was investigated first, particularly due to the inability to measure the aircraft MOI with the main wing attached. Despite this deficiency, scaling of the aircraft weight and performance to the other aircraft in Table 6 suggests that the MOI data taken for the aircraft model was in fact accurate, and that the miscalculation must have occurred in the aerodynamic calculations.

The variable $C_{M\alpha}$ describes the change in moment that occurs with a corresponding change in aircraft angle of attack. This parameter is generally dependent upon the airfoil shape and position, but is also characterized by the time rate of change of the moment, $C_{M\dot{\alpha}}$. The derivative value, however, varies proportionately with the value of

$C_{Mq}$, which is the second suspect parameter chosen for error analysis. $C_{Mq}$ is based highly upon the tail lifting surface efficiency and moment arm. The vast majority of parameters that go into calculation of $C_{Mq}$ are based on the defined geometric distances and wing areas of the aircraft, leaving only the tail efficiency factor, which was previously set to 0.809, as suggested in Nelson (1998). Further analysis using the combined Jet5-Nelson model was unable to achieve the natural frequency demonstrated in the flight test.

The final possibility for the inability to model the aircraft short period modes is the notion that the Condor wings and tail section are further increasing the dampening of the natural pitching modes. Excessive dampening caused by the large wingspan could potentially account for the inability to effectively excite the short period mode. This infers that the frequencies calculated from the flight test data were secondary or tertiary harmonics of the true short period frequency, or the short-period frequency was damped with a $\zeta_{sp}$ value of nearly 0.98. These two conclusions are likewise based on the assumption that the test pilot was successful in excitation of the actual aircraft short-period mode.

### 4.4.1 Throttle Changes between AC1 and AC2

Throttle PID tuning and analysis for AC2 was unavailable, as AC2 was lost on the second takeoff attempt. After roughly 150 feet of takeoff roll, the right main wheel of the aircraft detached, causing the aircraft to skid down an embankment at Camp Atterbury, eventually careening into the grass. The damage sustained by the aircraft was extensive enough to eliminate the possibility of further flight testing without extensive repairs to the fuselage and wing collar. Perceived differences in the takeoff roll comparison of AC1 and AC2 point to a lack of available thrust on the AC2 takeoff attempts. This was apparent in the differences in both the audible propeller noise, as well as the distance required for takeoff between the two aircraft.

### 4.5 Chapter Conclusion

Flight test results from the AC1 and AC2 tests demonstrate that a high level of accuracy was achieved in the modeling process for the aircraft. The Jet5 and static parameterization was able to predict the Phugoid mode to within 1% of the actual value. Likewise the PID tuning process used with the developed Simulink® model was able to effectively reduce the system time delay and increase autopilot response by up to 45% without the need for additional in-flight tuning.

# 5 Conclusions and Recommendations

## 5.1 Chapter Overview

The overall results of the Condor modeling and tuning process indicate a very successful integration of previous S-RPA modeling methods with the Jet5 Software tool. Without further tuning or adaptation, the Condor airframe is capable of flying with the determined gains in a stable and efficient manner for periods of up to two hours. This time period could be easily extended to up to seven hours with the inclusion of additional fuel tanks and batteries (English and Molesworth, 2012). The modeling process was able to bring forth several important characteristics of the aircraft-model combination that demand further investigation.

## 5.2 Evaluation of Methodology

Adoption of the Jacques/Stryker dynamic aircraft model provided a very efficient template to start the dynamic analysis predictions. Further integration and comparison with the Nelson model and previous S-SPA parameterization allowed for coarse verification of the aircraft parameters. The overall result of this multi-faceted approach was success in the mathematical modeling of the Condor. Indication of this success were found in the marked improvement in flight performance and an inability to further improve PID gains in-flight to achieve better results.

The one major shortcoming of the process was the inability to predict the short-period response. This problem was likewise exhibited in the Stryker analysis of the AFIT OWL longitudinal model, where there was noted a significant inability to effectively model the short period mode or track to determined altitudes or pitch settings. The additional fuselage length and higher pitching MOI were most likely beneficial to the Condor in allowing for a more efficient natural dampening of the airframe, allowing the aircraft to not exhibit the multiple longitudinal complications experienced in the Stryker analysis. The inclusion of and comparison to the Jodeh, Nelson, NPS and Stevens aircraft stability derivatives potentially further diluted any inherited errors (Jodeh, 2006; Nelson, 2003; Choon Seong 2008; Stevens, 2003)

The inability to effectively predict the rudder interconnect to the aileron control was overcome by small in-flight tuning procedures. The modeling approach, however, was ineffective in predicting the rudder control, as the final PID gain utilized in-flight is shown as a destabilizing value in the model. This performance disconnect is more than likely an error in the model, but corrected, and not observable in the proprietary feed-forward parameters in the Kestrel® autopilot code.

Modifying the model to incorporate the full HE system involved very few necessary changes to the PID gains or aircraft model. The foresight of the systems engineering approach to fly AC1 at the predicted weight and balance of AC2 eliminated necessary model changes due to weight or loading changes. The only parameter that required investigation was throttle command PID gains, due to scaling differences between the two aircraft propulsion systems. The predicted changes were minimal due to the lack of fidelity in the Kestrel® input command for throttle, and masking nature of the Kestrel® code, but were unable to be accurate investigated with the loss of AC2.

## 5.3 Significance of Research

The modeling and tuning process of the Condor aircraft is significant due to the amalgamation of modeling programs and previous research utilized. Utilizing the manufacturer-provided data in conjunction with Jet5, Digital DATCOM and previous S-RPA data allowed for the dilution of errors found in a single method. This process also enabled a further refinement of modeling parameters based on scaling when wind tunnel testing and aeronautical testing are feasible or available.

## 5.4 Recommendations for Future Research

The Condor research developed several key areas with problems requiring future research and analysis. Continued development in the following areas would allow for a further increase in the utility for Condor aircraft, as well as the field of S-RPA modeling as a whole.

In order to investigate potential errors in short-period eigenvalue prediction a comparative evaluation of the mathematical models used in the AFIT Condor, OWL and BATCAM models should be performed. The lineage of AFIT aircraft mis-predicting and failing to effectively model the short-period modes can be traced back to the start of use of the Kestrel autopilot, and the derivation of the Jacques A-4 model for use with AFIT S-RPA and MAVs. An evaluation of the techniques used to scale the Jacques model would be incredibly beneficial in determining the source of the longitudinal errors.

The inexplicable high dampening of the Condor short-period oscillations indicated either model flaws or non-linear effects. The primary candidate for further analysis of non-linear dampening effects is the flexing of the wings. The single aluminum spar and foam core wing sections allowed for nearly 10 degrees of dihedral when the aircraft was loaded to the AC2 flying weight. Further investigation of this potential phenomenon could very well explain the discontinuities between model and flight results.

The Kestrel Autopilot is a user-friendly system for flying S-RPAs in military and other environments that require secure communications. That being said, the proprietary nature of the Kestrel® code and significant cost of the system make it less than ideal for use in academic applications, where the free analysis of data and adaptation is critical for continued progress. The inability to access the feed-forward parameters, access the actual Kestrel® control diagram, or change the processes involved in the PID control significantly inhibit the user and developer's ability to openly and honestly evaluate an airframe. The most significant problem is the considerable masking of erroneous user inputs. Switching to an open-source autopilot, such as an Ardupilot or OpenPilot system, would not only eliminate the coding limitations of proprietary software, but allow for true aircraft responses, at less than one-tenth of the cost of the Kestrel®.

## 5.5 Summary

The work detailed in this thesis demonstrates the iterative process of fusing multiple sources at each step of the modeling process. The continuous juxtaposition of aircraft parameters and stability values with multiple sources throughout the process proved to be an effective practice for successful determination of a mathematical model that emulates actual aircraft performance. The successful modeling of the Condor allowed for significant development in S-RPA longevity and acoustic data for mission-type analysis, as well as an aircraft characterization process that can expedite the modeling and tuning for future parallel HE-RPA projects.

# Appendix A Kestrel Telemetry Parser

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MatlabTelemParser.m
% Version: 1.0.1
% Author: Neil Johnson, Procerus Technologies
%
% Description: This file can be used with Matlab or Octave to
% parse standard telemtry files saved by the Virtual Cockpit.
%
% Instructions: Load the telemetry file into Matlab and then run
% this script.  A list of variables will be printed out to the
% terminal.  You can then plot any of the variables using the
% 'time' variable as follows:
%
% plot(time, varname1, 'b', time, varname2, 'r')
%
% You can also modify and copy the contents of this file into the top
of
% any file created to parse Virtual Cockpit telemetry.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%Updated 9/27/2011
% 1)Velocities Converted to Miles Per Hour From M/s
% 2)Distances and Altitudes Converted to Feed from Meters
% 3)Angles and Angular Rates Converted to Deg and Deg/s From Rad and
Rad/s
% 4)Time Variable Parsed from reletive start time.

AlreadyLoaded = exist('telemetry', 'var');

if AlreadyLoaded == 0
        [File, FilePath, FilterIndex] = uigetfile();
        TelemetryIn = [FilePath,File]
        run(TelemetryIn)
elseif AlreadyLoaded == 1
    reply = upper(input('There is already Telemetry in the Workspace.
\n Do you want to use this data? Y/N, or <esc> to cancel: [N] ', 's'));
    if isempty(reply)
        reply = 'N';
    end
    if reply == 'N'
        clear telemetry;
        [File, FilePath, FilterIndex] = uigetfile();
        TelemetryIn = [FilePath,File];
        run(TelemetryIn)
    end
end
    nheader_string = regexprep(telemetry.heading,'\W',''); %Begin
original Procerus code.
    fprintf(1, 'New Variable Names:\n');
    j = 0;
for i=1:length(nheader_string);
    fprintf(1, '%s\n', nheader_string{i});
```

```
    % Parse the UTC times correctly
    if strfind(nheader_string{i}, 'UTCTime') > 0,
        % Parse the STD TElEM UTC Time
        s = [nheader_string{i} ' = telemetry.data(:, ' num2str(i+j) ':'
num2str(i+j+5) ');'];
        j = j+6;
    else
        s = [nheader_string{i} ' = telemetry.data(:,' num2str(i+j)
');'];
    end

    eval(s);
end
%Converting Speeds to MPH
Airspeed=Airspeed*2.23693;
DesAirspd=DesAirspd*2.23693;
GPSVelocity=GPSVelocity*2.23693;
WindSpd=WindSpd*2.23693;
%Converting Altitudes and Distances to Feed
Altitude=Altitude*3.2808;
DesAlt=DesAlt*3.2808;
DistancetoTarget=DistancetoTarget*3.2808;
GPSAlt=GPSAlt*3.2808;
%Converting Radians to Degrees
rd=57.3
Pitch=Pitch*rd;
PitchRate=PitchRate*rd;
YawRate=YawRate*rd;
Roll=Roll*rd;
RollRate=RollRate*rd;
ServoAileron=ServoAileron*rd;
ServoRud=ServoRud*rd;
ServoElev=ServoElev*rd;
TurnRate=TurnRate*rd;
DesRoll=DesRoll*rd;
DesPitch=DesPitch*rd;
DesHdg=DesHdg*rd;
Heading=Heading*rd;


for n=1:length(RelativeTimems)
    time(n)=(RelativeTimems(n)-RelativeTimems(1))*0.001;
end
```

## Appendix B ERAU 3-d DATCOM Viewer Matlab Code

```
%**ERAU 3-D Viewer************************************************
% The source code contained herein was developed for Embry-Riddle
% Aeronautical University by Glenn P. Greiner, Professor and Jafar
% Mohammed, Student Assistant of the Aerospace Engineering Department,
% Daytona Beach Campus. Copyright 2008. All rights reserved.

% Although due care has been taken to present accurate programs this
% software is provided "as is" WITHOUT WARRANTY OF ANY KIND, EITHER
% EXPRESSED OR IMPLIED, AND EXPLICITLY EXCLUDING ANY IMPLIED WARRANTIES
% OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR USE. The entire risk
as
% to the quality and performance of the software is with the user. The
% program is made available only for education and personal research.
It
% may not be sold to other parties. If you copy some or all of the
% software you are requested to return a copy of any source additions
that
% you believe make a significant improvement in its range of
application.
%*********************************************************************
***

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% datcom3d v1.2 Input File
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%

clear
clc
clf

%%% VISUALIZATION and RESOLUTION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wframe = 1;         %0 = Shaded model
                    %1 = Wireframe model (default)

fusres = 20;        %Fuselage resolution
wgres  = 20;        %Wing,HT,VT resolution

%%% (DO NOT CHANGE VALUES IN THIS BOX)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
XW=0;ZW=0;ALIW=0;XH=0;ZH=0;ALIH=0;XV=0;ZV=0;YV=0;numVT=1;VERTUP=1;
%%
NX=0;X=zeros(20);S=zeros(20);R=zeros(20);ZU=zeros(20);ZL=zeros(20);
%%
CHRDR_WG=0;CHRDBP_WG=0;CHRDTP_WG=0;SSPN_WG=0;SSPNOP_WG=0;SAVSI_WG=0;
%%
```

```
SAVSO_WG=0;CHSTAT_WG=0;DHDADI_WG=0;DHDADO_WG=0;TC_WG=.12;
%%
CHRDR_HT=0;CHRDBP_HT=0;CHRDTP_HT=0;SSPN_HT=0;SSPNOP_HT=0;SAVSI_HT=0;
%%
SAVSO_HT=0;CHSTAT_HT=0;DHDADI_HT=0;DHDADO_HT=0;TC_HT=.12;
%%
CHRDR_VT=0;CHRDBP_VT=0;CHRDTP_VT=0;SSPN_VT=0;SSPNOP_VT=0;SAVSI_VT=0;
%%
SAVSO_VT=0;CHSTAT_VT=0;TC_VT=.12;
%%
SPANFI_F=0;SPANFO_F=0;CHRDFI_F=0;CHRDFO_F=0;DELTA_F=0;
%%
SPANFI_A=0;SPANFO_A=0;CHRDFI_A=0;CHRDFO_A=0;DELTAL_A=0;DELTAR_A=0;
%%
SPANFI_E=0;SPANFO_E=0;CHRDFI_E=0;CHRDFO_E=0;DELTA_E=0;
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%

%%% INPUT PARAMETERS BELOW
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% SYNTHS parameters

% BODY parameters

% WING parameters (add suffix "_WG" to variables)

% WING FLAPS (add suffix "_F" to variables)

% WING AILERONS (add suffix "_A" to variables)

% HORIZONTAL TAIL parameters (add suffix "_HT" to variables)

% ELEVATOR (add suffix "_E" to variables)

% VERTICAL TAIL parameters (add suffix "_VT" to variables)
% For twin vertical tails, you need to define:
%   numVT - number of vertical tails (for twin VT, should be 2)
%      YV - distance from FRL to stb. VT vertex


%%% PLOTTING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
warning off MATLAB:divideByZero
hold on

plotFuselage(NX,X,S,R,ZU,ZL,fusres)
plotWing(XW,ZW,ALIW,CHRDR_WG,CHRDBP_WG,CHRDTP_WG,SSPN_WG,SSPNOP_WG,SAVS
I_WG,SAVSO_WG,CHSTAT_WG,DHDADI_WG,DHDADO_WG,...

SPANFI_F,SPANFO_F,CHRDFI_F,CHRDFO_F,DELTA_F,SPANFI_A,SPANFO_A,CHRDFI_A,
CHRDFO_A,DELTAL_A,DELTAR_A,TC_WG,wgres)
```

```
plotHT(XH,ZH,ALIH,CHRDR_HT,CHRDBP_HT,CHRDTP_HT,SSPN_HT,SSPNOP_HT,SAVSI_
HT,SAVSO_HT,CHSTAT_HT,DHDADI_HT,DHDADO_HT,...
       SPANFI_E,SPANFO_E,CHRDFI_E,CHRDFO_E,DELTA_E,TC_HT,wgres)

plotVT(XV,YV,ZV,CHRDR_VT,CHRDBP_VT,CHRDTP_VT,SSPN_VT,SSPNOP_VT,SAVSI_VT
,SAVSO_VT,CHSTAT_VT,VERTUP,TC_VT,wgres)
if numVT > 1
    plotVT(XV,-
YV,ZV,CHRDR_VT,CHRDBP_VT,CHRDTP_VT,SSPN_VT,SSPNOP_VT,SAVSI_VT,SAVSO_VT,
CHSTAT_VT,VERTUP,TC_VT,wgres)
end

%%% VIEWPORT/FIGURE PROPERTIES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if wframe == 0
    %colormap([1 .7 .1])      %Set a/c to gold
    colormap([0 0 1])         %Set a/c to blue
    shading interp            %Interpolated shading
    lighting gouraud          %Smooth airplane mesh
    %camlight right           %Apply a light source

    %Custom Lighting Options, Note:[X Y Z]
    light('Position',[1 -2 1],'Style','infinite');
    light('Position',[1 2 1],'Style','infinite');
    light('Position',[0 0 -6],'Style','infinite');
else
    colormap([1 1 1])         %Set a/c to white
end

axis off                      %Turn off axis
axis equal                    %Correct aspect ratio
%camva(4.5)                   %Zoom in a/c to fit figure
view(3)                       %Apply initial viewport rotation
%camproj('perspective')       %Perspective viewing (not R2006a
compatible)
rotate3d  on                  %Rotate icon enabled at start up

%showplottool('plotbrowser')   %Enable the plot browser on startup
set(gcf,'NumberTitle','off','Name','Aircraft Plot','Color',[1 1 1]);
```

## Appendix C Condor Flight Test Cards

### FT-01: *CONDOR Manual Flight Handling Qualities Test Card*

**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. CONDOR pre-flight procedures complete.

**Configuration:**

Base airframe, ½ tank fuel, ~20-lb, R/C only mode

Note: Mission requires a safety pilot (SP), and operator (O). The entire flight will be conducted in RC Mode

**Objective:**

1. Determine aircraft performance under manual RC mode

| **FT-01: PROCEDURES** | Notes: | **Dur:** 30 min |
| --- | --- | --- |

| **FT-01: PROCEDURES** | Notes: **Dur:** 30 min |
|---|---|

**Basic Response**

1. **SP:** Switch to RC Mode
2. **O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”
3. **O:** Perform *Launch Checklist*
4. **SP:** Trim the CONDOR for level flight at 700 ft
5. **O:** Verify the GPS maintains lock
6. **O:** Verify the airspeed and altitude values in the artificial horizon are reasonable values
7. **O:** Verify the roll, pitch, and heading angles shown in the artificial horizon are reasonable. (may need to instruct SP to bank and change heading)
8. **SP:** Vary throttle response from trim to 100%
9. **SP:** Perform left and right rolls, vary from ~10 deg to 60 deg,, vary throttle as needed
10. **SP:** Perform yaw maneuvers, vary from 5 deg to 20 deg, vary throttle as needed
11. **SP:** Perform pitch maneuvers, vary from ± 5 deg to 30 deg, vary throttle as needed
12. **SP:** Perform coordinated flight maneuvers, note response, vary throttle as needed
13. **SP:** Recover CONDOR to trimmed level flight at 700 ft, Record **SP**

**Response:**______________________

evaluation

14. **SP:** Repeat steps 4 – 12 for different altitudes (500, 800, 1000-ft)

**SP Evaluation:**__________________

**<u>Evaluate Stall Characteristics</u>**



15. **O:** Verify the GPS maintains lock
16. **O:** Verify the airspeed and altitude values in the artificial horizon are reasonable values
17. **SP:** Begin steady Backstick pressure **– do not use rudder or flaps**
18. **SP:** Use sufficient aileron to maintain level flight
19. **O:** Note Buffet airspeed
20. **SP:** Continue Backstick until rear stops
21. **O:** Note departure speed and/or other characteristics
22. **SP:** Recover CONDOR to trimmed level flight at 700 ft

| **FT-01: PROCEDURES** | Notes: **Dur:** 30 min |
|---|---|
| 23. **SP:** Land aircraft | |

**FT-02:** ***CONDOR First Flight PID Tuning Test Card***

**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. CONDOR pre-flight procedures complete.

**Configuration:**

Base airframe, ½ tank fuel, 30-lb

Note: Mission requires a safety pilot (SP), and operator (O). The entire flight will be conducted in RC Mode

**Objective:**

2. Trimming the aircraft and finding reasonable values for trim airspeed, trim throttle, and trim angle of attack.

**FT-02: PROCEDURES**

Notes:

**Dur:** 10 min

24. **O:** Disable rate damping PID Loops, navigate to the **F5 Settings page > Autopilot Config > Mode Configuration > RC Mode > PID Loops (Level I Loops)**. Uncheck all rate boxes
25. **SP:** Switch to RC Mode
26. **O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”
27. **O:** Perform *Launch Checklist*
28. **SP:** Trim the CONDOR for level flight
29. **O:** Verify the GPS maintains lock
30. **O:** Verify the airspeed and altitude values in the artificial horizon are reasonable values
31. **O:** Verify the roll, pitch, and heading angles shown in the artificial horizon are reasonable. (may need to instruct SP to bank and change heading)
32. **SP:** Fly an obit (less than 30 degrees of bank) at constant altitude and airspeed
33. **O:** Navigate to the Calibration screen in Virtual Cockpit **F5 Settings page > Calibration**
34. **O:** Click “Request” in the airspeed calibration window. Note the Bias error

## FT-02: PROCEDURES

Notes: **Dur:** 10 min

35. **O:** Click “start calibration”
36. **O:** Click “stop calibration”
37. **O:** Note the correction factor

**Bias Error:** ________.
This value is a wind corrected airspeed bias in m/s. If this value is above 1, you should calibrate the airspeed.

91

**Correction Factor:** ___________

This is the amount the autopilot scales the differential pressure before converting to airspeed. If this value is 1, there is very little cabin pressurization or other effect that cause airspeed bias errors. If this value is significant (less than .75 or greater than 2) then there are some cabin pressurization issues.

38. **O:** Click Accept (autopilot will use the new correction factor).
39. **SP:** Continues to fly orbit
40. **O:** Periodically click request and note the new bias error

**Bias Error 1 _______**

**Bias Error 2 _______**

**Bias Error 3**________

41. **SP:** Fly aircraft level at constant altitude and airspeed
42. **O:** Go to the PID screen in Virtual Cockpit **F5 Settings page > PID Values** and note the average airspeed, average pitch angle

Bias error should drop to below one.
If after several orbits the bias error is still above one, repeat the calibration procedure beginning at step 12.



43. **O:** Go to the servos screen in Virtual Cockpit **F5 Settings page > Servos**
44. **O:** In the Servo Travel window click the "Send/Req" a few times and note the average throttle position in %

**Average Airspeed** _________ (Use as Trim Airspeed and Cruise Airspeed)

**Average Pitch Angle** ________ (Use as Trim Angle of Attack)

45. **SP:** Land the aircraft manually. **Keep the airplane powered on**.

Notes: **Dur:** 10 min

46. **O:** Navigate to the Autopilot Config screen (under **Feed Forward and Trims**) and enter the Trim Airspeed, Trim Throttle, and Trim Angle of Attack [the trim angle of attack needs to be converted to radians (degree value / 57.3)]
47. **O:** Enter Cruise Airspeed (under **Mode Configuration > Common**)

**Average Throttle %** ________ (Use as Trim Throttle)

48. **O:** Click "Upload Config"
49. **O:** Navigate to the servos screen and click "Upload Trims"
50. **O:** Click "Request Bias"
51. **SP:** Manually re-zero the trim tabs on the RC controller

Trim and cruise airspeed should be the same value. After gain tuning, you may desire to adjust the cruise airspeed for different conditions. The trim airspeed should not be changed as this value is used for gain scaling and a change will require re-tuning the gains.

Typically the trim angle is between 0 and .1 radians

52. **O:** Click "0 Sticks"
53. **O:** Click "Update Flash"
54. **O:** Turn off CONDOR

**FT-02: PROCEDURES**

Notes: **Dur:** 10 min

The values from the Commbox column are added to the biases because the trims are now stored on the autopilot.

**FT-03: *CONDOR Open-Loop Maneuvers Test Card***

**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. CONDOR pre-flight procedures complete.



**Configuration:**

Base airframe, ½ tank fuel, 30-lb

Note: Mission requires a safety pilot (SP), and operator (O). The entire flight will be conducted in RC Mode

**Objective:**

3. Determine response to manual inputs in order to validate open-loop model

**FT-03: PROCEDURES** | Notes: | **Dur:** 30 min

**Pitch Response**

55. **O:** Navigate to **Settings** > **Data Logs,** select desired **Pitch** parameters for recording. Ensure data logger in Virtual Cockpit is properly configured for data acquisition
56. **SP:** Switch to RC Mode
57. **O:** Verify RC Mode (control boxes grayed out) and in "**Manual Mode**"
58. **O:** Perform *Launch Checklist*
59. **SP:** Trim the CONDOR for level flight at 700 ft
60. **O:** Verify the GPS maintains lock
61. **O:** Verify the airspeed and altitude values in the artificial horizon are reasonable values
62. **O:** Verify the roll, pitch, and heading angles shown in the artificial horizon are reasonable. (may need to instruct SP to bank and change heading)
63. **O:** Navigate to the **Settings > Autopilot Config** screen (under **Trims, Slews, and Feed Forward**) and observe enter the **Trim Airspeed**, **Trim Throttle**, and **Trim Angle of Attack (Pitch)** [the trim angle of attack needs to be converted to radians (degree value / 57.3)]
64. **O:** Record maneuver start time, start data logging
65. **SP:** Perform pitch doublet
66. **SP:** Recover CONDOR to trimmed level flight at 700 ft

Notes:

**Trim Airspeed: ________________**

67. **O:** Observe AoA/Pitch response, save m-file

**Trim Throttle:** _______________

**Trim AoA:**_______________

**<u>Determine Dutch Roll Natural Frequency</u>**

**<u>Determine Dutch Roll Damping Factor</u>**

**Time:**________



68. **O:** Navigate to **Settings** > **Data Logs,** select desired **Roll & Yaw** parameters for recording. Ensure data logger in Virtual Cockpit is properly configured for data acquisition
69. **O:** Verify the GPS maintains lock
70. **O:** Verify the airspeed and altitude values in the artificial horizon are reasonable values
71. **SP:** Perform rudder doublet – right then left to the stops
72. **SP:** Recover CONDOR to trimmed level flight at 700 ft
73. **O:** Observe the number of overshoots in Virtual Cockpit display
74. **O:** Record time between peaks

**<u>Determine Spiral Mode Response</u>**

75. **O:** Verify the GPS maintains lock
76. **O:** Verify the airspeed and altitude values in the artificial horizon are reasonable values
77. **SP:** Roll to 10 degrees **Left** bank

97 78. **O:** Record maneuver start time

79. **SP:** Release controls and allow deviation to occur
80. **SP:** Recover aircraft at either 40kts, 60 degree bank, or 15 seconds after start
81. **SP:** Recover CONDOR to trimmed level flight at 700 ft
82. **O:** Record time to recovery

83. **SP:** Roll to 10 degrees **Right** bank
84. **O:** Record maneuver start time
85. **SP:** Release controls and allow deviation to occur
86. **SP:** Recover aircraft at either 40kts, 60 degree bank, or 15 seconds after

**Number of Overshoots:________**

**Time between Peaks:________**

**Time:________**

**Time to Recovery or Time to Double**

**(left):________**

**Time:________**

**Time to Recovery or Time to Double**

| **FT-03: PROCEDURES** | Notes: **Dur:** 30 min |
|---|---|
| start | **(right):**________ |
| 87. **SP:** Recover CONDOR to trimmed level flight at 700 ft | |
| 88. **O:** Record time to recovery | |

**FT-04:** ***CONDOR Second Flight PID Tuning Test Card***

**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. FT-01: CONDOR First Flight PID Tuning Test Card complete.

**Configuration:**

Base airframe, ½ tank fuel, 30-lb

Note: Mission requires a safety pilot (SP), and operator (O).

**Objective:**

1. The purpose of the second flight is to tune the rate damping servo loops. The rate damping PID loops damp the aircraft rotation around the pitch, roll, and yaw axis.

| **FT-04: PROCEDURES** | Notes: **Dur:** 20 min |
|---|---|
| **Tuning Yaw Rate PID loop (Rudder only) Yaw Rate Kp** | |
| 89. **O:** Disable rate damping PID Loops, navigate to the **F5 Settings page > Autopilot Config > Mode Configuration > RC Mode > PID Loops (Level I Loops)**. Uncheck all rate boxes | |
| 90. **SP:** Switch to RC Mode | |
| 91. **O:** Verify RC Mode (control boxes grayed out) and in "Manual Mode" | |
| 92. **O:** Perform *Launch Checklist* | |
| 93. **SP:** Re-trim the CONDOR for level flight (if necessary) | |
| 94. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1 | |
| 95. **O:** Navigate to **(F5) Settings > PID Values** screen. **Enter .005 for Yaw Rate Kp**. | **Trim Airspeed from Flight #1: ___________** |
| 96. **O:** Click the "Use Desired" check box under Tuning | For most aircraft this value is between .005 and .2. This number is in radians of rudder deflection per radian second of yaw rate error. |
| 97. **O:** Enter zero for the desired roll angle. The desired turn rate should also | |

be zero

98. **O:** Check “Yaw Rate” under Level 1 Loops and ensure all other loops are unchecked

99. **O:** Click “Upload loops”

100. **SP:** Disable RC Mode

The autopilot is now setup such that when the pilot disables RC Mode, the Yaw Rate loop will be active
Safety Pilot is still flying the aircraft

100 101. **O:** Verify UAV Modes are not “grayed out” and Manual mode is green

102. **O:** Tune the Yaw Rate loop by increasing **Yaw Rate Kp** slowly **(.05 increments)** Increase the value of Yaw Rate Kp until small instabilities are noted in yaw and then lower the value by 25% (instabilities should go away). Record the Yaw Rate Kp Value.

As Kp is increased, the aircraft should feel more damped around the yaw axis. Use pilot feedback to verify that the aircraft is becoming more damped around the yaw axis.
**Yaw Rate Kp:** ___________

The desired turn rate that corresponds to a 15 degree roll will be indicated in the Desired Turn Rate Box

103. **O:** Enter a desired roll angle of **15 degrees** in the desired roll angle box

**Actual Roll Rate:** ______________
The roll angle does not have to track perfectly at this point. The roll angle controller will be tuned in flight 3 to improve the roll angle hold.

**FT-04: PROCEDURES**

Notes: **Dur:** 20 min

104. **O:** Verify by observing the HSI that the aircraft actual roll angle is between 10 and 20 degrees. Aircraft should be turning right. Record the actual roll rate.

You may try a higher bank angle if desired.

101

105. **O:** Command a 15 degree left bank **(enter -15 in the desired roll angle box)**. Verify the aircraft turns left on the HSI.

106. **O:** Command **0 degrees** bank to return the aircraft to level flight

107. **O:** Save the gains values to file with an incremented file name

For most aircraft this value is between .005 and .2. This number is in radians of rudder deflection per radian second of roll rate error.

**Tuning Roll Rate PID loop (Roll Rate Kp)**

102 108. **SP:** Switch to RC mode

109. **O:** Verify RC Mode (control boxes grayed out) and in "**Manual Mode**"

110. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1

111. **O:** Check "**Roll Rate**" and un-check "**Yaw Rate**" under Level 1 Loops and ensure all other loops are unchecked

112. **O:** Click "**Upload loops**"

113. **O:** Navigate to **(F5) Settings > PID Values** screen. **Enter .005 for Roll Rate Kp**.

As Kp is increased, the aircraft should feel more damped around the roll axis. Use pilot feedback to verify that the aircraft is becoming more damped around the roll axis.
**Roll Rate Kp:** ___________

For most aircraft this value is between .005 and .2. This number is in radians of elevator deflection per radian second of pitch rate error.

114. **SP:** Disable RC Mode

115. **O:** Verify UAV Modes are not "grayed out" and Manual mode is green

116. **O:** Tune the Roll Rate loop by increasing **Roll Rate Kp** slowly **(.05 increments)** Increase the value of Roll Rate Kp until small instabilities are noted in roll and then lower the value by 25% (instabilities should go away). Record the Roll Rate Kp Value.

As Kp is increased, the aircraft should feel more damped around the pitch axis. Use pilot feedback to verify that the aircraft is becoming more damped around the pitch axis.
**Pitch Rate Kp:** ___________

117. Save the gains values to file with an incremented file name

**Tuning Pitch Rate PID loop (Pitch Rate Kp)**

104 118. **SP:** Switch to RC mode

119. **O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”

120. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1

121. **O:** Check “Pitch Rate, Roll Rate , and Yaw Rate” under Level 1 Loops and ensure all other loops are unchecked

122. **O:** Click “Upload loops”

123. **O:** Navigate to **(F5) Settings > PID Values** screen. **Enter .005 for Pitch Rate Kp**.

**FT-04: PROCEDURES** | Notes: | **Dur:** 20 min

124. **SP:** Disable RC Mode

125. **O:** Verify UAV Modes are not “grayed out” and Manual mode is green

126. **O:** Tune the Pitch Rate loop by increasing **Pitch Rate Kp** slowly **(.05 increments)** Increase the value of Pitch Rate Kp until small instabilities are noted in pitch and then lower the value by 25% (instabilities should go away). Record the Pitch Rate Kp Value.



127. Save the gains values to file with an incremented file name

128. Land the CONDOR **leaving power “ON”**

129. **O:** “Update Flash”

130. **O:** Navigate to the **Autopilot Config > Mode Config > RC Mode** in Virtual Cockpit.

131. **O:** Check the PID Level 1 Loops for pitch rate, roll rate, and yaw rate.

132. **O:** Click “**Upload Config**”

| **FT-04: PROCEDURES** | Notes: **Dur:** 20 min |
|---|---|
| 133. **O:** Click "**Update Flash**"<br>134. **O:** Save the gains values to file with an incremented file name<br>135. | |

106

| **Card No.** | **FT-04a** |
|---|---|
| **Description** | **CONDOR Inner Loop PID Tuning – Yaw Rate** |
| **Objective** | **Tune yaw rate damping servo loop.** |
| | |
| | |

| Level 3 Loops | Level 2 Loops | Level 1 Loops |
|---|---|---|
| ☒ Hdg Fixed<br>☐ Dynamic-Waypoint | ☒ Roll Fixed Input<br>☐ Roll Dyn. Input<br>☐Heading | ☐ Roll<br>☐ Roll Rate<br>☐ Pitch<br>☐ Pitch Rate<br>☒ Yaw Rate |
| Tuning | ☒ Pitch Fixed Input<br>☐ Pitch Dyn. Input<br>☐ Altitude<br>☐ Airspeed | ☒ Thr->Airspd<br>☐ Thr->Alt<br>☐ Thr->Climb/Alt |
| ☒ Use Desired | | |

| **FT-04a: PROCEDURES** | Notes: **Dur:** 20 min |
|---|---|

**FT-04a: PROCEDURES**

Notes:

**Dur:** 20 min

**Tuning Yaw Rate PID loop (Rudder only) Yaw Rate Kp**

1. **SP:** Switch to **RC** Mode
2. **O:** Verify RC Mode (control boxes grayed out) and in "**Manual Mode**"
3. **O:** Perform *Launch Checklist*
4. **SP:** Re-trim the CONDOR for level flight (if necessary)
5. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1
6. **O:** Navigate to **(F5) Settings > PID Values** screen. **Enter .005 for Yaw Rate Kp**.

**Trim Airspeed from Flight #1: ___________**

7. **O:** Enter **zero** for the desired roll angle. The desired turn rate should also be zero

For most aircraft this value is between .005 and .2. This number is in radians of rudder deflection per radian second of yaw rate error.

8. **O:** Click "**Upload loops"**
9. **SP:** Disable **RC** Mode

The autopilot is now setup such that when the pilot disables RC Mode, the Yaw Rate loop will be active

10. **O:** Verify UAV Modes are not "grayed out" and Manual mode is green

Safety Pilot is still flying the aircraft

11. **O:** Tune the Yaw Rate loop by increasing **Yaw Rate Kp** slowly **(.05 increments)** Increase the value of Yaw Rate Kp

**FT-04a: PROCEDURES**

until small instabilities are noted in yaw and then lower the value by 25% (instabilities should go away). Record the Yaw Rate Kp Value.

12. **O:** Enter a desired roll angle of **15 degrees** in the desired roll angle box

13. **O:** Verify by observing the HSI that the aircraft actual roll angle is between 10 and 20 degrees. Aircraft should be turning right. Record the actual roll rate.

14. **O:** Command a 15 degree left bank **(enter -15 in the desired roll angle box)**. Verify the aircraft turns left on the HSI.

15. **O:** Command **0 degrees** bank to return the aircraft to level flight

16. **O:** Save the gains values to file with an incremented file name

Notes: **Dur:** 20 min

As Kp is increased, the aircraft should feel more damped around the yaw axis. Use pilot feedback to verify that the aircraft is becoming more damped around the yaw axis.

**Yaw Rate Kp:** ___________

The desired turn rate that corresponds to a 15 degree roll will be indicated in the Desired Turn Rate Box

**Actual Roll Rate:** ______________

The roll angle does not have to track perfectly at this point. The roll angle controller will be tuned in flight 3 to improve the roll angle hold.

You may try a higher bank angle if desired.

109 **Tuning Roll Rate PID loop (Roll Rate Kp)**

17. **SP:** Switch to RC mode
18. **O:** Verify RC Mode (control boxes grayed out) and in "Manual Mode"
19. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1
20. **O:** Check "Roll Rate" and un-check "Yaw Rate" under Level 1 Loops and ensure all other loops are unchecked
21. **O:** Click "Upload loops"
22. **O:** Navigate to **(F5) Settings > PID Values** screen. **Enter .005 for Roll Rate Kp**.

For most aircraft this value is between .005 and .2. This number is in radians of rudder deflection per radian second of roll rate error.

As Kp is increased, the aircraft should feel more damped around the roll axis. Use pilot feedback to verify that the aircraft is becoming more damped around the roll axis.

**Roll Rate Kp:** ___________

**FT-04a: PROCEDURES**

23. **SP:** Disable RC Mode
24. **O:** Verify UAV Modes are not "grayed out" and Manual mode is green
25. **O:** Tune the Roll Rate loop by increasing **Roll Rate Kp**
110 slowly **(.05 increments?)** Increase the value of Roll Rate Kp until small instabilities are noted in roll and then lower the value by 25% (instabilities should go away). Record the Roll Rate Kp Value.
26. Save the gains values to file with an incremented file name

Notes: **Dur:** 20 min

For most aircraft this value is between .005 and .2. This number is in radians of elevator deflection per radian second of pitch rate error.

As Kp is increased, the aircraft should feel more damped around the pitch axis. Use pilot feedback to verify that the aircraft is becoming more damped around the pitch axis.

**Pitch Rate Kp:** ___________

111

**Tuning Pitch Rate PID loop (Pitch Rate Kp)**

27. **SP:** Switch to RC mode
28. **O:** Verify RC Mode (control boxes grayed out) and in "Manual Mode"
29. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1
30. **O:** Check "Pitch Rate, Roll Rate , and Yaw Rate" under Level 1 Loops and ensure all other loops are unchecked
31. **O:** Click "Upload loops"
32. **O:** Navigate to **(F5) Settings > PID Values** screen. **Enter**

**.005 for Pitch Rate Kp**.

33. **SP:** Disable RC Mode
34. **O:** Verify UAV Modes are not "grayed out" and Manual mode is green
35. **O:** Tune the Pitch Rate loop by increasing **Pitch Rate Kp** slowly **(.05 increments?)** Increase the value of Pitch Rate Kp until small instabilities are noted in pitch and then lower the value by 25% (instabilities should go away). Record the Pitch Rate Kp Value.

36. Save the gains values to file with an incremented file name
37. Land the CONDOR **leaving power "ON"**
38. **O:** "Update Flash"
39. **O:** Navigate to the **Autopilot Config > Mode Config > RC**

| **FT-04a: PROCEDURES** | Notes: **Dur:** 20 min |
|---|---|
| **Mode** in Virtual Cockpit.<br>40. **O:** Check the PID Level 1 Loops for pitch rate, roll rate, and yaw rate.<br>41. **O:** Click "Upload Config"<br>42. **O:** Click "Update Flash"<br>43. **O:** Save the gains values to file with an incremented file name | |

113

**FT-05:** ***CONDOR Third Flight PID Tuning Test Card***

**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. FT-01: CONDOR First Flight PID Tuning Test Card and FT-02: CONDOR Second Flight PID Tuning Test Card complete. PID gains loaded from FT-02.

**Configuration:**

Base airframe, ½ tank fuel,  30-lb

Note:  Mission requires a safety pilot (SP), and operator (O).

**Objective:**

1. The purpose of the third flight is to tune the inner attitude hold loops and the outer airspeed and altitude hold PID loops.

| **FT-05  PROCEDURES** | Notes: **Dur:** 30 min |
|---|---|
| **Tuning Roll PID loop (Roll Kp)** | |

**1. SP:** Switch to RC Mode

**2. O:** Verify RC Mode (control boxes grayed out) and in "Manual Mode"

**3. O:** Perform *Launch Checklist* (skip step 17 in launch checklist)

**4. SP:** Re-trim the CONDOR for level flight (if necessary)

**5. SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1

**6. O:** Navigate to **(F5) Settings > PID Values** screen. **Enter zero for Roll Ki** and **enter .01 for Roll Kp.**

**Trim Airspeed from Flight #1:** ___________

| FT-05 PROCEDURES | Notes: **Dur:** 30 min |
|---|---|
| **7. O:** Click the “Use Desired” check box under Tuning | For most aircraft this value is between .01 and 1. This number is in radians of rudder deflection per radian roll angle error. |
| **8. O:** Enter zero for the desired roll angle. The desired yaw rate should also be zero. | |
| **9. O:** Check “Yaw Rate and Roll” under Level 1 Loops and ensure all other loops are unchecked | |
| **10. O:** Click “Upload loops” | |
| **11. SP:** Disable RC Mode | |
| **12. O:** Verify UAV Modes are not “grayed out” and Manual mode is green | The autopilot is now setup such that when the pilot disables RC Mode, the Yaw Rate and Roll loops will be active |
| **13. O:** Tune the Roll PID loop by **increasing Roll Kp slowly (.2 increments?)**. As Kp is increased, the aircraft should increasingly level itself in the roll axis. After each Roll Kp change, instruct the pilot to disturb the aircraft in the roll axis by giving rudder input. The aircraft should fight the pilot and return to level immediately when the roll stick is released. If this is the case, the roll loop is tuned ok. Record Roll Kp value. | Safety Pilot is still flying the aircraft |
| **14. O:** Enter a desired roll angle of **15 degrees** in the desired roll angle box | **Roll Kp:** ___________ |
| **15. O:** Verify by observing the HSI that the aircraft actual roll angle is close to 15 degrees. | You should see the desired turn rate ramp up to the yaw rate corresponding to a 15 degree roll angle at the current airspeed |
| **16. O:** Command a 15 degree left bank **(enter -15 in the desired roll angle box)**. Verify the aircraft turns left on the HIS | You may try a higher bank angle if desired. |

## FT-05 PROCEDURES

Notes: **Dur:** 30 min

17. **O:** Command **0 degrees** bank to return the aircraft to level flight
18. **O:** If instabilities were noticed in roll then reduce the Roll Kp gain by 25% and repeat step 14 – 17 until instabilities have reduced.

It is more important to have an aircraft that responds slowly than to have instabilities.

Since there is still more gain tuning to do, keep the Roll Ki at zero for now. Some steady state error in roll is acceptable. You can tune the roll Ki later when pilot-in-the-loop inputs are no longer needed.

19. Save the gains values to file with an incremented file name.



For most aircraft this value is between .01 and 1

## Tuning Pitch PID loop (Pitch Kp)

20. **SP:** Switch to RC mode

**FT-05 PROCEDURES** | Notes: | **Dur:** 30 min

21. **O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”
22. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1
23. **O:** Navigate to **(F5) Settings > PID Values** screen and enter **zero for Pitch Ki** and **.01 for Pitch Kp**

**Observed average pitch angle:** ____________
If the desired pitch angle is immediately overwritten, re-check that Level 2, “Pitch Fixed input” is clicked



24. **O:** Click the “Use Desired” check box under Tuning
25. **O:** In the PID loop window under Level 2 Loops ensure Pitch Cmd is “Pitch Fixed Input."
26. **O:** Enable or Check-on all Level 1 Loops (Roll, Roll Rate, Pitch, Pitch Rate, and Yaw Rate)
27. **O:** Click “Upload Loops”
28. **O:** Observe the current average pitch angle (level flight pitch angle) on the HSI. Enter this value for the desired pitch and record the value.

If during the tuning procedure the aircraft is losing altitude, increase the desired pitch, or have the pilot take over and climb the aircraft to a safe altitude.

The aircraft should respond in a timely fashion to desired pitch commands without showing signs of instabilities. It is more important to have an aircraft that responds slowly than to have instabilities.

**Pitch Kp:** ___________

29. **SP:** Disable RC Mode
30. **O:** Verify UAV Modes are not "grayed out" and Manual mode is green
31. **O:** Tune the pitch PID loop by increasing **Pitch Kp** slowly **(.05 increments?)** As Kp is increased, the aircraft should increasingly level itself in the Pitch axis. After each Pitch Kp change, instruct the pilot to disturb the aircraft in the pitch axis by giving elevator input. The aircraft should fight the pilot and return to level immediately when the elevator stick is released.



Because this is an outer PID loop that is governed by standard aircraft dynamics, little tuning may be required. The units of this loop are radians of desired pitch per m/s of airspeed error.

32. **O:** If instabilities were noticed in the pitch axis then reduce the Pitch Kp gain by 25% and continue to observe pilot disruption for instabilities. Repeat 25% decrease until instabilities have reduced. Record Pitch Kp

The autopilot is now setup such that when the pilot disables RC Mode, Manual Mode will be active.

**33. O**: Enter a variety of pitch angles for desired pitch. Ensure the aircraft responds accordingly. If not repeat steps 31 and 32

**34. O:** At this point, the user may choose to add a little bit of Pitch Ki gain. This will aid in tracking at larger pitch angles. The down side is that the integrator will fight the pilot inputs. If Ki is added, instruct the pilot to keep the elevator stick neutral while the Pitch loop is enabled.

**35. O:** Save the gains values to file with an incremented file name

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**Tuning Pitch from Airspeed PID loop (Pitch<-airspeed Kp)**

**36. SP:** Switch to RC mode

**37. O:** Verify RC Mode (control boxes grayed out) and in "Manual Mode"

**38. SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1

**39. O:** Navigate to **(F5) Settings > PID Values** screen and enter **zero for Pitch Ki** and **.02 for Pitch<-Airspeed Kp**

**40. O:** Click the "Use Desired" check box under Tuning

41. **O:** Enable all tuned loops at this time. Enable Level 2 Pitch from Airspeed Loop (Ensure "Pitch Dyn Input" is visible. If it isn't, click "Pitch Fixed Input" once. Under "Pitch Dyn Input", select "Airspeed" and ensure that

Typically Kp for this loop does not exceed 0.1

**Pitch<-airspeed Kp: _______________**

Ki for this loop is typically around ½ the value of Kp.

At this point, Manual Mode is tuned.

"Auto Alt" is unchecked.

**42. O:** Click "Upload Loops"

**43. SP:** Disable RC Mode

**44. O:** Verify UAV Modes are not "grayed out" and Manual mode is green

**45. O:** Increase the Pitch<-airspeed Kp until slow oscillation in pitch is noticed. Reduce the Kp gain by 25% or until oscillations are no longer present. Not the value of Pitch<-airspeed Kp.

This loop is used to maintain airspeed while in level flight. Because this is an outer PID loop that is governed by standard aircraft dynamics, little tuning may be required. The units of this loop are percent throttle per m/s of airspeed error.

In addition to the Kp and Ki values, the user may wish to tune the throttle slew rate limit and throttle->velocity feed forward value. The slew rate is the maximum rate of change of throttle that can be commanded by the throttle PID loops. This value is in percent/second. It is typically between 10 and 35. This value prevents the autopilot from changing the throttle setting too quickly.

**46. O:** Now, with Kp tuned, slowly increase Ki.

**47. SP:** Increase the throttle and verify the aircraft pitches up to decrease the airspeed. Decrease the throttle and verify the aircraft pitches down to maintain the desired airspeed.

**48. O:** Enter a higher airspeed for the desired airspeed. Verify the aircraft responds and tracks.

**49. O:** If the aircraft is sluggish to respond to changes in desired airspeed, you may wish to increase the magnitude of the Pitch->Velocity Feed Forward

Gain value found under **Autopilot Config > Feed Forward and Trims > Pitch**.

**50.** Save the gains values to file with an incremented file name.

This throttle value is coming from the RC controller (it is the throttle that the pilot is currently commanding to maintain level flight).

**Tuning Throttle from Airspeed PID loop (Throttle-<airspeed Kp)**

The autopilot is now setup such that when the pilot disables RC Mode, the autopilot will hold zero roll angle and maintain airspeed using the throttle.

The pilot will be responsible for keeping pitch near level and holding altitude.

**FT-05 PROCEDURES**

51. **SP:** Switch to RC mode

52. **O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”

53. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1

Notes: **Dur:** 30 min

**Throttle-<airspeed Kp:__________**

The Throttle from Altitude loop is used for transition the aircraft to different altitudes. Once the desired altitude is reached, the autopilot will switch to controlling altitude with pitch. Because of this, do not expect perfect altitude hold during this procedure. You will likely encounter a phugoid behavior in level flight. This behavior is characterized by a shallow dive with an increase airspeed followed by climbing with decreased airspeed. This behavior will be cleaned up with the Pitch from Altitude Loop.

**54. O:** Double check the trim throttle setting. With the aircraft flying level in RC Mode, navigate to the Servos window in Virtual Cockpit. Click "Send/Req" in the Desired Servo Position window. The current throttle servo position can be read in the Des Servo Position column. Verify this value is similar to the value entered previously in F-CONDOR-01 seep #21 as the Throttle Trim. This can also be found in **Autopilot Config > Feed Forward and Trims > Throttle > Trim Throttle**

The autopilot is now setup such that when the pilot disables RC Mode, the autopilot will hold zero roll angle and maintain airspeed pitch. The altitude will be maintained using throttle.



**55. O:** In the PID Values window enter a value near **10 for Throttle<-Airspd Kp**. Set **Throttle<-Airspd Ki=0**

**56. O:** Click the "Use Desired" check box under Tuning

**57. O:** Pre-select Manual Mode by clicking "Man" in the UAV Modes window (Click "Man" again even if already selected)

The tracking does not have to be perfect as this loop is only used for transitioning to different altitude. The PID loop responsible for holding altitude will be tuned next.

**Throttle<-Altitude Kp: ___________**

**58. O:** Select "Pitch fixed input" in level 2 pitch. Disable Pitch in Level 1

**59. O:** Select Thr->Airspeed Level 1 Loop and Leave all other loops as they were for Manual Mode.



**60. SP:** Disable RC Mode

***As soon as the autopilot can reasonably control the aircraft (i.e. hold altitude and navigate to home or rally), enable the Loss of Comm failsafe****. Disable the Flight Termination failsafe unless it is required for safety or local regulation.*

**61. O:** Verify Manual Mode should show green on the UAV Mode indicator.

**62. O:** Verify the following PID loops are enabled and that the Upload Loops button is not red:

a. Level 1 Roll, Roll Rate, Pitch Rate, Thr->Airspd and Yaw Rate (

b. Level 2: Roll Fixed input, Pitch Fixed input.

At this point, the Pitch, Roll, Pitch<-Airspeed, Throttle<-Airspeed, Throttle <-Altitude, and all rate damping loops should be tuned. It is now time to move to the Pitch from Altitude PID loop. Because this is an outer PID loop that is governed by standard aircraft dynamics, little tuning may be required. The units of this loop are radians of desired pitch per meter of altitude error. This loop is a little tricky as the pitch<-

**63. O:** If the aircraft is trimmed is should maintain near level flight at cruise speed using the trim throttle value entered in **Autopilot Config > Feed**

**Forward and Trims > Throttle**. Verify level flight at cruise speed.

**64. O:** Tune Throttle-<airspeed Kp such that the aircraft tracks desired airspeed. Record value to the right.

**65. O:** If the throttle seems to over modulate decrease the throttle slew rate. This is found in **Autopilot Config > Feed Forward and Trims > Throttle > Slew Rate**.

**66. O:** As the pilot pitches up, the throttle should increase to track airspeed. As the pilot pitches down the throttle should reduce. Try commanding different airspeeds and verify the UAV tracks the desired airspeed.

**67. O:** It may be desirable to add some integral gain to compensate for reduced thrust as the batteries run down. Try adding between .1 and 1 for Throttle<-Airspd Ki.

**68. O:** Save the gains values to file with an incremented file name.

**Tuning Throttle form Altitude PID loop (Throttle<-Altitude Kp)**

altitude limit also needs to be tuned. If the limit is too high, this loop may command a pitch that will stall the aircraft. If it is too low, the aircraft will not be able to maintain altitude.

The autopilot is now setup such that when the pilot disables RC Mode, the aircraft will hold altitude with pitch and airspeed with throttle.

**FT-05 PROCEDURES**

126 **69. SP:** Switch to RC mode

**70. O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”

**71. SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1

**72. O:** Enter a value of **1.5 for Throttle<-Altitude Kp. Set Throttle<-Altitude Ki=0**

**73. O:** Click the “Use Desired” check box under Tuning

**74. O:** Pre-select Manual Mode by clicking “Man” in the UAV Modes window (Click “Man” again even if already selected)

**75. O:** Select Thr->Altitude Level 1 Loop. Leave all other loops as they were for Manual Mode.

Notes: **Dur:** 30 min

It may be helpful to look at onboard video for this purpose. Typically Kp for this loop does not exceed 1.

**Pitch<-Altitude Kp:** _______________

During the tuning process keep an eye on the desired pitch. If the aircraft is below the desired altitude and the desired pitch is pegged with the aircraft still descending, then the pitch<-altitude limit needs to be increased to allow the altitude loop to command a higher pitch angle.

**Pitch<-Altitude Ki:** _______________

Larger increments may not be necessary as the altitude tracker is designed to handle those with constant airspeed climbs and descents.

**76. O:** Enter the current indicated altitude for the desired altitude.

**77. SP:** Disable RC Mode

**78. O:** Verify Manual Mode should show green on the UAV Mode indicator.

If all went well and per the instructions, then Altitude Mode is tuned.

**79. O:** If the aircraft is trimmed it should maintain near level flight at cruise speed using the trim throttle value entered in **Autopilot Config > Feed Forward and Trims > Throttle**.

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**80. O:** Tune Throttle<-Altitude Kp such that the aircraft tracks the desired altitude. Note the final Throttle<-Altitude Kp value to the right

Ensure all PID gains and flash values have been written to file and also all changes have saved in an appropriately named file. (You don' t want all your work during Flight 3 to be lost!)

***As soon as the autopilot can reasonably control the aircraft (i.e. hold altitude and navigate to home or rally), enable the Loss of Comm failsafe****. Disable the Flight Termination failsafe unless it is required for safety or local regulation.*

**81. O:** If the throttle seems to over modulate decrease the throttle slew rate. This is found in **Autopilot Config > Feed Forward and Trims > Throttle > Slew Rate**.

**FT-05 PROCEDURES**

Notes:

**Dur:** 30 min

82. **O:** With the aircraft holding altitude reasonably well (a small phuguoid is ok at this point). Command the aircraft to a higher altitude (maybe 30 meters up). The throttle should increase and the aircraft should climb to the new altitude. Adjust the Throttle<-Altitude Kp so that this occurs. \

83. **O:** Next try commanding the aircraft to a lower altitude.

84. **O:** It may be desirable to add some integral gain to compensate for reduced thrust as the batteries run down. Try adding between .1 and 1 for Throttle<-Altitude Ki.

85. **O:** Stop tuning when you are confident that the aircraft can reliably transition to different altitudes using the throttle.

86. **O:** Save the gains values to file with an incremented file name.

**FT-05 PROCEDURES** | Notes: | **Dur:** 30 min

**Tuning Pitch from Altitude PID loop (Pitch<-Altitude Kp)**

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**87. SP:** Switch to RC mode

**88. O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”

**89. SP:** Maintain altitude and keep the airspeed near the trim airspeed found in Flight 1

**90. O:** Enter a number around .04 as a starting place for Pitch<-Altitude Kp. Start with Ki=0.

**91. O:** Click the “Use Desired” check box under Tuning

**FT-05 PROCEDURES**

Notes:

**Dur:** 30 min

**92. O:** Pre-select Manual Mode by clicking “Man” in the UAV Modes window (Click “Man” again even if already selected)

**93. O:** Select Thr->Airspd level 1 loop. Ensure Level 2 “Pitch Dyn Input” button is visible and select Altitude. Ensure “Auto Alt” is unchecked.

**94. O:** Click “Upload Loops”

**95. O:** Enter the current altitude for the desired altitude.

**96. SP:** Disable RC Mode

**97. O:** Verify Manual Mode should show green on the UAV Mode indicator

**FT-05 PROCEDURES** | Notes: | **Dur:** 30 min

**98. O:** Verify the aircraft should hold altitude, airspeed, and level roll

**99. O:** Increase the Pitch<-Altitude Kp until an oscillation in pitch is noticed. Reduce the Kp gain by 25% or until oscillations are no longer noticed. Record Pitch<-Altitude Kp to the right.

131 **100. O:** Now, with Kp tuned, slowly increase Ki. Ki should be small on this loop (< 1/15 of Kp) to prevent integrator windup for large altitude errors. Record Pitch<-Altitude Ki to the right.

| **FT-05 PROCEDURES** | Notes: **Dur:** 30 min |
|---|---|
| **101.** **O:** Once it seems that the aircraft is holding the current desired altitude, change the desired altitude by increments of 5 meters. Verify the aircraft tracks the new desired altitude.<br>**102.** **O:** Once the aircraft is responding well to small increments in desired altitude, try bigger increments (5 to 20 meters).<br>**103.** **O:** Once the altitude loop is sufficiently tuned, you may test Altitude Mode.<br>**104.** **O:** Click Altitude Mode and verify that the aircraft holds altitude and airspeed (current alt, cruise airspeed).<br>**105.** **O:** Enter a desired altitude 20 meters higher than the current altitude. Verify the Altitude Tracker goes to Climb Mode (Artificial Horizon).<br>**106.** **O:** Once the desired altitude is reached, the Altitude Tracker should go to Hold Mode.<br>**107.** **O:** Enter a desired altitude 20 meters below the current altitude. | |

| FT-05 PROCEDURES | Notes: **Dur:** 30 min |
|---|---|
| The altitude tracker should respond with Auto Descent then Altitude hold.<br><br>**108.** **O:** Save the gains values to file with an incremented file name.<br>109. **SP:** Land the aircraft in RC Mode. **Do not turn the autopilot off** | |

**FT-06:** ***CONDOR Fourth Flight PID Tuning Test Card***



**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. FT-01: CONDOR First Flight PID Tuning Test Card complete, FT-02: CONDOR Second Flight PID Tuning Test Card complete, and FT-03: CONDOR Third Flight PID Tuning Test Card complete.

**Configuration:**

Base airframe, ½ tank fuel, 30-lb

Note: Mission requires a safety pilot (SP), and operator (O).

**Objective:**

1. Verify that waypoint and loiter navigation work correctly.



| **FT-06: PROCEDURES** | Notes: **Dur:** 20 min |
|---|---|
| **Navigation Verification**<br><br>1. **O:** Verify that fail safes enabled (**F5) Settings > Fail Safes .** 'On' selected for fail safes and values inputted as stated in *UAV Preflight with RC (Cold Start) Checklist* (step 39).<br>2. **O:** Generate 'rectangle' flight plan with of altitude 300 ft (150 m) and airspeed near the trim speed found in Flight 1. Ensure waypoints are at least 250 meters apart.<br>3. **O:** Verify the lateral and fore/aft balance of the airplane is proper | If the lateral balance of the airplane is off, the airplane will tend to always roll one way when entering deep stall or during deep stall. The lateral balance must be correct for a stable deep stall.<br><br>The fore/aft CG must not be too far forward (nose heavy), or the airplane will not deep stall. |

**FT-06: PROCEDURES** Notes: **Dur:** 20 min

4. **SP:** Switch to RC Mode
5. **O:** Verify RC Mode (control boxes grayed out) and in "Manual Mode"
6. **O:** Perform *Launch Checklist* (skip step 17 in launch checklist for RC mode takeoff)
7. **SP:** Re-trim the CONDOR for level flight (if necessary)
8. **SP:** Maintain altitude and keep the airspeed near the trim airspeed found in F-CONDOR-01 test card.
9. **O:** Select NAV mode
10. **O:** Disable RC mode
11. **O:** Verify that CONDOR navigates to the first waypoint at desired altitude.
12. **O:** Upon reaching first waypoint, verify that CONDOR begins navigation to the second waypoint at the desired altitude.
    a. If the CONDOR overshoots its path or is delayed in getting back on the path, adjust the x-track hand distance **(F5 Settings > Autopilot Config > Mode Config > Navigation Mode > X-Track Hand Dist**). Decreasing the value will cause the aircraft to turn in more to

**Trim Airspeed from F-CONDOR-01:**

____________

**X-track distance (m):** __________

**Final X-track distance(m):** _________

**FT-06: PROCEDURES** | Notes: | **Dur:** 20 min

get on path.

b. If oscillations around the path occur, increase the x-track hand distance **(F5 Settings > Autopilot Config > Mode Config > Navigation Mode > Cross Track Hand Dist(m))**.

c. Record x-track distance.

**13. O:** Generate a loiter flight plan.

**14. O:** Upload loiter flight plan after waypoint navigation verification complete. Record any changes for the X-track distance.

**15. O:** Verify the CONDOR loiters correctly.

**Tuning Deep Stall**

**16. O:** Generate ‘rectangle’ flight plan with of altitude 500 ft (150 m) and airspeed near the trim speed found in Flight 1. Ensure waypoints are at least 250 meters apart. Set Rally Point at Flight 1 airspeed, set altitude to 500 ft, and break height alt to 450 ft. Upload flight plan.

**17. O:** Navigate to **(F5) Settings > Mode Config > Land Mode** screen. **Enter -0.05 for Deep Stall Fixed Pitch** and **enter -0.19 for Deep Stall Elevator Offset.**

**18. O:** Navigate CONDOR to Rally Point.

**19. O:** Command CONDOR to land.

**20. O:** Watch the vehicle enter deep stall and transition to a steady state deep stall.

**21. O:** If you are using a fixed pitch deep stall and not getting stable

Notes:

Values based on Kestrel Installation/Configuration Guide. Values are in radians.

The airplane should become stable within a few oscillations and remain stable when tuned correctly. If the oscillations at the start of the deep stall are very large, decrease the elevator offset and repeat. If the oscillations do not subside during the descent, make the fixed pitch angle more negative.

**Deep Stall Fixed Pitch:** _________

**Deep Stall Elevator Offset:** _________

characteristics, change the values for your deep stall fixed pitch and elevator offset.

**22. O/SP:** Abort the deep stall by going to NAV mode or RC control before about 40 meters (130 ft) alt and climb to 500 ft.

**23. O:** Repeat steps 17 to 21 until deep stall oscillations have almost subsided.

**24. O:** Navigate to PID tuning screen for pitch.

**25. O:** Command CONDOR to land.

**26. O:** When the vehicle reaches steady state deep stall, further tune values using PID tuning screen.

**27. O:** Abort the deep stall by going to NAV mode or RC control before about 40 meters (130 ft) alt and climb to 500 ft.

**28. O:** Repeat steps 23 to 26 until deep stall tuning complete. Record Deep Stall Fixed Pitch value and Deep Stall Elevator Offset.

| **FT-06: PROCEDURES** | Notes: **Dur:** 20 min |
|---|---|
| **29. SP:** In RC Mode, Land the CONDOR **leaving power "ON"**<br>**30. O:** "Update Flash"<br>**31. O:** Save the gains values to file with an incremented file name | |



**FT-07:** ***CONDOR Throttle PID Test Card***

**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. CONDOR pre-flight procedures complete. Runway setup for takeoff test accomplished.

**Configuration:**

Base airframe, ½ tank fuel, 30-lb

Note: Mission requires a safety pilot (SP), and operator (O). The entire flight will be conducted in RC Mode

**Objective:**

4. Evaluate throttle PID parameters and/or obtain acceptable values

**FT-07: PROCEDURES** | Notes: | **Dur:** 15 min

139

**<u>Throttle PID Determination</u>**

136. **O:** Disable rate damping PID Loops, navigate to the **F5 Settings page > Autopilot Config > Mode Configuration > RC Mode > PID Loops (Level I Loops)**. Uncheck all rate boxes

137. **SP:** Switch to RC Mode

138. **O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”

139. **O:** Perform *Launch Checklist*

140. **SP:** Trim the CONDOR for level flight at 600-ft

**FT-07: PROCEDURES** | Notes: | **Dur:** 15 min

141. **SP:** Fly a racetrack obit at constant altitude and airspeed

142. **O:** Verify the GPS maintains lock

143. **O:** Verify the airspeed and altitude values in the artificial horizon are reasonable values

144. **O:** Verify the roll, pitch, and heading angles shown in the artificial horizon are reasonable. (may need to instruct SP to bank and change heading)

145. **O:** Switch to autopilot altitude- hold mode for 600-ft

146. **O:** Input new altitude parameter of 700-ft (100-ft altitude step)

147. **O:** Send altitude step command to aircraft, note start time of maneuver and time to complete maneuver. Note maneuver velocity

148. **SP:** Switch to RC Mode

149. **O:** Verify RC Mode (control boxes grayed out) and in “Manual Mode”

150. **SP:** Recover CONDOR to trimmed level flight at 700 ft

151. **O/SP:** Repeat steps 2-15 for 700-800-ft

152. **SP:** Land the aircraft manually

**Maneuver Time**:_____________

**Maneuver Velocity: ___________**

**FT-08:** ***CONDOR Takeoff Performance Test Card***

**Preconditions:**

Autopilot installation and ground configuration procedures accomplished as described in Section 1 through Section 2.1 of the Procerus Installation and Configuration Guide Document Version 2.0, dated 10/27/08. CONDOR pre-flight procedures complete. Runway setup for takeoff test accomplished.

**Configuration:**

142 Base airframe, 35-lb Gross Weight, incremental thereafter. Fuel – ½ tank or as needed.

Note: Mission requires a safety pilot (SP), and operator (O). The entire flight will be conducted in RC Mode

**Objective:**

5. Determine Condor takeoff distance variance with weight
6. Determine Condor takeoff speed variance with weight

| **FT-08: PROCEDURES** | Notes: | **Dur:** 15 min |
|---|---|---|

**FT-08: PROCEDURES**

Notes:

**Dur:** 15 min

**Takeoff Performance**

153. **O:** Ensure runway setup is complete
154. **SP:** Switch to RC Mode
155. **O:** Verify RC Mode (control boxes grayed out) and in "Manual Mode"
156. **O:** Perform *Pre-Flight* Checklist, ensure weight and CG appropriate for test
157. **O:** Verify runway and airspace clearance
158. **O:** Note wind speed and direction
159. **SP:** Taxi downwind min throttle
160. **SP:** Turn aircraft 180 deg or until suitable upwind takeoff orientation
161. **O:** Note takeoff starting location
162. **SP:** Advance throttle until max (or safe level) for takeoff – hold until lift off
163. **O:** Note velocity at takeoff
164. **O:** Note distance until wheels off the ground
165. **SP:** Recover CONDOR to trimmed level flight at 700 ft

**Wind Speed:**________

**Wind Direction:**________

| **FT-08: PROCEDURES** | Notes: **Dur:** 15 min |
|---|---|
| 166. **SP:** Land CONDOR<br>167. **O/SP:** Repeat steps 1-14 for each weight/CG configuration<br>168. **SP/O:** Proceed to test car FT-01 | **Takeoff velocity:**________<br><br>**Takeoff distance:**________ |

## Bibliography


"Army-Lockheed YO-3A "Quiet Star"" *YO-3A Association*. Quiet Aircraft Association, Spring 2004. Web. 01 Feb. 2012. <http://www.yo-3a.com/home.html>.

Ausserer, Joseph K. *Integration, Testing, and Validation of a Small Hybrid-Electric Remotely Piloted Aircraft.*MS Thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH, March 2012.

Brandt, Steven A. *ElectricJet Aircraft Designer*. Vers. 5.55. Colorado Springs, Co: United States Air Force Academy, 2011.

Brandt, Steven A. *Introduction to Aeronautics: A Design Perspective*. Reston, VA: American Institute of Aeronautics and Astronautics, 2004.

Choon Seong, C. *Generic UAV Modeling to Obtain its Aerodynamic and Control Derivatives*, MS Thesis, Naval Postgraduate School, Monterey, CA. 2008.

Christiansen, R. S. *Design of an Autopilot for Small Unmanned Aerial Vehicles,* MS Thesis, Bringham Young University, Provo, UT. 2004

English, Jacob K., and Michael P. Molesworth. *Concept Evaluation of a Remotely Piloted Aircraft Powered by a Hybrid-Electric Propulsion System*. MS thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH, March 2012.

Farrell, S. M. *Waypoint Generation Based on Sensor Aimpoint*, MS thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH, March 2009.

Foster, T., and Bowman. J. "Dynamic Stability and Handling Qualities of SmallUnmanned-Aerial-Vehicles." *43rd AIAA Aerospace Sciences Meeting and Exhibit.* January 2005. (AIAA 2005-1023).

Gardner, L. Society of Flight Test Engineers Reference Handbook, Society of Flight Test Engineers, Lancaster, CA. 2001.

Greiner, Glenn P., and Jafar Mohammed. *Digital Datcom 3-D Viewer*. Dayton Beach, FL: Embry-Riddle Aeronautical University, 2008. Computer software.

Harmon, F., A.Frank and J.Chattot, *Concetpual Design and Simulation of a Smll Hybrid-Electric Unmanned Aerial Vehicle.* University of California-Davis, Davis, CA. September 2006. (JOA Vol 43, No. 5).

Higgs, Travis J. *Modeling, Stability, and Control of a Rotatable Tail on a Micro Air Vehicle.* MS Thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH. 2006.

Jacques, D. *Optimal Mixed-Norm Control Synthesis for Discrete-Time Linear Systems,* Ph.D dissertation, Air Force Institute of Technology, Wright-Patterson AFB, OH. 1995.

Jodeh, N. M. *Development of Autonomous Unmanned Aerial Vehicle Research Platform: Modeling, Simulating, and Flight Testing*, MS thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH, March 2006.

*Matlab & Simulink R2011b*. Vers. 7.12. Natick: The MathWorks, 2010. Computer software

McRuer, D., I. Ashkenas, and D. Graham. *Aircraft Dynamics and Automatic Control*, Princeton University Press, Princeton, NJ. 1973.

Nelson, R. C. *Flight Stability and Automatic Control*, Second Edition, McGraw Hill Higher Education, Boston, MA. 1998.

Ogata, K. *Modern Control Engineering*, Prentice Hall PTR, Upper Saddle River, NJ. 2001.

"Open DATCOM - OpenAE Forum." *Open Source Aerospace Software Community | OpenAE*. Oct. 2010. Web. Summer 2011. <http://openae.org/forum/22-flightgear/121-open-datcom>.

Procerus Technologies, Inc. Installation and Con_guration Guide, Kestrel Autopilot, Procerus Technologies, Inc., Vineyard, UT. 2008.

Raymer, Daniel P. *Aircraft Design : A Conceptual Approach*. Reston, VA: American Institute of Aeronautics and Astronautics, 1999.

Roskam, Jan. *Airplane Flight Dynamics and Automatic Flight Controls: Part I.* Lawrence KS: Design, Analysis and Research Corporation, 1995.

Roskam, Jan. *Airplane Flight Dynamics and Automatic Flight Controls Part II*. Lawrence, KS: Roskam Aviation and Engineering, 1979.

Stevens, B. L., and F. L. Lewis. *Aircraft Control and Simulation*, second ed., John Wiley and Sons, Hoboken, NJ. 2003.

Stryker, A. *Integration and Tuning of a PID Control Autopilot.*MS Thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH. March 2010.

Yechout, Thomas R. *Introduction to Aircraft Flight Mechanics*. Reston, VA: American Institute of Aeronautics and Astronautics, 2003.

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Don Gelosh (Donald.gelosh@osd.mil)
DDR&E/ Systems Engineering
Crystal Mall 3, Suite 102
1851 S. Bell Street
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**14. ABSTRACT**
This thesis describes the modeling and verification process for the stability and control analysis of the Condor hybrid-electric Remote-Piloted Aircraft (HE-RPA). Due to the high-aspect ratio, sailplane-like geometry of the aircraft, both longitudinal and lateral/directional aerodynamic moments and effects are investigated. The aircraft is modeled using both digital DATCOM as well as the JET5 Excel-based design tool. Static model data is used to create a detailed assessment of predictive flight characteristics and PID autopilot gains that are verified with autonomous flight test. PID gain values were determined using a six degree of freedom linear simulation with the Matlab/SIMULINK software. Flight testing revealed an over-prediction of the short period poles natural frequency, and a prediction to within 0.5% error of the long-period pole frequency. Flight test results show the tuned model PID gains produced a 21.7% and 44.1% reduction in the altitude and roll angle error, respectively. This research effort was successful in providing an analytic and simulation model for the hybrid-electric RPA, supporting first-ever flight test of parallel hybrid-electric propulsion system on a small RPA.

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