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A PROPOSED SYSTEM ARCHITECTURE FOR ESTIMATION OF ANGLE-OF-ATTACK AND SIDESLIP ANGLE

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ABSTRACT

This paper examines a method for air data estimation to derive the angle-of-attack and the sideslip angle of an aircraft. Continuing on earlier work [1], this paper proposes an avionics system architecture that, by sensing both the N_y and N_z acceleration components of the aircraft, can analytically derive both the angle-of-attack, α, and the sideslip angle, β, in the presence of turbulence. A model of the U-2S aircraft is used along with the control model by the air data estimation system to compare simulation results against the actual dynamics of the U-2S aircraft. Finally, an avionics system architecture for air data estimation is proposed.

INTRODUCTION

A modern control configured vehicle requires a complex pitot-static system along with an air data computer to calculate the necessary α and β signals for its instruments, autopilot, and stability augmentation system. Furthermore, the aircraft requires probes to measure the pressures, temperatures, α, and β. These probes can be easily damaged, require power to heat, add weight and complexity, and require calibration.

By using the onboard INS/GPS system in conjunction with the Flight Management System, a robust and accurate system for air data estimation can be provided which can allow for the use of a simplified air data system.

Several methods for providing air data estimates [1] were proposed, all of which failed to provide adequate stability under severe atmospheric turbulence. This paper addresses deficiencies that were seen in accounting for environmental disturbances.

The intent of this paper is to verify the plausibility of the architectural scheme by theoretical derivations and simulation results. The proposed method could improve redundancy by providing the vehicle's stability augmentation flight control system with back up signals in the event of a catastrophic air data system failure. A potential application for this work is to calculate β to use in correction curves for an α probe. Another potential use is for small or μUAVs, which due to their size cannot carry a pitot-static system.

Flight test data has been generated using a variety of sensors. These sensors include a flight test air data boom, fuselage mounted α and β sensors, accelerometers, and rate gyros. Uncorrected, corrected, and synthesized signals are compared at a variety of flight conditions for two different nose configurations.

U-2S AIRCRAFT MODEL

The U-2 aircraft is a subsonic, high altitude reconnaissance aircraft whose original airframe was developed in the early 1950s. The aircraft is unique for its sustained high altitude cruise performance. The U-2S is the current model and was developed from the U-2R by incorporating a more efficient engine powerplant and a new integrated digital autopilot and air data system [2]. Figure 1 shows the U-2S aircraft.

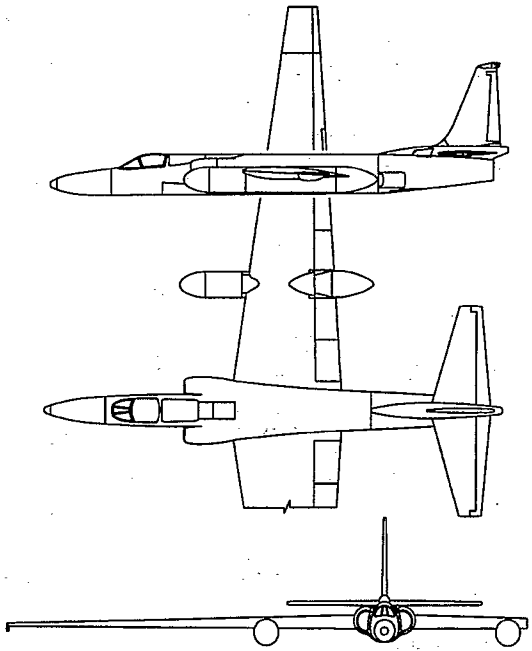

Figure 1. U-2S Aircraft

The linearized longitudinal model for the U-2S aircraft at cruise altitude is shown below in Equation 1.

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{\varpi} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \\ \Delta\dot{h} \end{bmatrix} = \begin{bmatrix} -0.0053 & 0.0646 & 0 & -32.19 & 0 \\ -0.129 & -0.632 & 692 & -0.28 & 0 \\ .0000019 & -0.00728 & -0.049 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & -692 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta\varpi \\ \Delta q \\ \Delta\theta \\ \Delta h \end{bmatrix} + \begin{bmatrix} 0 \\ -1.07 \\ -.109 \\ 0 \\ 0 \end{bmatrix} [\delta_e]$$

(Equation 1)

The lateral/directional model for the U-2S aircraft at cruise altitude is shown in Equation 2.

$$\begin{bmatrix} \dot{\beta} \\ \dot{p} \\ \dot{r} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} -0.029 & 0.00025 & -0.999 & 0.0465 \\ -0.714 & -0.11 & 0.27 & 0 \\ 1.1 & -0.08 & -0.047 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ p \\ r \\ \varphi \end{bmatrix} + \begin{bmatrix} 0 & 0.0002 \\ 0.085 & 0.0038 \\ 0 & -0.011 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix}$$

(Equation 2)

For both models, the weight of the aircraft is 29,000 lb. and the airspeed of the aircraft is 135 KIAS.

The installation of the air data test equipment on the U-2S aircraft is shown in Figure 2. A reference α and β probe were installed on a wing pod to provide comparative data to two α probes and a β probe and an accelerometer package mounted in the nose area. The hardware system architecture used is shown in Figure 3.

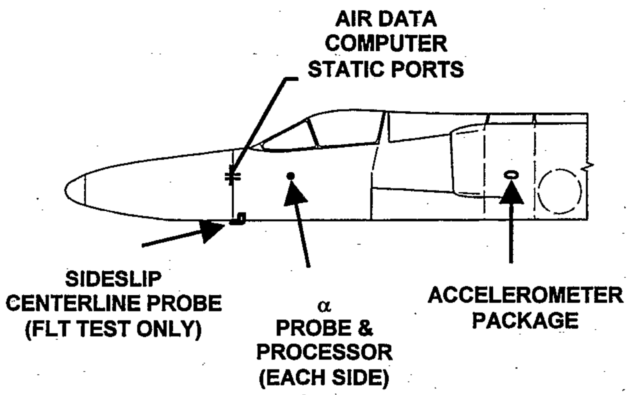

Figure 2. Sensor Locations

THEORETICAL DERIVATIONS

It was found that the results from the air data estimation algorithms were not accurate enough to control the aircraft without compensating for the environmental effect of turbulence [1]. A method was proposed which uses derived α and β signals and includes compensation for turbulence to accurately reflect the instantaneous response of the aircraft.

The basic kinematic relationship states that force is proportional to the mass times the acceleration of a moving object,

$$F = m \cdot a. \qquad \text{(Equation 3)}$$

Acceleration is simply the force divided by the mass of the object,

$$N_y = a_y = \frac{F_y}{m} \qquad \text{(Equation 4)}$$

where the lateral acceleration, N_y is the acceleration along the lateral axis. This acceleration signal can be simply measured by an accelerometer or an INS system. The aircraft's mass, m, is stored in the Flight Management System computer of the aircraft prior to takeoff and updated regularly during flight based on fuel consumption and stores release.

A derived lateral gust velocity can be calculated by integrating the acceleration experienced on an object over a particular range of time. Equation 5 is the gust velocity equation for the lateral axis of an aircraft,

$$v_{\hat{G}} = \int_{T_1}^{T_2} \frac{F_{ygust}}{m} dt + C_1 \qquad \text{(Equation 5)}$$

where C_1 is an integration constant.

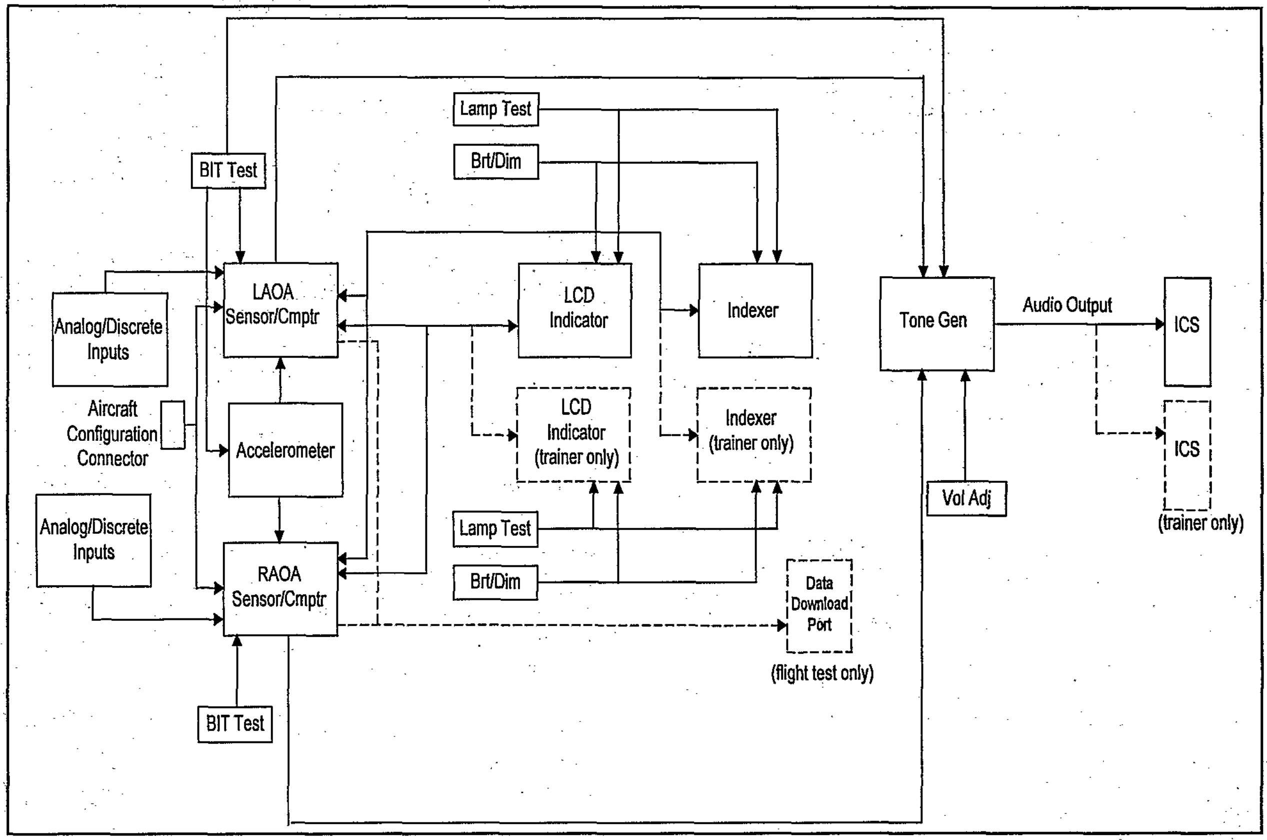

Figure 3. U-2 α/Stall Warning System Architecture

Equation 5 has a force divided by mass component $\frac{F_{ygust}}{m}$, which is equivalent to the acceleration in Equation 4, and in turn is equivalent to the lateral acceleration. Therefore, by substituting lateral acceleration, Ny, for the acceleration, a derived lateral gust velocity can be calculated using the lateral accelerometer signal as shown in Equation 6 below,

$$v_{\hat{G}} = \int_{T_1}^{T_2} N_y dt + C_1 . \qquad \text{(Equation 6)}$$

Summing the inertial velocity component along with the derived lateral gust velocity component from Equation 6, a derived velocity component can be calculated as shown in Equation 7. This equation is the total velocity summation along the lateral axis of the aircraft,

$$v_{\hat{BG}} = v_B + v_{\hat{G}} \qquad \text{(Equation 7)}$$

and takes into account both the velocities along the lateral axis plus the derived gust velocity. In Equation 7 V_B is the body axis lateral velocity obtained from the Inertial Navigation System (INS).

Finally, a derived β can be calculated using Equation 8 which takes the arcsine of the derived lateral velocity component divided by the total aircraft's velocity magnitude.

$$\hat{\beta} = \sin^{-1} \frac{V_{\hat{BG}}}{\|Vt\|} . \qquad \text{(Equation 8)}$$

Similar to the β derivation, a derived α can be calculated using two accelerometer signals. By using both longitudinal and vertical acceleration, N_x and N_y respectively, as shown in Equation 9,

$$N_x = a_x = \frac{F_x}{m}$$
$$N_z = a_z = \frac{F_z}{m} \qquad \text{(Equation 9)}$$

the longitudinal and vertical gust velocity components can be calculated using Equation 10 below,

$$u_{\hat{G}} = \int_{T_1}^{T_2} N_x dt + C_1$$
$$w_{\hat{G}} = \int_{T_1}^{T_2} N_z dt + C_2 \qquad \text{(Equation 10)}$$

where $u_{\hat{G}}$ is the longitudinal gust velocity and $w_{\hat{G}}$ is the vertical gust velocity.

Both the longitudinal and vertical velocity components can be calculated using Equation 11,

$$u_{\hat{BG}} = u_B + u_{\hat{G}}$$
$$w_{\hat{BG}} = w_B + w_{\hat{G}} \qquad \text{(Equation 11)}$$

By taking the arctangent of the vertical and longitudinal velocity components as shown in Equation 12,

$$\hat{\alpha} = \tan^{-1} \frac{w_{\hat{BG}}}{u_{\hat{BG}}} \qquad \text{(Equation 12)}$$

the angle-of-attack can be calculated.

The forward velocity component is the third velocity component in the equation for total aircraft velocity

$$\|V_t\| = \sqrt{u_B^2 + v_B^2 + w_B^2}\,. \qquad \text{(Equation 13)}$$

When both of the other velocity components V_B and W_B are known from N_y and N_z measurements and $\|V_t\|$ is available from the aircraft's airspeed system (as addressed in the next section) u_B can be derived without a third accelerometer. Note also that u_B is close to $\|V_t\|$ in magnitude.

Therefore, a scheme has been established where a derived α and β can be calculated which takes into account the environmental effects of turbulence. Both α and β can then be used to derive the necessary states of the aircraft.

INS DERIVED ANGLE-OF-ATTACK

A comparison of INS derived α versus actual α was studied on another aircraft to observe the INS sensitivity to wind turbulence. Figure 4 shows the comparison between INS derived α and actual aircraft measured α during a turn. As shown, the two parameters are very similar. The third parameter is the INS α computed without compensation for wind.

Figures 5 through 7 are representative coefficient of lift curves for the U-2S aircraft under various surface configurations that were used during the investigation. The data points provide a baseline for which to compare derived α points.

Figure 8 shows a representative α correction curve that can be implemented in software. Figure 8 shows a linear curve but a nonlinear curve can be just as easily be implemented.

These figures illustrate that the INS can compute an angle-of-attack that is reasonably accurate when compensated for winds and turbulence. Also shown is that α curves can be implemented by software within the architecture.

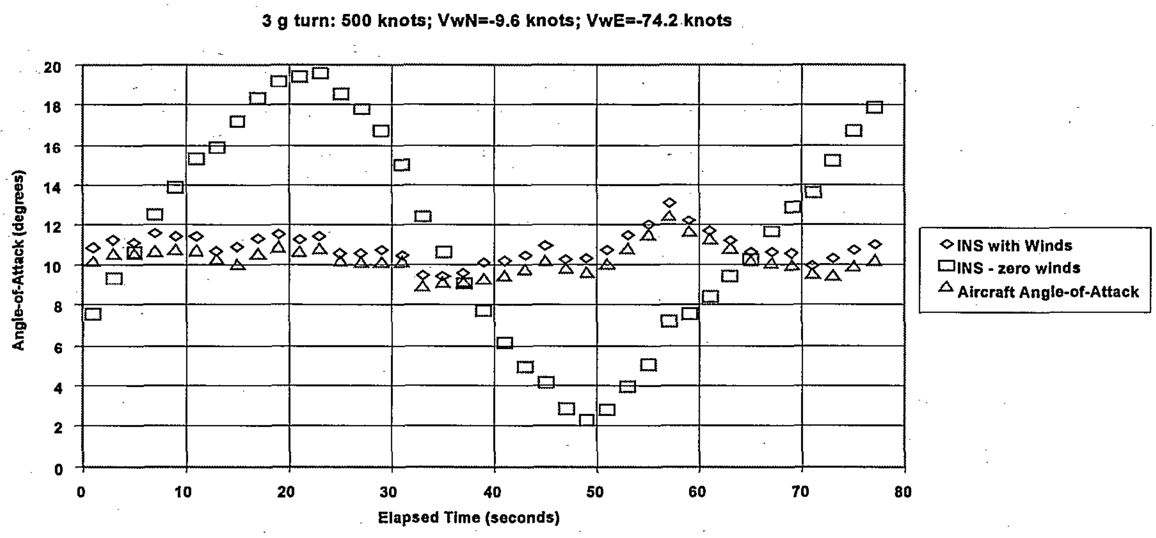

Figure 4. INS Derived Angle-of-Attack versus Actual Aircraft Sensed Angle-of-Attack

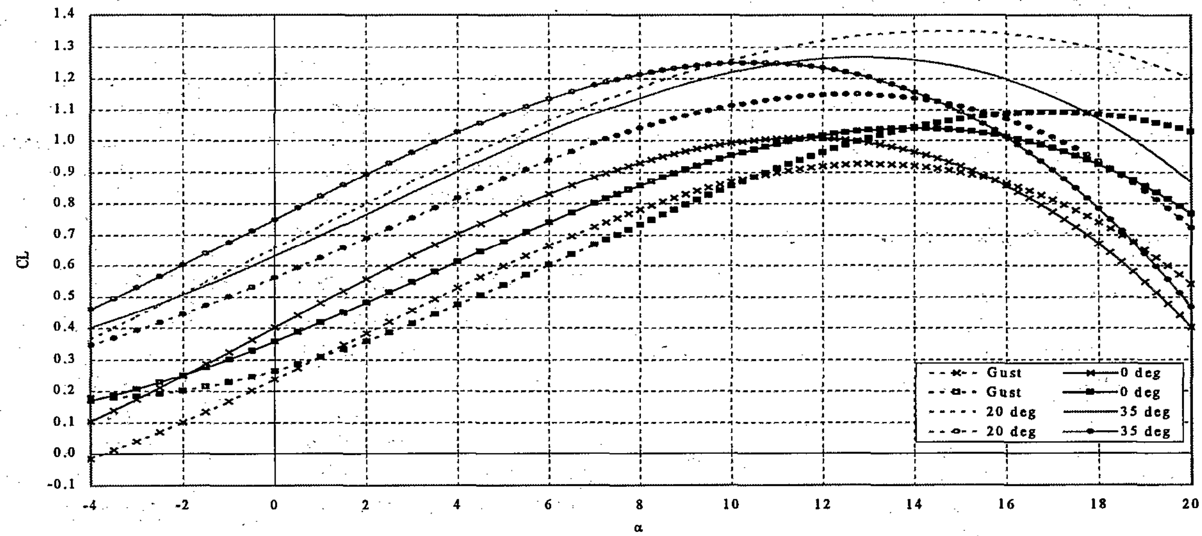

Figure 5. Lift Curves versus Angle-of-Attack for Flap Effects

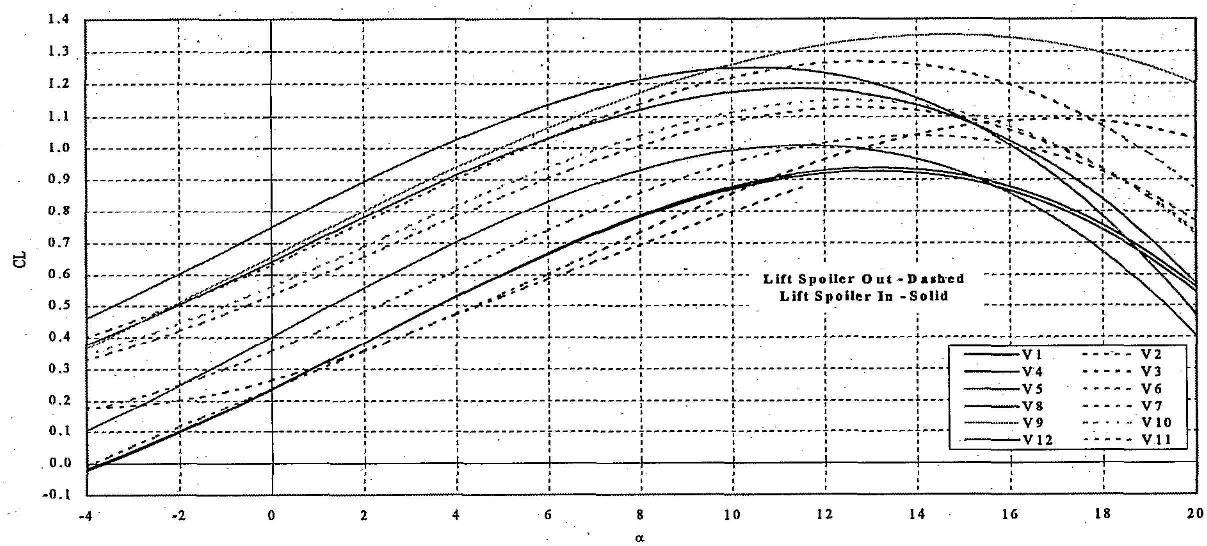

Figure 6. Lift Curves versus Angle-of-Attack for Lift Spoiler Effects

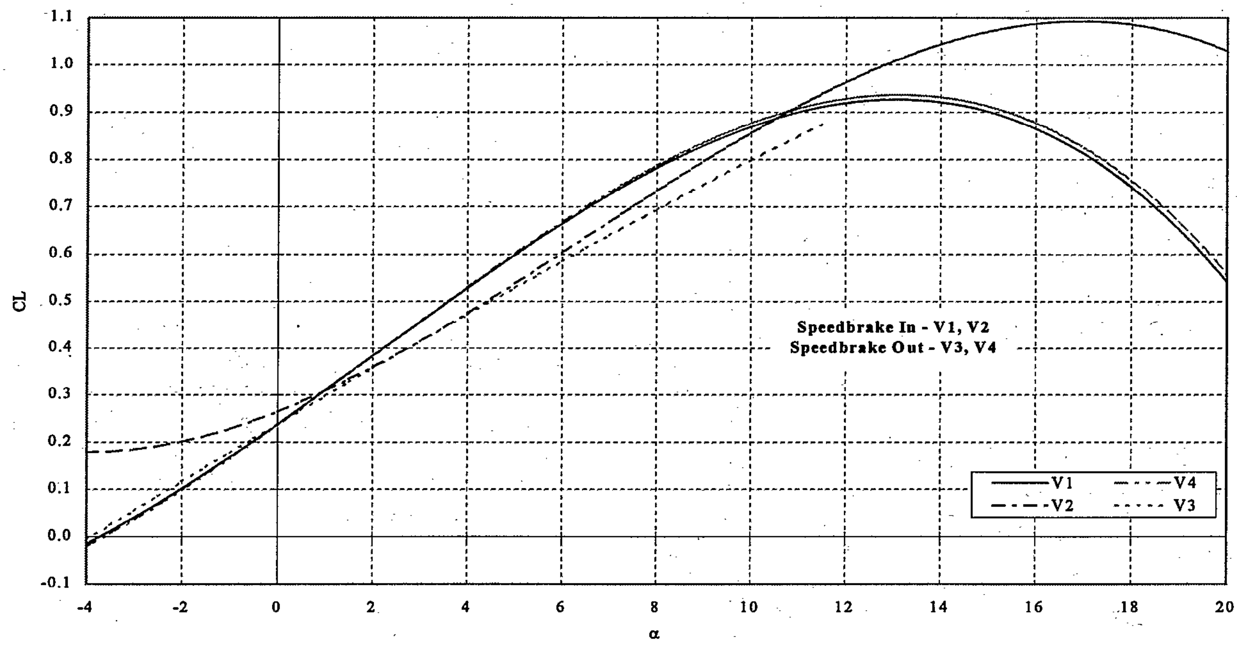

Figure 7. Lift Curves versus Angle-of-Attack for Speedbrake Effects

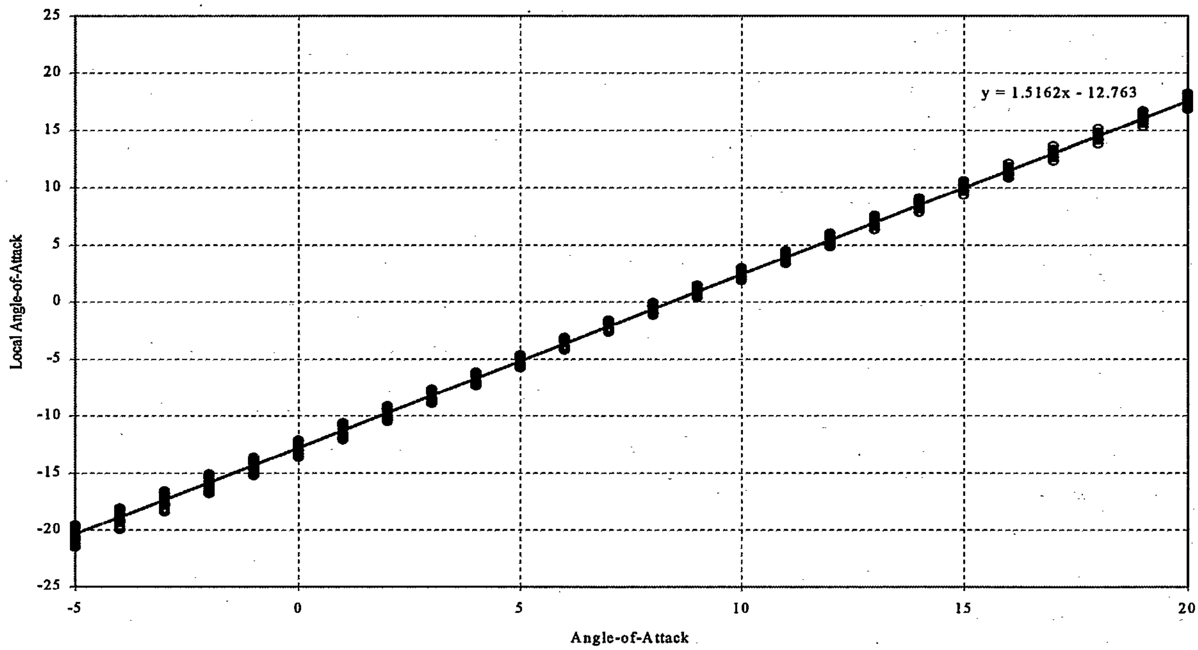

Figure 8. Representative Linearized Angle-of-Attack Curve

AVIONICS SYSTEM ARCHITECTURE

The proposed avionics system architecture is shown in Figure 10 [1]. The system will use the INS/GPS system to provide position, rate, and acceleration data. An Air Data Computer (ADC) is still used for altitude measurements. The ADC could also be used to provide airspeed and the results combined with those from the estimator using a complementary or Kalman filter. To achieve lower precision requirements, for example, for a small or μUAV, the estimated airspeed would be calculated using U_b, V_b, and W_b.

Body axis angular rates, Earth axis velocities, and Earth axis acceleration signals are provided to the Body Velocity and Body Acceleration Module as was discussed in the previous sections. Derived body velocities are then determined by Equations 9 and 11. Note that the INS will provide a total velocity signal that includes all the wind turbulence components. Estimated gust velocities are determined by the accelerations about the center of gravity (CG) from the INS and the aircraft's mass using the discussed procedures for gust estimation.

The body axis velocities in conjunction with the estimated gust velocities are then used to derive the estimated α and β in the Alpha and Beta Module using the algorithm proposed in the previous section. For added robustness, a series of α correction curves for various surface configurations could be added. Also, a correction from the INS could be used to provide a more accurate α and β measurement. Conversely, the α and β derived from the total velocity can be complementary filtered with measurements from probes to give improved derived signals over the entire frequency spectrum. The estimated α and β is then provided to the module with the nonlinear model of the aircraft to determine aircraft states.

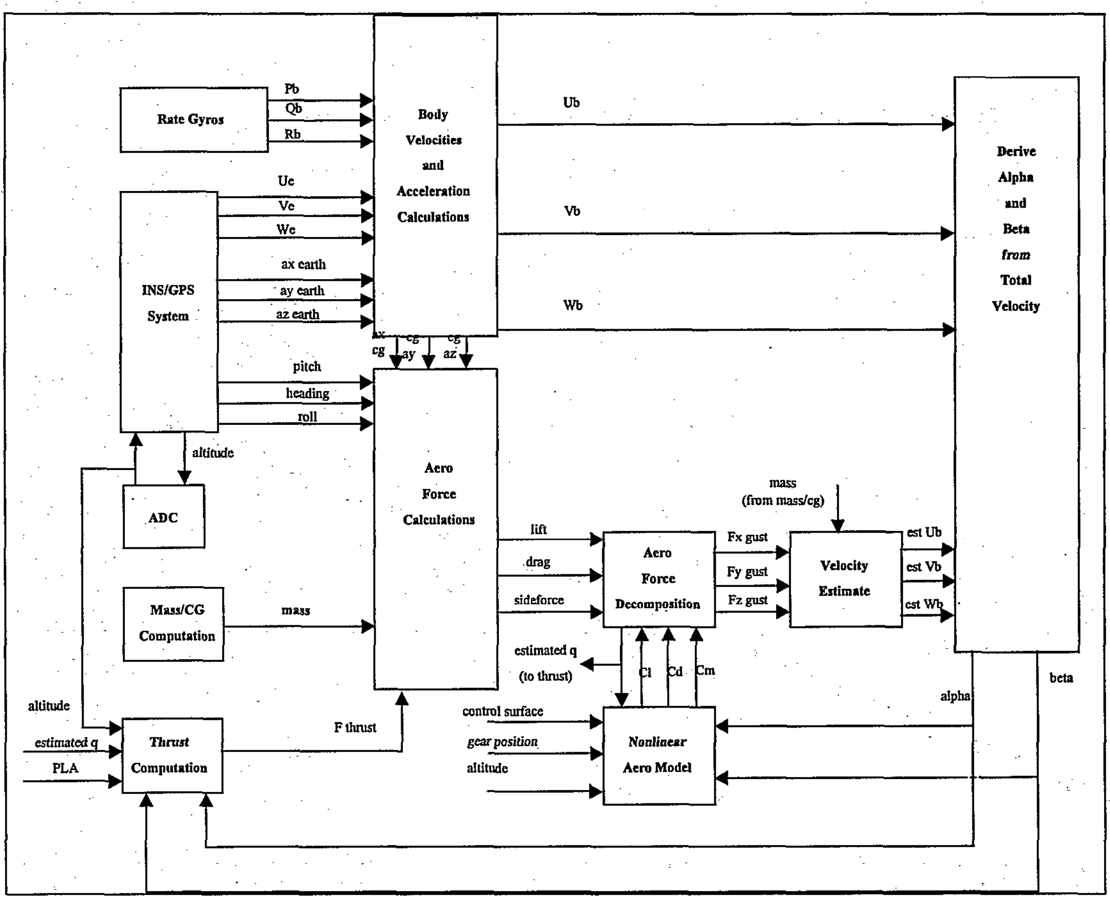

Figure 9. Avionics System Architecture for Air Data Estimation

CONCLUSION

This paper discussed a proposed architecture for air data estimation using derived α and β calculations from the INS/GPS system. As it is currently perceived, this architecture would be used as a backup system for a conventional air data system. The possibility exists that the system could be used for UAVs as the primary sensing system.

REFERENCES

[1] Colgren, Richard D. "The Feasibility of Using an INS for Control System Feedbacks." Presented at the World Aviation Congress and Exposition, 1998.

[2] Colgren, Richard D. "Results of the U-2 Autopilot and Air Data System (APADS) Development and Flight Test Program." Presented at the AIAA Guidance, Navigation, and Control Conference, 1996.