Real-time Aerodynamic Modeling and Control of Optimum Power-Off Glide Performance during Emergency Forced Landings

Nevada NASA Space Grant Consortium Since 1991

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USAF Test Pilot School

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Overview

Objective: Demonstrate the ability to use real-time data analysis methods to determine, command, and control optimal performance conditions during engine malfunction emergencies.

- Applicable to off-nominal/failure scenarios - stuck landing gear, doors, surfaces, seized engine, or external carriage of stores that change aerodynamics.
- Use of real-time aerodynamic modeling to determine optimal path and state for glide vehicles in terminal area operations.

Introduction

Manned Aircraft

- Over a 10 year period, 282 general aviation accidents due to loss of engine
- "A significant number of general aviation fatalities could be avoided if pilots were better informed and trained in determining and flying their aircraft at the best glide speed while maneuvering to complete a forced landing." – FAA

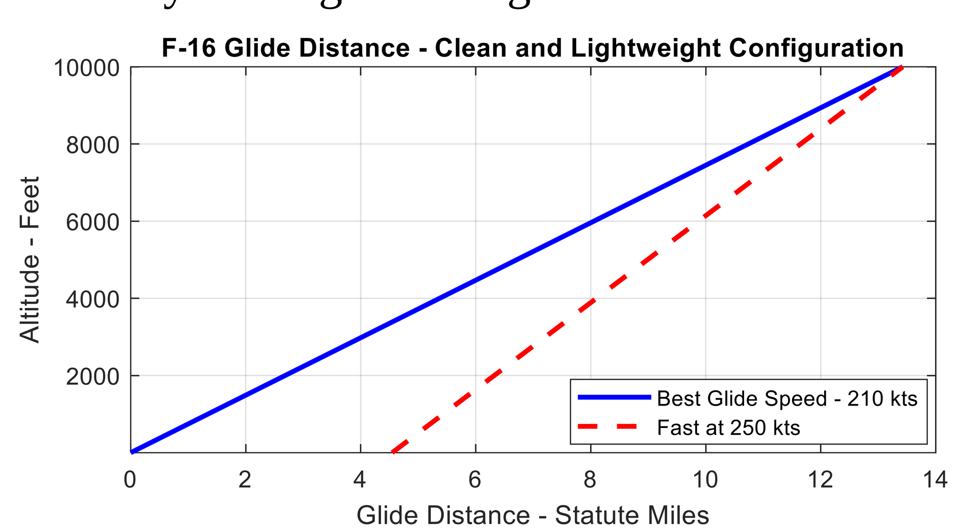
Autonomous Vehicles

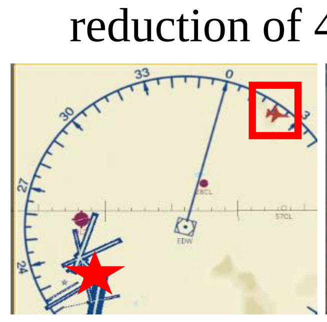
- Emergency Landing Zone – Currently rely on predicted glide ratio from models

Flying $V_{Best\ Glide}$: The difference between safely making a landing zone or not!

Example: An F-16 at 10,000 feet can glide over 13 statute miles

- Flying 40 knots fast results in a reduction of 4.5 miles





Optimum Performance: Optimal performance conditions can be determined from aerodynamic modeling alone. Does **not** require empirical steady state data to determine.

- Drag $D = (C_{D_0} + C_{D_I}) * \bar{q} * S$ where $\bar{q}$ dynamic pressure, S Reference area
- C_{D_0} Parasite drag coefficient and C_{D_i} Induced drag $= kC_L{}^2$
- C_L Lift Coefficient $= \frac{L}{\bar{q}*S}$ where L is the lift force

	Performance Characteristic	Best Case of Flight	Parasite vs Induced Drag
Powered Cruise	Maximum endurance (time airborne)	$\left(\frac{L}{D}\right)_{max}$	$C_{D_0} = C_{D_i}$ $(= k\,C_L^2)$
	Maximum range (distance traveled)	$\left(\frac{D}{V}\right)_{min}$	$C_{D_0} = \mathbf{3}\,C_{D_i}$ $(= 3\,k\,C_L^2)$
Gliding Flight	Maximum endurance (time airborne)	$(D * V)_{min}$	$3\,C_{D_0} = C_{D_i}$ $(= k\,C_L^2)$
	Maximum range (distance traveled)	$\left(\frac{L}{D}\right)_{max}$	$C_{D_0} = C_{D_i}$ $(= k\,C_L^2)$
Powered Climb	Maximum climb angle	$\left(\frac{L}{D}\right)_{max}$	$C_{D_0} = C_{D_i}$ $(= k\,C_L^2)$

Maximum Range Glide Example:

Best Glide $C_{D_0} = k\,C_L^2$

Optimal Condition:

$\tan(\gamma) = -2\sqrt{kC_{D_0}}$

Glide Ratio $\left(\frac{L}{D}\right) = \frac{1}{2\sqrt{kC_{D_0}}}$

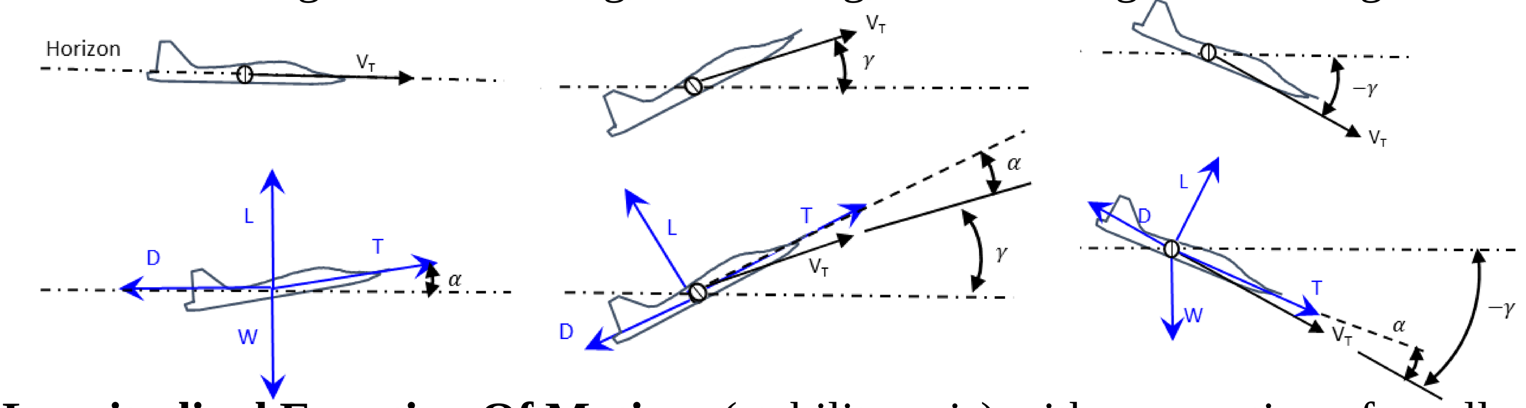
Range $= \frac{Altitude}{2\sqrt{kC_{D_0}}}$

Airspeed $= \sqrt{\frac{2mg\cos(\gamma)}{\rho S}}\left(\frac{k}{C_{D_0}}\right)^{1/4}$

Optimum Performance: Determination of aerodynamic coefficients C_{D_0} and k provide an estimation of achievable range and required flight path angle command to optimize glide performance.

Methodology

Physics Based Modeling: The aircraft longitudinal equations of motion were utilized for wings level climbing, descending, and level segments of flight.



Longitudinal Equation Of Motion: (stability axis) with assumption of small angle of attack for thrust incidence angle ($\sim\alpha < 10\ deg$):

$$ma_{\parallel V} = m\frac{dV_T}{dt} = T - D - W\sin(\gamma) \quad \& \quad ma_{\perp V} = L \text{ (assumption } a_{\perp V} \approx a_Z)$$

Drag Model: $D = (C_{D_0} + C_{D_I}) * \bar{q} * S = (C_{D_0} + kC_L{}^2) * \frac{1}{2}\rho V_T{}^2 * S$

$$= C_{D_0} * S * \frac{1}{2}\rho V_T{}^2 + k(ma_{\perp V})^2\, V_T{}^{-2}/(\tfrac{1}{2}\rho * S)$$

Linear Regression Model: Unknown Constants: Thrust (T), C_{D_0} , k

Known Constants: reference area (S), mass (m), density ρ

Measurements: $\frac{dV_T}{dt}, V_T, a_Z, \gamma$

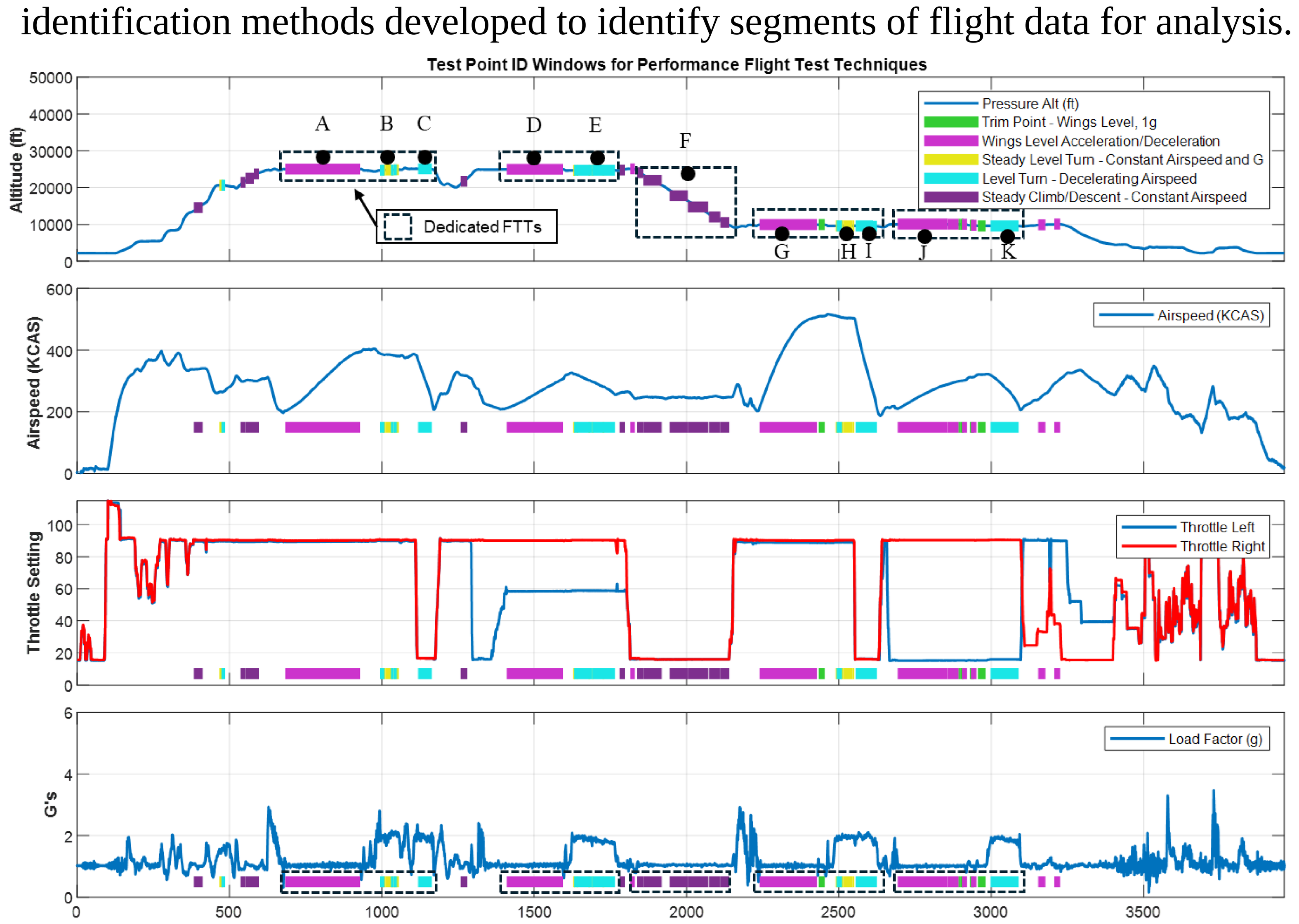
$$x_1 = 1, x_2 = S * \frac{1}{2}\rho V_T{}^2, and\ \ x_3 = (ma_{\perp V})^2\, V_T{}^{-2}/(\tfrac{1}{2}\rho * S)$$

$$\boldsymbol{X} = \begin{bmatrix} x_{1,k} & x_{2,k} & x_{3,k} \\ x_{1,k+1} & x_{2,k+1} & x_{3,k+1} \\ \dots & \dots & \dots \end{bmatrix} \qquad \boldsymbol{y} = \begin{bmatrix} y_k \\ y_{k+1} \\ \dots \end{bmatrix} = \begin{bmatrix} m\dot{V}_{T_k} + W\sin(\gamma_k) \\ m\dot{V}_{T_{k+1}} + W\sin(\gamma_{k+1}) \\ \dots \end{bmatrix}$$

Determination of unknown constants: $\begin{bmatrix} T_0 & C_{D_0} & k \end{bmatrix}^T = (\mathbf{X}^\top \boldsymbol{X})^{-1}\mathbf{X}^\top \boldsymbol{y}$

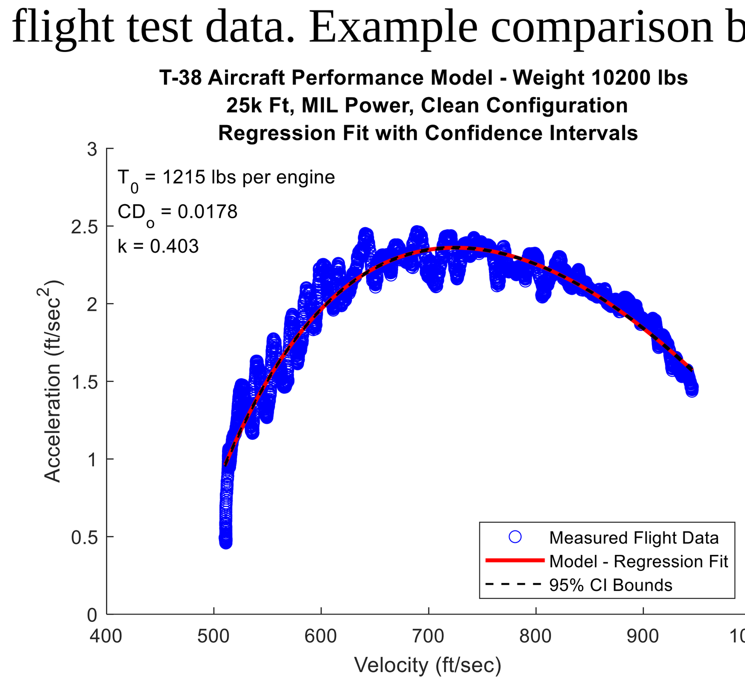
Results – Flight Test Data

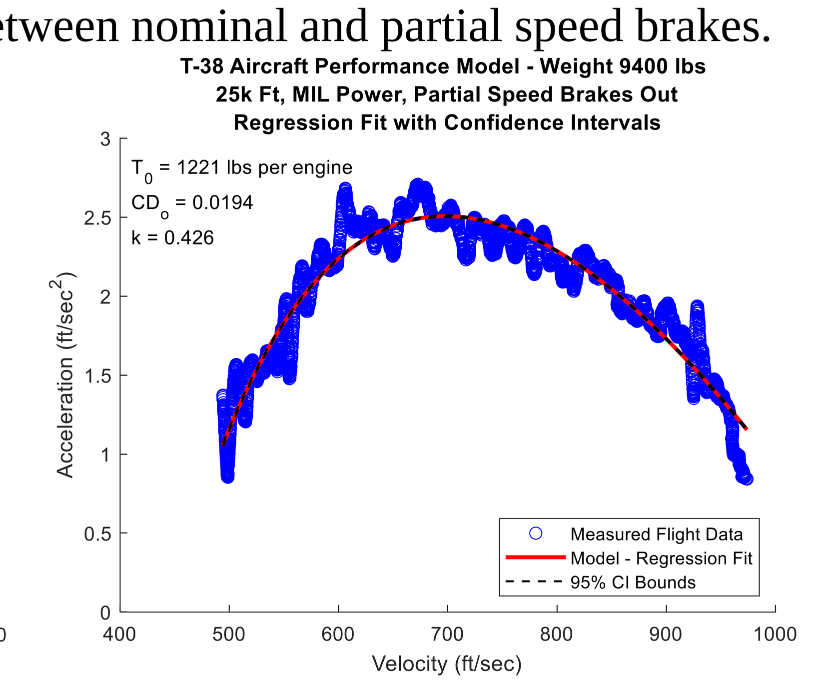
Data Collection: USAF Test Pilot School (USAF TPS) T-38 trainer aircraft. Modified with on-board Flight Test Data Acquisition System (DAS). Test point identification methods developed to identify segments of flight data for analysis.



Results - Continued

Linear Regression Model Results: Aerodynamic modeling from segments of flight test data. Example comparison between nominal and partial speed brakes.



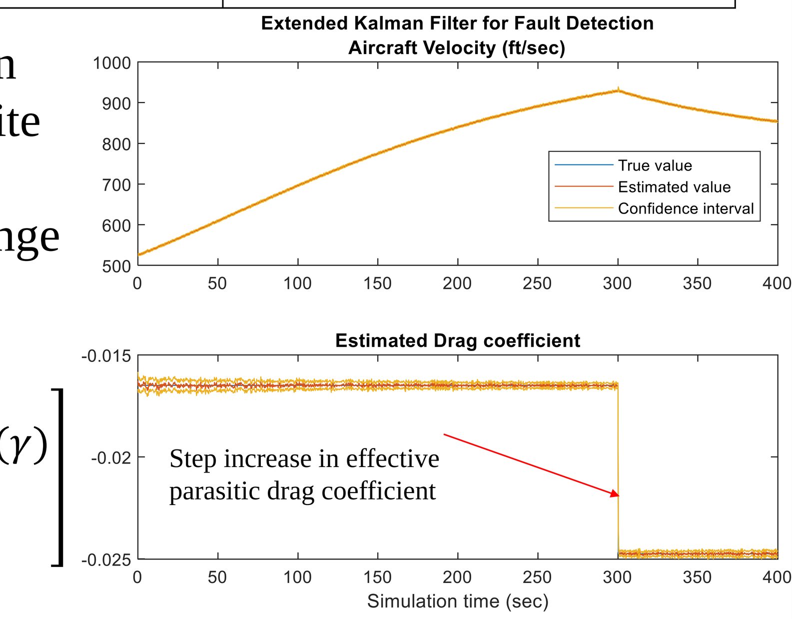


	Nominal T-38	Added Drag T-38
Aerodynamic parameters	C_{D_0}: 0.0178, k: 0.403	C_{D_0}: 0.0194, k: 0.426
Predicted best flight path angle	-9.6 degrees	-10.3 degrees
Predicted glide ratio	6	5.5
Predicted achievable range from an altitude of 10k feet	11.2 statute miles	10.4 statue miles

Current Work: Use of an extended Kalman filter to detect and estimate change in parasite drag, termed an r factor.

State Vector $\boldsymbol{x} = [V_T, r]^T$ where r is the change in C_{D_0}. Use predicted T, C_{D_0}, and k values from linear regression modeling results.

$$\begin{bmatrix} \dot{V}_T \\ \dot{r} \end{bmatrix} = \begin{bmatrix} T - rC_{D_0}S\frac{1}{2}\rho V_T{}^2 - \frac{k(ma_Z)^2}{\frac{1}{2}\rho S V_T{}^2} - W\sin(\gamma) \\ 0 \end{bmatrix}$$



Simulation Results: Use of an EKF was able to detect and estimate the r value and corresponding change to parasite drag. Next step is to apply to offline analysis of flight test data during configuration changes

Conclusion & Future Work

USAF Test Pilot School (USAF TPS) Summer 2025:

- Implement control room methods for real-time system identification methods to determine C_{D_0}.
- Apply aerodynamic models to determine optimal aircraft glide path trajectories. Compare model predictions to traditional steady state empirical results.

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