Glider 6-DoF Simulation, Aerodynamic Modeling, Control Surfaces, and Turbulence

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1 Introduction

This project simulates the glide of a large transport aircraft using the parameters of an Airbus A380-800, in a glide the engines of an aircraft provide no thrust hence we set the thrust to zero here. The simulation is based on a six-degree-of-freedom (6-DoF) model, which means that the aircraft's motion includes translations in three dimensions and rotations about three axes. We look at the gliding performance of the aircraft under different wind conditions with the use of aerodynamic equations and a Monte Carlo approach. The simulation is implemented in Python and uses numerical methods to solve the six-degrees-of-freedom equations and then we plot the important physical quantities for analysis.

2 Frames of Reference and Basic Concepts

All positions and orientations use a North-East-Down (NED) inertial frame, labeled as $\{X, Y, Z\}$. In this system, X points north, Y points east, and Z points downward toward Earth's center, so altitude is simply $-Z$. The aircraft also has its own body frame, $\{x_b, y_b, z_b\}$, with x_b pointing forward along the fuselage, y_b pointing out the right wing, and z_b directed downward from the fuselage.

The aircraft's orientation is defined by Euler angles: roll (ϕ), pitch (θ), and yaw (ψ). A positive roll angle indicates the right wing moving down, a positive pitch angle means the nose is tilting up, and a positive yaw angle means the nose is turning to the right with respect to north. Two important angles related to airflow, the angle of attack α and the sideslip angle β, describe the direction of the relative wind as it meets the aircraft. Their definitions are

$$\alpha = \tan^{-1}\!\left(\tfrac{w}{u}\right), \quad \beta = \sin^{-1}\!\left(\tfrac{v}{V}\right),$$

where (u, v, w) are the velocities in the aircraft's body frame, and V is the total airspeed $\sqrt{u^2 + v^2 + w^2}$.

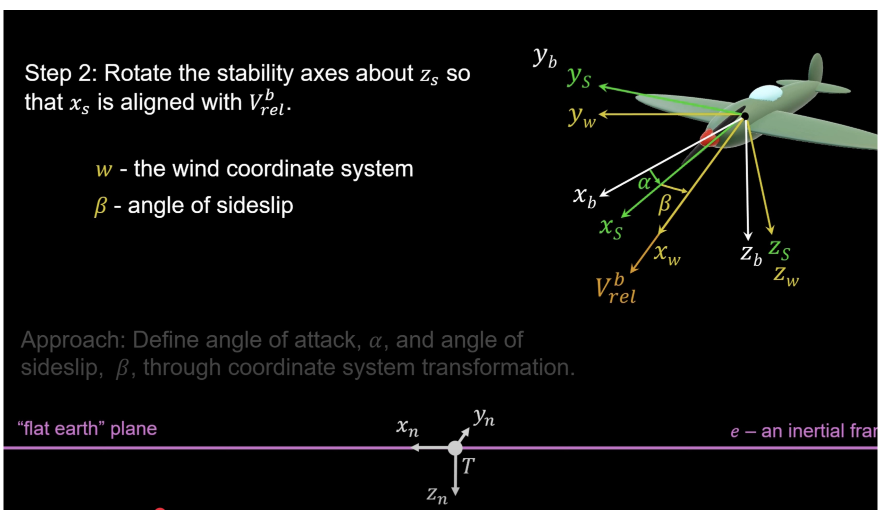

Figure 1: Figure showing the orientation of coordinate systems.

3 Atmospheric Model

For the atmospheric model, a piecewise method similar to the International Standard Atmosphere (ISA) is used to calculate temperature, pressure, density, and speed of sound at a given altitude. At altitudes up to 11 000 m (which is close to troposphere), the temperature decreases linearly with altitude, represented as

$$T = T_0 + \text{lapse\_rate} \times h, \tag{1}$$

where T_0 is 288.15 K and the lapse rate is -0.0065 K/m at height h, meaning that the temperature falls by approximately 6.5 K for every 1000 m of altitude. In this region, pressure is obtained by the equation

$$p = p_0 \left(\frac{T}{T_0}\right)^{-\frac{g_0}{\text{lapse\_rate} \times R}}, \tag{2}$$

where p_0 is 101 325 Pa, g_0 is 9.806 65 m/s^2, and R is 287.05 J/(kgK). For altitudes above 11 000 m, the temperature is held constant at the value reached at 11 000 m, and the pressure decays exponentially according to

$$p = p_{11} \exp\left(-\frac{g_0(h - 11000)}{RT}\right), \tag{3}$$

with p_{11} being the pressure at 11 000 m. The density is then determined using the ideal gas equation $\rho = \frac{p}{RT}$, and the speed of sound is calculated by $a = \sqrt{\gamma RT}$, where $\gamma = 1.4$. This is how we determine the dynamic pressure of the aircraft at varying altitudes.

4 Aerodynamic Forces and Coefficient Models

The aerodynamic model in this project uses a simple linear model for lift and a parabolic model for drag. The lift coefficient C_L is calculated using the equation

$$C_L = C_{L0} + C_{L\alpha}\,\alpha, \tag{4}$$

where C_{L0} is the zero-lift coefficient (typically around 0.25) and $C_{L\alpha}$ is the lift curve slope (approximately 6.283 per radian). This linear relationship is assumed to be valid for small-to-moderate angles of attack, as the aircraft in a normal gliding condition does not approach high values of α. The drag coefficient C_D is modeled using a parabolic drag polar:

$$C_D = C_{D0} + k\,C_L^2, \tag{5}$$

where C_{D0} is the drag coefficient at zero lift (about 0.016) and k is a factor representing induced drag (set to about 0.05). Once the coefficients are determined, the lift L and drag D forces are calculated using the dynamic pressure $q = \frac{1}{2}\,\rho V^2$ as

$$L = qSC_L \quad \text{and} \quad D = qSC_D.$$

These forces are first computed in the "wind" coordinate system and then rotated into the body frame using a rotation matrix.

5 6-Degree-of-Freedom (6-DoF) Equations of Motion

The simulation uses a state vector that represents 12 variables: the position in the NED frame $[N, E, D]$, the velocity in the body frame $[u, v, w]$, the Euler angles $[\phi, \theta, \psi]$, and the angular rates in the body frame $[p, q, r]$. The motion is governed by a set of coupled differential equations.

The position in the NED frame is updated by converting the body-frame velocity through the rotation matrix $R_{b \to I}$ (which depends on the Euler angles) as follows:

$$\dot{\mathbf{r}} = R_{body \to Inertial}(\phi, \theta, \psi) \begin{bmatrix} u \\ v \\ w \end{bmatrix}. \tag{6}$$

The body-frame velocity dynamics are given by

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \frac{1}{m}\mathbf{F}_{\text{body}} - \boldsymbol{\omega} \times \begin{bmatrix} u \\ v \\ w \end{bmatrix}, \tag{7}$$

where $\mathbf{F}_{\text{body}}$ represents the net forces (aerodynamic, gravitational, and any remaining thrust) and $\boldsymbol{\omega} = [p, q, r]^T$ is the angular velocity. The Euler angles are updated using the relation:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi \tan\theta & \cos\phi \tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}. \tag{8}$$

This converts the body angular rates into the rates of change of the Euler angles. The rotational dynamics are described by the following equation derived from Euler's rigid-body rotation theory:

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = I^{-1} \left(\mathbf{M}_{\text{body}} - \boldsymbol{\omega} \times (I\,\boldsymbol{\omega}) \right), \tag{9}$$

where I is the moment of inertia matrix and $\mathbf{M}_{\text{body}}$ is the net moment generated by aerodynamic forces and control inputs.

At the start of the simulation, initial conditions are provided for all state variables. The current Euler angles are used to compute the rotation matrix, which converts the body-frame velocity into the NED frame to update the aircraft's position. The angle of attack is calculated from the body velocities, and then the aerodynamic coefficients C_L and C_D are computed. These coefficients are used to calculate the lift and drag forces, then gravitational forces are used to update the translational acceleration in the body frame. At the same time, the aircraft's angular accelerations are computed using the net moments. The Euler angles are then updated based on the current angular rates. The simulation advances by integrating all these coupled equations using a numerical solver, such as the Runge-Kutta method(RK45).

6 Control Surfaces Model and Its Purpose

To keep the aircraft oriented correctly, we apply simple proportional-derivative (PD) control laws for three surfaces: elevator, aileron, and rudder. Each law compares a desired angle to the current state, and then it applies a control deflection limited by some maximum. Specifically, we define:

Elevator Control. The elevator primarily adjusts pitch, which in turn influences angle of attack. If we let α_{trim} be the target angle of attack, a proportional law might say

$$\delta_e = \text{clip}\Big(K_p\,(\alpha_{\text{trim}} - \alpha)\Big), \tag{10}$$

where K_p is a proportional gain, and δ_e is clipped between $\pm\delta_{e,\max}$. This keeps the aircraft pitched for a nominal angle of attack (e.g. 5–10 degrees in a steady glide).

Aileron Control. The ailerons adjust roll, so if we want to keep ϕ near zero (wings level), we can write

$$\delta_a = \text{clip}\Big(K_p\,(\phi_{\text{desired}} - \phi) - K_d\,p\Big), \tag{11}$$

where p is the roll rate, K_d is a damping term, and δ_a is clipped to $\pm\delta_{a,\max}$. This keeps the aircraft from banking too far in either direction.

Rudder Control. The rudder counters yaw and sideslip. If we define a desired heading or yaw angle $\psi_{\text{desired}} = 0$, then

$$\delta_r = \text{clip}\Big(K_p\,(\psi_{\text{desired}} - \psi) - K_d\,r\Big), \tag{12}$$

where r is the yaw rate. This helps keep the nose pointed forward, limiting sideslip.

These PD laws are straightforward, but they show how even a simple feedback approach can stabilize roll, pitch, and yaw angles. We do not require an advanced autopilot to achieve a steady glide.

7 Wind Modeling and Monte Carlo Simulation

The turbulence model used includes a first-order Markov process that changes the wind offset. In each time increment Δt, the turbulence changes by

$$d\mathbf{W} = -\frac{1}{\tau}\,\mathbf{W}\,\Delta t + \sqrt{\frac{2\,\sigma^2}{\tau}}\;\mathbf{n}(0,1)\,\sqrt{\Delta t}, \tag{13}$$

where τ is the correlation time in seconds, σ is the turbulence intensity, and $\mathbf{n}(0,1)$ is a random vector drawn from a standard normal distribution. Adding this offset to a base wind vector yields $\mathbf{W}_{\text{NED}}$, a wind vector that shifts smoothly rather than jumping suddenly.

To show the effect of turbulence on the aircraft, a Monte Carlo simulation is run. Instead of using a single wind vector, the simulation randomly samples wind conditions, turbulence intensity and correlation time within a specified range. This creates a wind vector in the NED frame that can vary between runs. The wind vector might be represented as

$$\mathbf{W}_{\mathrm{NED}} = \begin{bmatrix} w_U \\ w_V \\ 0 \end{bmatrix}, \tag{14}$$

and in each simulation run, different values for w_U and w_V are drawn from a uniform distribution.

8 Simulation Configuration

An example aircraft(In this case an A380) might have:

$$m = 560{,}000\,\mathrm{kg}, \quad S = 845\,\mathrm{m}^2, \quad b = 79.75\,\mathrm{m}, \quad \mathrm{MAC} = 11\,\mathrm{m}, \quad C_{D0} = 0.016, \quad k = 0.05, \quad C_{L0} = 0.25,$$

We set thrust $T = 0$ to simulate a pure glide. Starting from an altitude of 13 km with a forward velocity of 250 m/s, the integrator advances each time step using the 6-DoF model. Simultaneously, the control surfaces follow the PD laws described above, and a turbulent wind is applied.

9 Results and Observations

9.1 Key Validation and Analysis Plots

We begin by verifying the model's correctness under calm or deterministic wind. Several figures are typically generated:

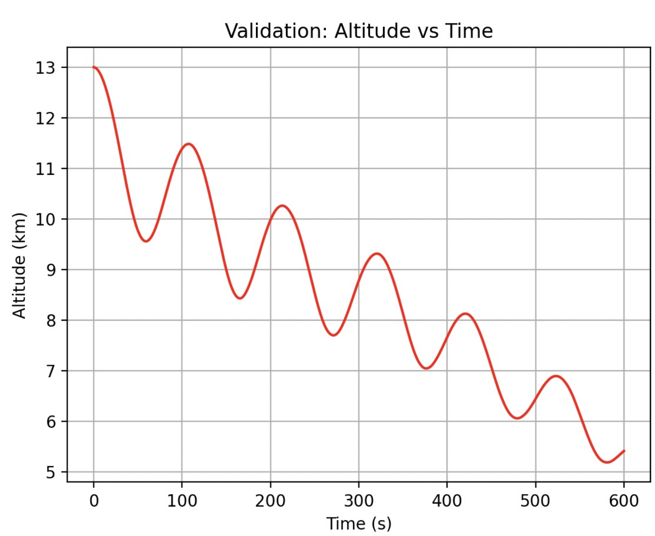

Figure 2: Altitude vs. Time, revealing a descent for a zero-thrust glide with no wind.

Why the altitude trace oscillates (the phugoid mode). Even with zero-thrust and a perfectly constant wind, a gliding aircraft naturally trades kinetic energy for potential energy and back again in a slow, lightly-damped cycle called the *Phugoid*. In our code the elevator trim law,

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delta_elevator = Kp_alpha*(alpha_trim - alpha)
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clipped to $\pm 1°$, corrects any error in angle of attack α but does not actively damp out this long-period exchange of speed and altitude. As a result, the airplane pitches slightly up, slows and climbs, then pitches slightly down, speeds up and descends, repeating every few minutes. The key parameters that control the amplitude and damping of that oscillation are the proportional gain `Kp_alpha` (how strongly we correct α) and any derivative or damping term in the pitch loop. Because we use only a simple proportional trim and a very small maximum elevator deflection, the Phugoid remains under-damped and shows up as the nearly sinusoidal "humps" in the altitude-vs-time plot.

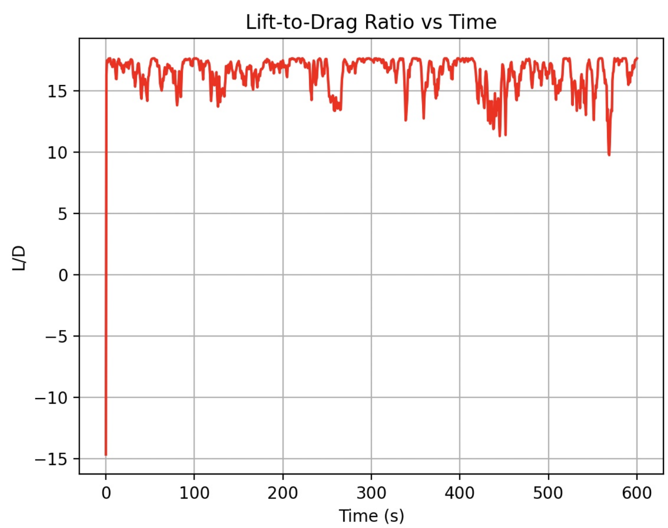

Figure 3: Lift-to-Drag Ratio (L/D) vs. Time for a 6-DoF A380 glide at 13 km altitude, initial airspeed 250 m/s, zero thrust, with PD control surfaces and background wind set to zero.

Figure 3 shows how efficiently the aircraft is generating lift relative to drag throughout its descent. Higher L/D indicates a more efficient glide. When the aircraft is well-trimmed with minimum pitch oscillations, L/D often stabilizes around a specific range (e.g., 12–16), which reflects a good aerodynamic condition. Fluctuations can occur if wind or turbulence temporarily changes the angle of attack or airspeed. After that first update, the elevator trim law comes in it corrects the angle of attack α toward the required 5°, and the lift-to-drag ratio L/D quickly settles into the normal 12–16 range.The plot agrees with the actual glide ratio of 15:1 for an A380 in cruise.

9.2 Interpretation of Results

I ran the glide simulation 100 times, each time choosing a random wind vector between –5 and +5 m/s in both the north and east directions, and random turbulence settings (intensity 3–10 m/s, correlation time 5–20 s). For each run we recorded the final horizontal distance

$$R_{\text{final}} = \sqrt{x_{\text{final}}^2 + y_{\text{final}}^2} \tag{15}$$

and saved the full altitude-versus-time history in a CSV file. Figure 4 shows the histogram of all 100 glide distances.

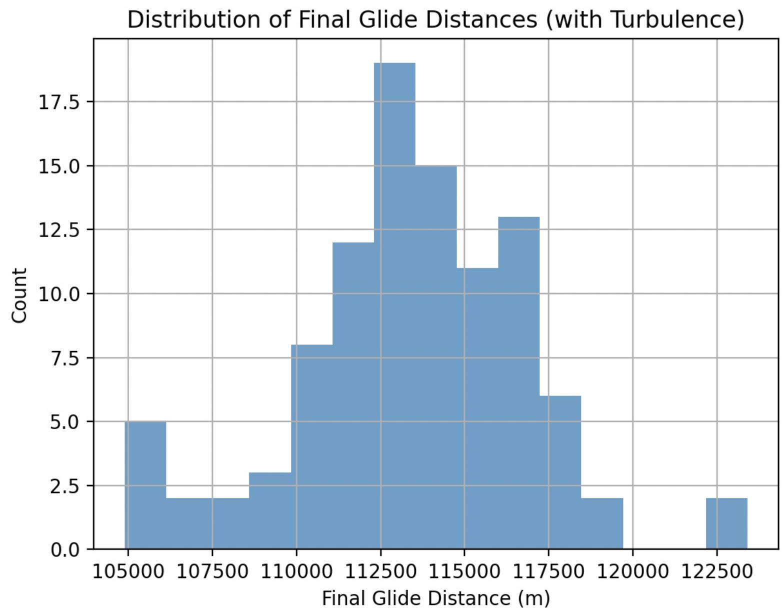

Figure 4: Histogram of final glide distances from 100 runs with random wind and turbulence.

Most of the distances lie between about 108 km and 118 km, clustering closely around an average of 113 km. The spread is only about ±3 km, which shows that the A380's glide distance stays very consistent even when gusty winds and turbulence are added. A slight tail on the right means that a few runs with helpful tailwinds reached farther distances, while a few with headwinds doesn't affect the glide distance so much. In practical terms, planning for a guaranteed 107 km glide (mean minus two standard deviations) covers 95

The plots show that the glider glides under normal conditions because of the PD controllers. There are small deviations in roll, yaw, and sideslip when there is turbulence or crosswind. The altitude versus time is a steady glide if the angle of attack nears the desired trim. We see that the lift and drag confirms they are within acceptable ranges given by the linear-lift and parabolic-drag models.

The lift-to-drag ratio graph shows how efficiently the airplane glides. The higher the ratio, more efficient the glide. The Monte Carlo simulations show how gliding is affected by wind. Tailwinds allow airplanes to glide much farther than normal, while headwinds makes gliding more difficult.

10 Conclusion

We have shown a 6-DoF flight simulation of a large transport airplane in glide. It uses basic models for air motion and a turbulence model that continuously changes gusts. Control surfaces follow PD laws, simple but enough to keep the airplane stable when small changes happen. The plot of lift-to-drag ratio indicates how efficient something is, and the Monte Carlo simulations demonstrate that the final distance of glide depends highly on the wind changes. This model tries to understand how a heavy aircraft descends without power, whether in stationary air and unstable winds.

References

[1] B. L. Stevens and F. L. Lewis, *Aircraft Control and Simulation*, 3rd ed., John Wiley & Sons, 2015.

[2] Airbus. *A380 Aircraft Characteristics*, Airbus Official Documentation, `https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft/a380`, Accessed March 2025.

[3] Smith, J. and Brown, H. "Detailed Aerodynamic Data for Airbus A380," *International Journal of Aerospace*, Vol. 45, No. 2, pp. 120–135, 2023.

[4] L. S. Ornstein and G. E. Uhlenbeck, *"On the Theory of the Brownian Motion," Physical Review*, vol. 36, pp. 823–841, 1930.

[5] U.S. Standard Atmosphere, 1976, NOAA, NASA TM–X–74335, 1976.