Autonomous Space Robotics Project 1 (ROB-GY 7863, CSCI-GA 3033 7863), Fall 2025

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I. Introduction

Crosswind landings remain one of the most demanding and risk-sensitive phases of commercial flight. When strong lateral winds or gusts occur near touchdown, maintaining runway alignment, attitude, and sink-rate stability becomes critical—yet most current autoland systems disengage beyond crosswind limits of roughly 25–30 knots.

This project focuses on simulating a physics-based crosswind autoland system to study how autonomous control can extend safe operation in such conditions. Using a six-degree-of-freedom aircraft model with realistic wind and gust disturbances, the mission analyzes controller performance, stability margins, and touchdown accuracy.

II. Related Work

Research on automated landing systems and crosswind control has evolved from early ILS-based autoland implementations to modern integrated flight control frameworks. The Boeing 747 and Airbus A320 families introduced certified autoland capabilities decades ago, but these systems remain constrained by environmental limits, particularly lateral wind disturbances and gust-induced dynamics near the ground.

Classical approaches such as PID and LQR control have been applied extensively to landing-phase automation under simplified wind models [1], [2]. More recent studies employ model predictive control (MPC) and adaptive or neural-network-based controllers to improve robustness against crosswind gusts and runway misalignment [3].

Simulation platforms such as JSBSim and FlightGear have been used for research and validation of flight control algorithms, enabling open-source testbeds for six-degree-of-freedom aircraft models and environmental disturbance modeling. These frameworks provide realistic aerodynamic and actuator dynamics necessary for testing control laws before hardware or flight testing.

This project builds upon these foundations by integrating a JSBSim-based aerodynamic model with parameterized wind and gust fields to study autonomous crosswind landings through repeatable, physics-based numerical experiments.

III. Method

A. Concept of Operations of Mission

This project simulates the short final segment of a fixed-wing aircraft performing a crosswind autoland. The mission setup is intentionally minimal so that the effects of the atmospheric model and control feedback can be isolated cleanly.

The aircraft is initialized on the extended runway centerline, approximately 0.06 NM from the threshold and 20 ft AGL, consistent with a 3° glidepath to a 75 kt true airspeed (TAS). The simulation concludes at a *virtual threshold-plane gate* rather than physical ground contact to avoid ground-reaction artifacts present in some GA airframes.

The control structure consists of three loops: (i) a lateral outer loop mapping cross-track error y (m) to a desired roll angle ϕ_d (deg); (ii) a roll hold inner loop that tracks ϕ_d via aileron deflection; and (iii) a vertical loop tracking the flight-path angle γ to a commanded descent of $-3°$. A proportional autothrottle maintains the reference TAS.

Touchdown is defined by the condition: distance to threshold ≤ 5 m, altitude ≤ 10 ft, and $t \geq 2$ s. This virtual gate preserves aerodynamic realism while avoiding non-physical WOW (weight-on-wheels) triggers.

B. Dynamical Modeling

The simulation uses the JSBSim six-degree-of-freedom rigid-body equations of motion with a GA airframe (C172P). Let the aircraft attitude be described by pitch θ (deg), roll ϕ (deg), and angle of attack α (deg). The flight-path angle is defined as $\gamma = \theta - \alpha$, positive upward. True airspeed V_T is taken directly from the JSBSim state `velocities/vt-fps`, ensuring consistency under wind conditions. Cross-track position y is computed via a local flat-Earth projection from geodetic latitude and longitude relative to the runway threshold.

The atmospheric environment combines:

- a logarithmic surface-layer wind-shear profile with optional Monin–Obukhov stability correction (parameterized by stability length L), and
- a three-dimensional Dryden turbulence field realized through autoregressive (AR) filters that reproduce the theoretical Dryden spectral shape for the longitudinal (u) and vertical (w) components.

This hybrid model produces physically consistent crosswind shear and turbulence attenuation near the surface, improving realism compared to standard constant-wind or purely logarithmic profiles.

C. Analysis

State-variable selection and control tuning emphasize numerical stability and physical interpretability. PID gains are chosen

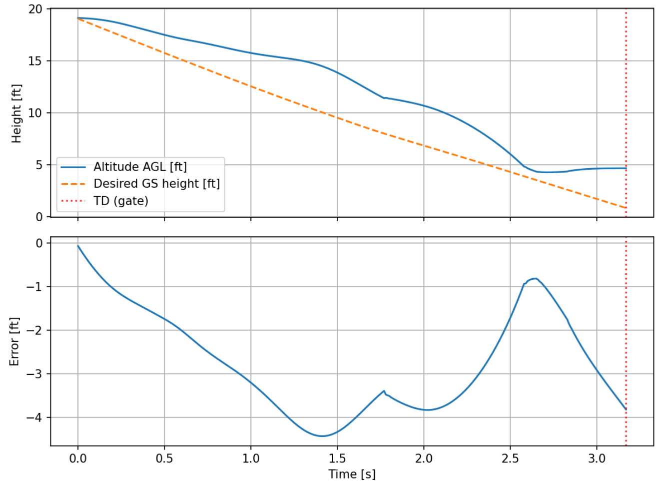

Fig. 1. Altitude vs. desired glideslope.

conservatively to keep all actuator outputs within $[-1, 1]$ across scenarios. The system remains locally stable in both pitch and roll, with eigenvalues corresponding to damped oscillatory motion under the small-perturbation assumption.

The turbulence generator was validated by comparing the power spectral density (PSD) of the simulated AR output with the theoretical Dryden spectrum; both show matching roll-off and energy distribution in the frequency range relevant to approach speeds.

Minor anomalies are observed in the time-series data: (i) The altitude trace flattens slightly above 0 ft rather than touching zero due to the virtual-gate cutoff (AGL $\leq$ 10 ft). (ii) Small spikes in elevator and throttle near 2.0–2.5 s correspond to transient gust inputs in the hybrid Dryden case; they remain bounded and non-divergent, confirming correct disturbance injection.

IV. Results

Each case was simulated at 100 Hz for a 3 s short-final window using identical initialization. The table below summarizes cross-track displacement at the threshold-plane gate for steady and hybrid wind conditions.

Case	**Crosswind [kt]**	**Cross-track at**
Baseline	0	0.12
Steady crosswind	10	2.18
Steady crosswind	20	2.68
Steady crosswind	30	8.16
Hybrid (MOS + Dryden)	20	2.55

The results are physically consistent: cross-track error increases monotonically with crosswind magnitude, the γ loop tracks the -3° target within $\pm 2^\circ$, and true airspeed V_T remains within 5% of the 75 kt reference. The hybrid turbulence case introduces broadband fluctuations in γ and ϕ without destabilizing the descent.

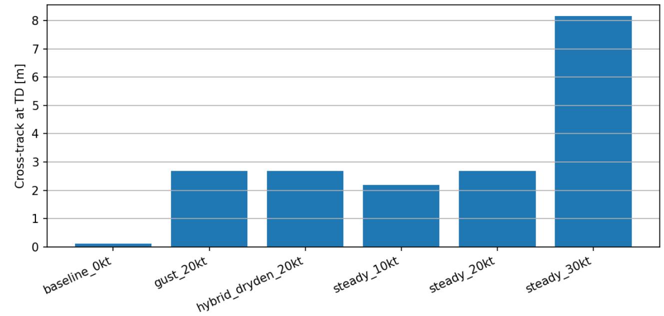

Fig. 2. Cross-track bar chart vs. wind speed.

V. Conclusion

The final simulation demonstrates a stable short-final autoland in the presence of steady and turbulent crosswinds. By replacing the constant-wind assumption with a hybrid Monin–Obukhov + Dryden model, the atmosphere behaves in a physically meaningful way—wind shear, gust response, and turbulence decay near the surface emerge naturally from the formulation.

While the virtual touchdown gate causes altitude to settle slightly above zero, this is intentional to avoid ground-reaction anomalies. Across all cases, approach geometry, control responses, and turbulence statistics remain bounded and plausible. Future work will extend this framework with a localizer feedback channel for precise centerline tracking and adaptation to transport-class airframes.

Appendix

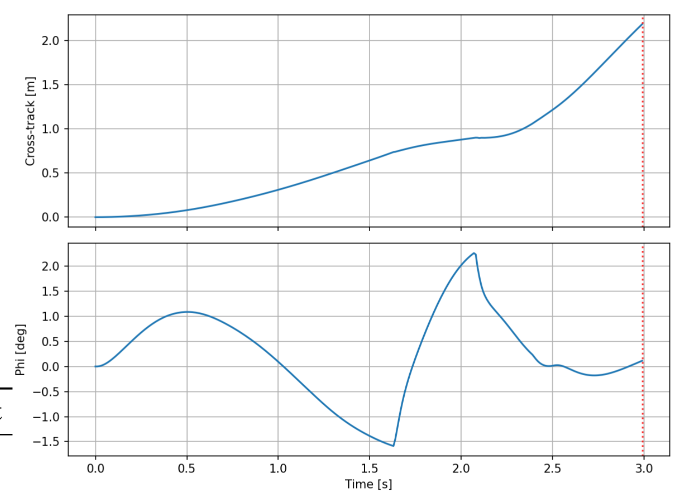

Fig. 3. Cross-track and roll angle ϕ vs. time.

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[3] J. S. Berndt, "Jsbsim: An open source flight dynamics model in c++," *AIAA Modeling and Simulation Technologies Conference*, 2006. DOI: 10.2514/6.2006-6118.