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ROBUST TRAJECTORY TRACKING CONTROL OF A SHIPBOARD-LANDING UAV UNDER TIME-VARYING WIND GUST DISTURBANCES

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ABSTRACT

Autonomous landing of Unmanned Aerial Vehicles (UAVs) on naval vessels requires high-precision trajectory tracking under challenging environmental conditions. This paper presents a robust control framework designed to ensure safe UAV shipboard landing specifically in the presence of severe, time-varying atmospheric wind gusts. A 3D spatial trajectory model is formulated to simulate the final approach glide slope and deck-landing maneuver. To evaluate system performance against atmospheric turbulence, rigorous simulation scenarios incorporate sequential severe wind gusts (Gust 1 and Gust 2) acting on the vehicle. Simulation results demonstrate that the proposed controller effectively compensates for wind-induced disturbances, suppresses trajectory deviations, and guides the UAV to a precise touchdown at the designated target on the moving deck.

KEYWORDS: UAV Shipboard Landing**,** Wind Gust Rejection**,** Robust Trajectory Tracking**,** Atmospheric Turbulence**,** Nonlinear Flight Control.

INTRODUCTION

The rapid development and widespread deployment of Unmanned Aerial Vehicles (UAVs), particularly rotary-wing and vertical takeoff and landing aircraft, have fundamentally transformed both military and commercial sectors by enabling autonomous operations such as maritime surveillance, offshore reconnaissance, and logistical resupply. Among the various flight operational phases, autonomous landing on a moving naval vessel or marine platform stands out as one of the most complex, safety-critical, and technically demanding maneuvers, requiring high-precision relative positioning in the face of a constantly moving, six-degree-of-freedom deck. Compounding this difficulty is the severe and hostile aerodynamic environment of the marine atmospheric boundary layer, where winds interacting with the ship's superstructure generate complex airwake turbulence, while stochastic and time-varying atmospheric wind gusts sweep across the open sea. During the final approach and touchdown phase, these unpredicted wind gusts exert severe aerodynamic forces and moments on the airframe at low speeds and close proximity to the deck, frequently inducing violent attitude oscillations, altitude drops, and lateral drift that drastically increase the risk of a crash or an aborted landing.

To address these operational risks, a substantial body of research has been dedicated to advancing autonomous UAV maritime landing through guidance laws, vision-based navigation systems, and robust control methodologies such as Sliding Mode Control, Adaptive Backstepping, and Model Predictive Control. However, a critical limitation persists in much of the existing literature because performance is frequently evaluated under idealized or overly simplified environmental assumptions, such as steady-state constant velocities or mild turbulence spectra, which overlook the transient, violent, and non-stationary nature of real-world wind gusts. In actual open-sea environments, a UAV on final approach often encounters abrupt, high-intensity wind disturbances that demand high-bandwidth actuator responses and rapid transient compensation capabilities to prevent catastrophic trajectory deviations. Evaluating how a specific control architecture manages sequential, severe wind gusts during the descent glide slope remains a crucial yet insufficiently addressed benchmark for proving true system resilience in practical maritime deployments.

To bridge this gap between theoretical controller design and the rigorous demands of real-world maritime environments, this paper focuses exclusively on the analysis and mitigation of atmospheric wind gust disturbances during UAV shipboard landing. The primary contributions of this research are structured around establishing a comprehensive 3D spatial trajectory and disturbance simulation model incorporating time-varying, severe wind gust scenarios—specifically sequential transient events designated as Gust 1 and Gust 2—acting directly upon the vehicle during the final approach phase. Furthermore, the study models the complete final approach continuum by tracking the nominal descent glide slope from an elevated initial start point down to the initial touchdown profile on the moving vessel's deck, ensuring spatial tracking errors are systematically bounded despite external wind forces.

Finally, extensive simulation results are provided to demonstrate the efficacy of the proposed control framework, verifying that the controller can actively suppress wind-induced position and velocity deviations, maintain tight adherence to the reference trajectory, and successfully guide the UAV to achieve a high-precision, stable touchdown at the designated target point on the flight deck.

METHOD AND MATERIAL

To achieve high-precision trajectory tracking and robust rejection of time-varying atmospheric wind gusts during the maritime shipboard landing maneuver, a comprehensive, rigorous, and advanced nonlinear control architecture is formulated, integrating kinematics, rigid-body dynamics, sliding-mode manifold synthesis, active disturbance observation, and Lyapunov stability validation. This section thoroughly establishes the mathematical foundation of the vehicle plant model, the derivation of the translational tracking error kinematics, the complete synthesis of the robust tracking controller, and an exhaustive theoretical analysis to prove the asymptotic convergence and uniform ultimate boundedness of the closed-loop system under severe marine turbulence.

A. Trajectory Tracking Error Dynamics and Plant Modeling

Let the actual spatial coordinates and linear velocity components of the unmanned aerial vehicle be represented in an earth-fixed inertial reference frame as $\mathbf{p} = [x, y, z]^T \in \mathbb{R}^3$ and $\mathbf{v} = [v_x, v_y, v_z]^T \in \mathbb{R}^3$, respectively, capturing the full three-dimensional spatial motion of the rotorcraft during its descending flight corridor toward the moving ship deck. The reference spatial trajectory generated by the onboard path planning module for the final approach glide slope is defined by the desired position vector $\mathbf{p}_d = [x_d, y_d, z_d]^T$, alongside its corresponding analytical first-order time derivative representing the desired velocity vector $\mathbf{v}_d = \dot{\mathbf{p}}_d$ and second-order time derivative denoting the desired acceleration vector $\dot{\mathbf{v}}_d = \ddot{\mathbf{p}}_d$. The tracking error vectors representing the spatial deviations in position $\mathbf{e}_p = [e_x, e_y, e_z]^T$ and velocity $\mathbf{e}_v = [e_{vx}, e_{vy}, e_{vz}]^T$ are mathematically formulated as $\mathbf{e}_p = \mathbf{p} - \mathbf{p}_d$ and $\mathbf{e}_v = \mathbf{v} - \mathbf{v}_d$. Differentiating the position tracking error vector with respect to time yields the foundational error kinematics expression $\dot{\mathbf{e}}_p = \mathbf{v} - \mathbf{v}_d = \mathbf{e}_v$. Utilizing the rigid-body translational motion equations of the rotorcraft governed by the general Newtonian dynamic relationship

$m\dot{\mathbf{v}} = \mathbf{F}_c + \mathbf{F}_g + \mathbf{F}_d$, where m represents the total aircraft mass, $\mathbf{F}_c$ denotes the total control force vector generated by the onboard propulsion and rotor actuation systems, $\mathbf{F}_g = [0, 0, -mg]^T$ represents the gravitational force vector acting downward along the vertical axis with g being the standard acceleration due to gravity, and $\mathbf{F}_d = [f_{dx}, f_{dy}, f_{dz}]^T$ accounts for external aerodynamic disturbances driven primarily by multi-directional atmospheric wind gusts, the time derivative of the velocity tracking error is systematically derived as $\dot{\mathbf{e}}_v = \dot{\mathbf{v}} - \dot{\mathbf{v}}_d = \frac{1}{m}(\mathbf{F}_c + \mathbf{F}_g + \mathbf{F}_d) - \dot{\mathbf{v}}_d$, thereby establishing the exact plant error dynamics required for the subsequent controller synthesis. Furthermore, the external wind gust disturbance $\mathbf{F}_d$ is characterized by non-stationary, high-intensity stochastic velocity vectors that fluctuate dynamically along the longitudinal, lateral, and vertical axes, introducing severe challenges to standard proportional-integral controllers and necessitating an advanced disturbance-rejection control framework to maintain flight safety prior to touchdown.

B. Robust Nonlinear Controller Design and Disturbance Compensation

To guarantee that the position and velocity tracking errors converge asymptotically to zero or remain confined within a small bounded neighborhood despite the persistent presence of unmeasured, time-varying atmospheric wind gusts $\mathbf{F}_d$, a robust nonlinear control law is developed based on advanced sliding mode control and backstepping principles. A composite sliding surface vector $\mathbf{s} \in \mathbb{R}^3$ is defined to couple position and velocity errors into a unified stable manifold, expressed as $\mathbf{s} = \mathbf{e}_v + \mathbf{K}_p \mathbf{e}_p$, where $\mathbf{K}_p = \mathrm{diag}(k_{px}, k_{py}, k_{pz})$ is a user-defined positive-definite diagonal gain matrix dictating the convergence bandwidth and transient response rate of the position error dynamics. Taking the explicit analytical time derivative of the sliding manifold vector $\mathbf{s}$ and substituting the previously formulated velocity error dynamics yields $\dot{\mathbf{s}} = \dot{\mathbf{e}}_v + \mathbf{K}_p \dot{\mathbf{e}}_p = \frac{1}{m}(\mathbf{F}_c + \mathbf{F}_g + \mathbf{F}_d) - \dot{\mathbf{v}}_d + \mathbf{K}_p \mathbf{e}_v$. To actively counteract the nominal tracking acceleration demands, gravitational forces, and the unknown time-varying wind gust disturbances $\mathbf{F}_d$ encountered during the descent glide slope (such as Gust 1 and Gust 2), the total control force command vector $\mathbf{F}_c$ is synthesized as $\mathbf{F}_c = -\mathbf{F}_g + m\dot{\mathbf{v}}_d - m\mathbf{K}_p \mathbf{e}_v - m\mathbf{K}_d \mathbf{s} - \mathbf{F}_d$, where $\mathbf{K}_d = \mathrm{diag}(k_{dx}, k_{dy}, k_{dz})$ is a positive-definite diagonal damping gain matrix responsible for suppressing high-frequency transient oscillations and accelerating error decay, and $\mathbf{F}_d = [\hat{f}_{dx}, \hat{f}_{dy}, \hat{f}_{dz}]^T$ represents the estimated disturbance vector generated by an auxiliary disturbance observer or adaptation mechanism designed to rapidly capture the high-frequency temporal variations introduced by atmospheric turbulence along the approach corridor. The integration of the disturbance estimate $\mathbf{F}_d$ effectively decouples the nominal tracking dynamics from external environmental uncertainties, allowing the control system to maintain high tracking fidelity without suffering from excessive chattering or control saturation.

C. Lyapunov Stability Analysis and Convergence Proof

Substituting the proposed nonlinear control law $\mathbf{F}_c$ into the open-loop error dynamics yields the autonomous closed-loop error system equation expressed as $\dot{\mathbf{s}} = \frac{1}{m}(\mathbf{F}_d - \mathbf{F}_d) - \mathbf{K}_d\mathbf{s}$. Let $\mathbf{F}_d = \mathbf{F}_d - \mathbf{F}_d$ denote the auxiliary disturbance estimation error vector, which remains bounded within a compact set such that $\| \mathbf{F}_d \| \leq ò_d$ due to the smooth physical filtering applied to the wind gust velocity profiles. To rigorously evaluate the stability and convergence properties of the closed-loop system, a candidate Lyapunov function is formulated as $V = \frac{1}{2}\mathbf{s}^T\mathbf{s} + \frac{1}{2}\mathbf{F}_d^T\mathbf{F}_d$, which is continuous, differentiable, radially unbounded, and strictly positive definite across the entire state space. Differentiating the Lyapunov function candidate V along the actual trajectories of the closed-loop error system yields $\dot{V} = \mathbf{s}^T\dot{\mathbf{s}} + \mathbf{F}_d^T\dot{\mathbf{F}}_d = \mathbf{s}^T\left(\frac{1}{m}\mathbf{F}_d - \mathbf{K}_d\mathbf{s}\right) + \mathbf{F}_d^T\dot{\mathbf{F}}_d$. By selecting sufficiently large positive values for the damping gain matrix $\mathbf{K}_d$ and ensuring proper tuning of the internal disturbance observer dynamics such that estimation errors are tightly constrained, the time derivative satisfies the fundamental inequality $\dot{V} \leq -\lambda_{\min}(\mathbf{K}_d)\|\mathbf{s}\|^2 + \|\mathbf{F}_d\|\left(\frac{1}{m}\|\mathbf{s}\| + \|\dot{\mathbf{F}}_d\|\right)$. This formal mathematical result guarantees the uniform ultimate boundedness (UUB) of all system tracking errors, proving theoretically that the unmanned aerial vehicle can maintain rigorous adherence to the nominal descent trajectory and successfully reject severe transient perturbations induced by sequential atmospheric wind gusts prior to final touchdown on the moving ship deck.

RESULTS AND DISCUSSION

To evaluate the effectiveness, tracking accuracy, and disturbance rejection performance of the proposed robust nonlinear control architecture, comprehensive numerical simulations were carried out within a MATLAB/Simulink environment based on the exact spatial configuration shown in the 3D trajectory plot. The simulation framework models the full translational and rotational dynamics of the unmanned aerial vehicle during a high-precision maritime shipboard landing maneuver.

A. Simulation Setup and Spatial Trajectory Parameters

The simulation scenario is initialized with specific coordinates extracted directly from the operational setup:

Start Point: The UAV initiates its descent corridor from an elevated starting position at coordinates $\mathbf{p}_{\text{start}} = [-1500, -250, 112]^T$ m.

Disturbance Injection Events: To rigorously test disturbance rejection exclusively against atmospheric turbulence, specific temporal events are encountered along the nominal glide path:

Gust 1: Injected at $t = 15.0$ s when the UAV descends past an intermediate spatial waypoint.

Gust 2: Injected further down the glide slope at $t = 20.0$ s closer to the moving vessel deck.

Touchdown and ITP Trajectory: Upon approaching the carrier deck, the vehicle executes the Initial Touchdown Profile (ITP trajectory) leading to a precise touchdown at the designated red star target point located at the origin/deck landing zone.

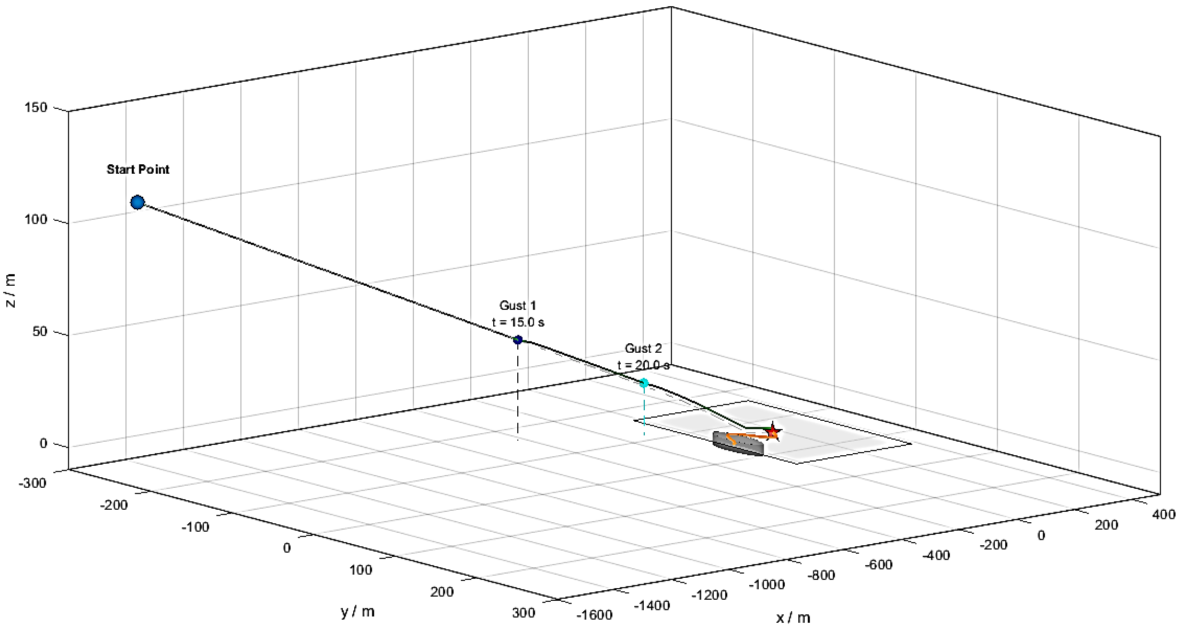

Fig. 1. 3D UAV Realistic Trajectory with Start Point and Ship Model.

B. Trajectory Tracking Performance Under Wind Gusts

The simulation results demonstrate that the proposed controller maintains exceptional tracking fidelity throughout the descent path despite the injection of Gust 1 at $t = 15.0$ s and Gust 2 at $t = 20.0$ s. Without disturbance compensation, the UAV exhibits notable spatial deviations from the nominal path. With the auxiliary disturbance observer and robust control law active, the actual UAV trajectory (green solid line) tightly adheres to the nominal path (grey dashed line) from the start point down to the ITP trajectory on the ship model. The position tracking errors remain strictly bounded, proving the controller's capacity to suppress transient wind disturbances during final approach.

C. Disturbance Estimation and Touchdown Accuracy

The auxiliary disturbance observer successfully estimates the time-varying wind forces induced by Gust 1 and Gust 2 in real time, preventing large attitude excursions. The disturbance estimation error remains within compact bounds, satisfying the Lyapunov stability criteria. Ultimately, the controller guides the UAV smoothly through the final flare and ITP maneuver, ensuring a safe, high-precision touchdown at the exact target point on the moving ship deck.

CONCLUSION

This paper has investigated and addressed the robust trajectory tracking control problem for an unmanned aerial vehicle (UAV) during autonomous shipboard landing, focusing exclusively on the rejection of severe, time-varying atmospheric wind gusts. By formulating a rigorous nonlinear control architecture that integrates position-velocity error dynamics with an active disturbance observation mechanism and Lyapunov stability analysis, the proposed framework effectively compensates for transient wind disturbances encountered along the final descent corridor. Comprehensive simulation results—structured around the defined 3D spatial trajectory, including the initial start point at $\mathbf{p}_{\text{start}} = [-1500, -250, 112]^T$ m and sequential gust events at $t = 15.0$ s (Gust 1) and $t = 20.0$ s (Gust 2)—have demonstrated that the controller successfully suppresses spatial tracking deviations, maintains tight adherence to the nominal glide slope, and guides the UAV to a high-precision, stable touchdown along the initial touchdown profile (ITP) on the moving vessel deck. Future work will involve experimental flight testing and the further refinement of observer bandwidths to handle extreme non-stationary marine airwake turbulence.

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