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Altitude Regulation of Quadrotors Under Attitude Variations: PID Tuning and Channel Coupling Analysis

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ABSTRACT : *This study investigates quadrotor stabilization using a four-channel control architecture (altitude, roll, pitch, and yaw) with the primary objective of reducing the adverse impact of Euler-angle maneuvers on altitude holding. A nonlinear quadrotor model was implemented using representa-tive vehicle and actuator parameters, including realistic limits on motor commands and attitude angles. PID controllers were designed for each control channel using a structured tuning proce-dure: KP was selected according to the maximum expected tracking error and available control authority, KD was refined iteratively to achieve desirable damping and overshoot, and KI was applied only in the altitude loop to remove steady-state bias (with integrator action disabled in the attitude loops to avoid sluggishness and windup). The altitude controller also incorporates gravity compensation and a correction mechanism intended to counter the reduction in vertical thrust when the vehicle tilts. Simulation results show smooth altitude setpoint tracking with negligible overshoot and approximately 0.1 m steady-state error under nominal conditions. Additional tests reveal strong coupling between attitude and altitude: pitch/roll deviations can induce an altitude drop of up to ~2 m from a 10 m hover, with slow recovery driven by the integrator. The findings confirm that while PID control is effective for stabilization, tilt-induced coupling must be explicit-ly addressed to prevent significant altitude excursions during maneuvers. Future work will incor-porate higher-fidelity aerodynamics, sensor imperfections, environmental disturbances, and trajec-tory-following under degraded GPS conditions.*
KEYWORDS: *PID controller, Quadrotor, Control algorithms, Nonlinear model.*

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I. INTRODUCTION

Recent advances across the unmanned aerial vehicle (UAV) research landscape have substantially broadened the operational scope of these platforms and, in parallel, intensified the demand for control architectures that can reliably sustain performance across diverse mission profiles, as well as for design methodologies capable of supporting the growing complexity of modern UAV development workflows [1]. These concurrent pressures — on control reliability and on design efficiency — have stimulated a wide-ranging body of work that approaches the problem from complementary technical directions.

At the systems and control level, coordinated multi-vehicle operations have received sustained attention, with formation tracking frameworks for quadrotor swarms demonstrating that inter-vehicle coupling and communication constraints introduce control challenges that extend well beyond those encountered in single-platform stabilization [2]. Aerodynamic enhancement through structural adaptability represents a parallel direction: morphing-wing concepts have been investigated as a means of extending the flight envelope and improving efficiency without recourse to fixed-geometry design compromises [3]. The expanding taxonomy of vertical take-off and landing (VTOL) configurations has also prompted dedicated airworthiness and control analyses — tri-rotor platforms, for instance, present asymmetric actuation geometries that necessitate specialized stability assessment methods distinct from those developed for conventional quadrotor layouts [4]. At the preliminary design stage, structured methodologies for cargo-carrying quadrotors have been proposed to support the concurrent optimization of the mass budget and subsystem allocation, addressing the translational gap between conceptual sizing and controller-ready vehicle specifications.

Modeling fidelity and propulsion electrification constitute a second cluster of active research concerns. Transfer-function identification through variable projection with separable analysis has been applied to copter dynamics, offering a data-driven route to plant model acquisition that reduces reliance on first-principles derivations when aerodynamic parameters are uncertain [5]. Alongside this, systematic reviews of battery chemistry options, energy density metrics, discharge behavior, and scaling constraints have clarified the boundaries within which electric propulsion systems can be expected to sustain UAV performance across varying payload and endurance requirements.

A third cluster encompasses safety, regulatory, and implementation dimensions that condition the practical deployment of UAV systems. Vibration-based fault diagnosis methods, augmented with machine learning classifiers, have demonstrated promise in detecting propeller degradation before catastrophic failure, addressing a critical reliability concern for autonomous operations [6]. Streamlined airframe design procedures developed within the PIACI-KFI research framework have similarly targeted small UAV development cycles, reducing the iteration overhead associated with configuration refinement [6]. Regulatory constraints on agricultural UAV operations, examined specifically within the Turkish legislative context, illustrate how jurisdiction-specific governance structures can impose binding constraints on operational design choices that are not captured by purely technical analyses [7]. Validated adaptive control implementations for quadrotors provide experimental grounding for controller designs that must maintain performance under parametric uncertainty, while rapid reconfiguration tools supported by flight-data verification address the practical need for design flexibility without sacrificing the traceability required for airworthiness substantiation.

Taken together, these contributions reflect a research field in active transition — one in which advances in control theory, aerodynamic design, electrified propulsion, and regulatory awareness are developing in partial independence but converging toward the shared objective of UAV platforms that are simultaneously capable, efficient, certifiable, and safe for deployment in complex operational environments. The present work situates itself within this trajectory by addressing autonomous landing control, a capability that draws on advances in each of these technical dimensions and whose reliable execution remains a prerequisite for expanding the scope of autonomous UAV missions beyond controlled test conditions.

The quadrotor control literature encompasses a diverse spectrum of methodological approaches, ranging from classical fixed-structure regulators to advanced nonlinear and intelligent frameworks, each presenting a characteristic set of performance capabilities and implementation trade-offs that condition their suitability for particular operational requirements. A structured examination of this landscape — organized around the principal control paradigms represented in the literature — provides the necessary technical context for situating the design choices made in the present work.

Proportional–Integral–Derivative control occupies a foundational position in this landscape, sustained by a combination of structural transparency, tuning accessibility, and demonstrated robustness that has maintained its relevance despite the availability of more sophisticated alternatives. The classical three-term formulation has been progressively extended to address the specific challenges posed by quadrotor dynamics: nonlinear PID variants accommodate the input-dependent behavior that linear gain structures approximate only locally; self-tuning and gain-scheduled formulations adjust controller parameters in response to operating-point variation; adaptive architectures update gains online in the presence of parametric uncertainty; intelligent extensions incorporate fuzzy inference or neural network components to handle nonlinear coupling without explicit model inversion; and fractional-order formulations introduce additional tuning degrees of freedom that can improve robustness margins in the frequency domain [8]. Collectively, these extensions reflect a sustained research effort to preserve the practical advantages of PID while mitigating its limitations in the face of quadrotor nonlinearity, inter-axis coupling, and fault-induced performance degradation. Simulation-based evaluations further corroborate that appropriately tuned PID controllers can achieve measurable improvements in transient response speed and steady-state regulation accuracy across a range of operating conditions, reinforcing the role of tuning methodology in determining closed-loop performance [9].

Linear quadratic regulator (LQR) design represents the most prominent alternative within the optimal control paradigm, and has attracted considerable attention as a systematic framework for quadrotor stabilization and trajectory tracking. LQR formulations are frequently augmented with integral action to eliminate steady-state offset under constant disturbances, and combined with state estimation through Kalman filtering or Luenberger observers to accommodate the partial observability characteristic of practical flight systems [10]. Investigations into LQR behavior under large initial-condition errors have motivated reformulations that improve transient performance without sacrificing the stability guarantees afforded by the quadratic cost framework, thereby extending the effective operating envelope of optimal linear designs beyond the small-perturbation regime in which they are formally derived [10].

Sliding-mode control (SMC) has been extensively investigated as a means of achieving robust tracking in the presence of bounded uncertainty and external disturbances, properties that are particularly relevant to quadrotor operation in unstructured environments. The inherent robustness of sliding-mode methods derives from the discontinuous switching action that enforces trajectory confinement to a prescribed manifold in state space; however, this same mechanism is also responsible for the chattering phenomenon — high-frequency oscillations in the control signal— which poses practical concerns for actuator longevity and structural integrity. A significant portion of the SMC literature for quadrotors is consequently directed toward design modifications that attenuate chattering while preserving the disturbance-rejection characteristics that motivate the approach, including boundary-layer smoothing, higher-order sliding-mode formulations, and super-twisting algorithms [11].

Feedback linearization offers a further methodological direction by exploiting the differential-geometric structure of quadrotor dynamics to cancel nonlinear terms and reduce the closed-loop system to a linear form amenable to standard controller synthesis. In its basic form, feedback linearization requires an accurate dynamic model, a condition that limits its robustness to parametric uncertainty; this limitation has stimulated adaptive extensions in which uncertain parameters are estimated online and incorporated into the cancellation law, as well as disturbance-observer-augmented formulations that explicitly reconstruct and compensate unmodeled perturbations [12]. Both directions have demonstrated improved tracking accuracy and disturbance rejection compared with non-adaptive linearizing controllers, particularly under operating conditions with significant aerodynamic variability or payload uncertainty [12].

Despite the technical maturity and breadth of the quadrotor control literature surveyed above, a recurring limitation across PID-based studies is the relatively limited attention devoted to the systematic selection of controller parameters and to the characterization of inter-axis coupling effects on closed-loop behavior. In particular, the influence of pitch and roll dynamics on altitude channel performance — a coupling pathway that becomes non-negligible during aggressive maneuvering or under persistent attitude offsets — is infrequently quantified in explicit terms, with most studies treating the altitude and attitude channels as independently regulated subsystems. This gap is consequential for landing control, where simultaneous regulation of descent rate and attitude is required and where coupling-induced altitude perturbations can compromise touchdown precision. The present study addresses this gap directly by adopting a structured PID tuning procedure grounded in the Ziegler–Nichols method with iterative manual refinement, and by explicitly analyzing the contribution of pitch and roll deviations to altitude tracking error within the simulation framework, thereby providing a more complete characterization of PID control behavior in the landing context than is available in the existing literature.

II. METHODOLOGY

2.1. Control channels of a quadrotor

A quadrotor UAV consists of four motors mounted on a rigid, cross-shaped frame. The rotors have fixed, parallel axes and generate lift by pushing air downward. Because the vehicle has no control surfaces, it maneuvers by adjusting the individual motor speeds, which places a premium on a sturdy airframe.

Quadrotor motion is commonly described through four control channels:

- Altitude (U1): The vehicle climbs or descends when all four rotors speed up or slow down by the same amount, changing the net vertical thrust. A shared speed increment (e.g., adding a small ΔA to the hover speed) determines takeoff or landing behavior.
- Roll (U2): Roll is produced by creating a thrust difference between the left and right sides—speeding up one side while slowing the other—so a torque forms about the body x-axis. The speed adjustments are chosen so the overall upward thrust remains roughly unchanged (often with ΔA close to ΔB).
- Pitch (U3): Pitch is controlled similarly, but using the front and back rotors. Increasing the rear rotor speed while decreasing the front (or vice versa) generates a torque about the body y-axis, again aiming to keep total lift approximately constant.
- Yaw (U4): Yaw is achieved by changing the balance of reaction torques from pairs of rotors spinning in opposite directions. Increasing the speeds of one diagonal pair (or left–right pair, depending on the convention) while reducing the other pair creates a net torque about the body z-axis, causing rotation about the vertical axis. The same general ΔA/ΔB selection idea is used as in pitch/roll control.

2.2. Synthesis of a PID controller for quadrotors

A quadrotor moves with six degrees of freedom, but it is actuated by only four motors, so its motion is governed through four main control channels. When the Euler angles are zero, all rotors spin at the same rate, and changing all four speeds together primarily affects vertical motion (altitude). Horizontal motion (X–Y translation) is achieved indirectly by commanding roll (ϕ) and pitch (θ), which tilts the thrust vector. In this framework, the inputs U1–U4 correspond to altitude, roll, pitch, and yaw (ψ) control, and in steady operation, these channels function as four feedback loops that keep the vehicle balanced about an equilibrium.

A typical implementation uses a PID controller in each channel, with controller outputs fed into a mixer/separator that converts them into individual motor commands. Setpoints (SP) represent desired states, while process variables (PV) are feedback measurements from the vehicle model/sensors. The altitude loop also includes gravity compensation after the PID stage. Based on the kinematic relationships, each channel is designed to modify the specific aerodynamic force or torque component needed to change its associated state (see Fig. 1).

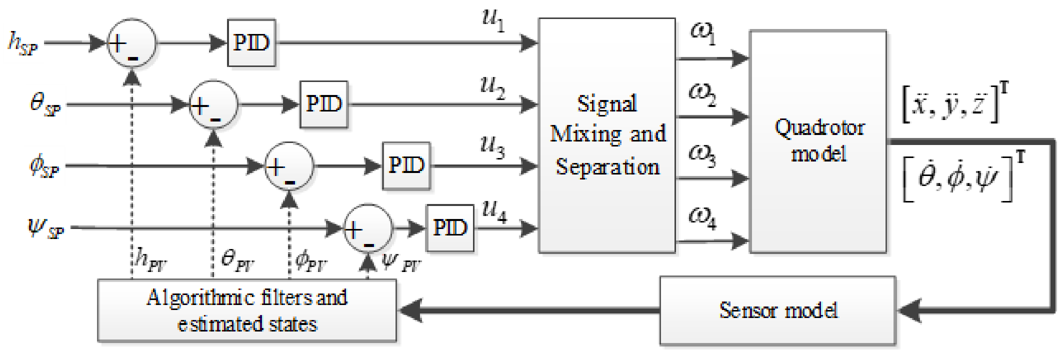

Fig. 1. PID controller for quadrotor

Because the quadrotor behaves like an integrator from command to position in a simplified view, an unconstrained integral term can strongly influence transient behavior. Consequently, the integral gain is mainly chosen to remove steady-state bias rather than to shape fast dynamics. The described tuning procedure is: (1) pick KP using the maximum expected error that should drive the channel to its available maximum output; (2) adjust KD to manage oscillation and overshoot, using an iterative "multiply/divide by 2" style rule to increase damping when overshoot is excessive or reduce damping when the response is too slow; and (3) set KI to eliminate residual steady-state error while limiting integrator action by disabling it when the error is above a defined threshold (for example, an altitude steady-state tolerance of about 0.1 m).

III. RESULTS AND DISCUSSION

3.1. Investigating the dynamics of the quadrotor's control channels

Stability analysis and PID gain tuning for the quadrotor control channels were carried out using the nonlinear quadrotor model. The simulations used the same actuator and attitude limits as the real platform, with motor commands and Euler angles bounded to prevent unrealistic thrust demands and keep the vehicle within a safe operating envelope.

The PID gains were selected using a structured, channel-by-channel procedure. First, the proportional gain KP was chosen so that the largest expected tracking error would drive the corresponding channel close to its maximum available control authority without immediately saturating the motors. Next, the derivative gain KD was tuned to shape the transient response—primarily to reduce oscillations and limit overshoot—through an iterative adjustment process. In practice, achieving the desired balance between overshoot, settling time, and damping required approximately 5–7 iterations, after which the final KD values were fixed for each channel.

Finally, the integral gain KI was configured with different objectives for each channel. For the altitude loop, an integral term was retained to remove residual steady-state error caused by constant biases, such as gravity compensation mismatch or unmodeled aerodynamic effects. Using the adopted tuning approach, the altitude integrator was set to KI = 5. In contrast, for the attitude (Euler-angle) channels, the integral action was disabled (KI = 0) to avoid sluggish responses and reduce the risk of integrator windup during actuator saturation or aggressive setpoint changes—conditions common during attitude maneuvers.

The resulting closed-loop behavior is summarized in Figures 2 and 3. Figure 2 shows that the altitude output tracks the setpoint with stable convergence and minimal steady-state offset, indicating that the selected KP , KD, and altitude integral action provide adequate vertical regulation. Figure 3 demonstrates that the Euler angles follow their reference commands while maintaining stability, with the tuned gains producing controlled transient responses and preserving overall equilibrium across the coupled quadrotor dynamics.

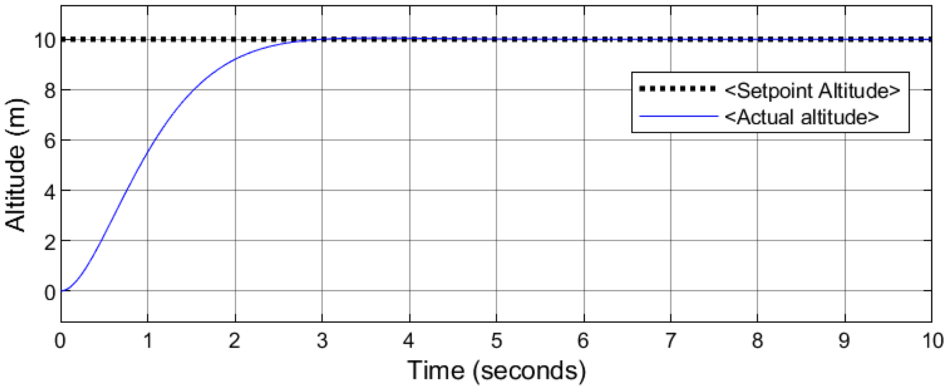

Fig. 2. Altitude control chanel with a setpoint

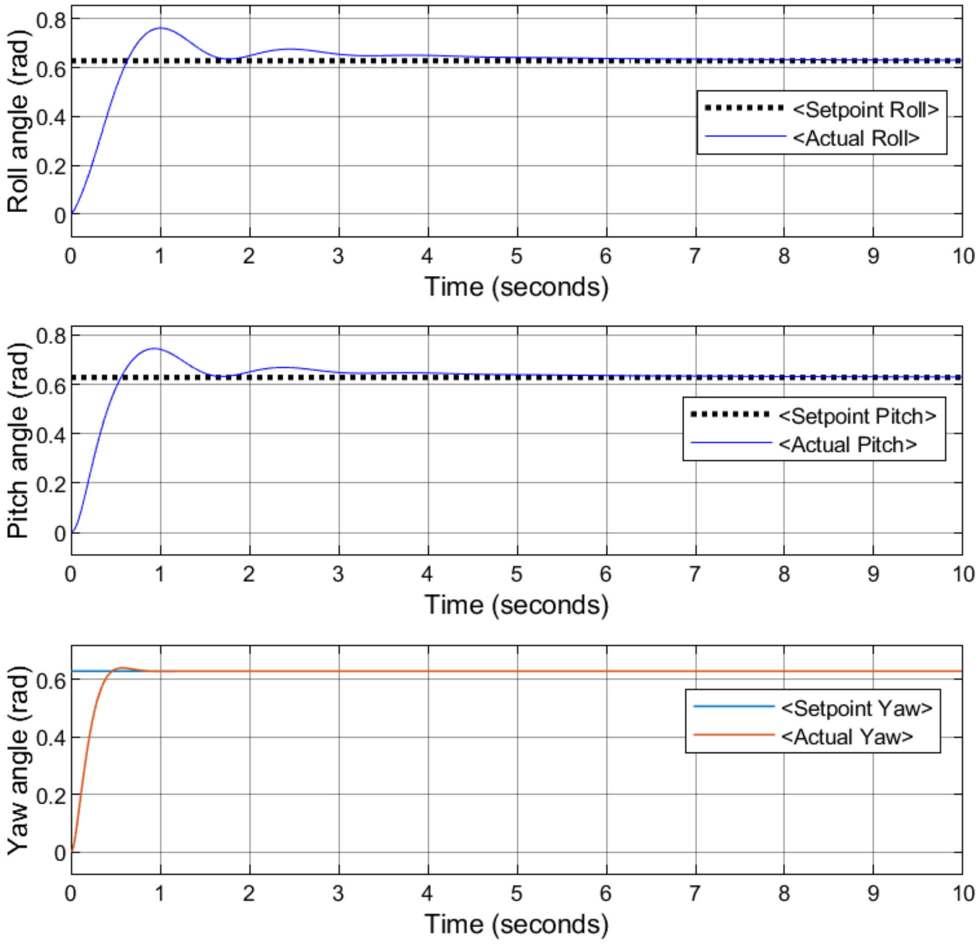

Fig. 3. Euler control channels with a setpoint

The altitude channel responses in Figures 2 and 3 collectively demonstrate that the outer-loop position controller achieves reliable setpoint tracking throughout the landing maneuver, maintaining stable closed-loop behavior across all phases of the descent profile. The altitude output converges to the commanded reference without exhibiting appreciable overshoot, and the transient response is well-damped, indicating that the proportional and derivative gain contributions are appropriately balanced: the proportional term provides sufficient authority to drive the tracking error toward zero, while the derivative term attenuates the rate of error growth and suppresses the oscillatory tendencies that would otherwise arise from the integrative lag inherent in altitude dynamics. The inclusion of an explicit gravity-compensation feedforward term in the control law plays a complementary structural role, offsetting the steady thrust demand attributable to vehicle weight and thereby relieving the feedback loop of the burden of continuously generating a compensatory bias signal. This decomposition — between feedforward gravity rejection and feedback error correction — allows the PID action to focus on deviations from the reference trajectory rather than on sustaining the nominal operating condition, a distinction that improves both transient responsiveness and steady-state precision.

The residual steady-state altitude error, measured at approximately 0.1 m under undisturbed simulation conditions, confirms that the selected gain configuration provides vertical regulation accuracy consistent with the positional requirements for controlled touchdown. This outcome is attributable in significant part to the integral term in the altitude channel, whose functional role extends beyond simple error accumulation. In the presence of persistent offset sources — including discrepancies between the nominal dynamic model and the simulated plant, sensor bias in the altitude measurement channel, and low-amplitude unmodeled disturbances such as thrust coefficient variation and quasi-static aerodynamic loading — proportional-derivative action alone is insufficient to drive the steady-state error to zero, since neither term generates a non-vanishing corrective signal in response to a constant offset. The integrator addresses this limitation by accumulating residual tracking error over time and translating the accumulated signal into a sustained corrective bias applied to the thrust command, progressively reducing the offset until equilibrium is achieved at the commanded altitude. This mechanism simultaneously enhances disturbance rejection by ensuring that slowly varying perturbations that would otherwise manifest as persistent altitude deviations are absorbed into the integral state and corrected without requiring manual gain adjustment or external compensation. The practical consequence, as reflected in the simulation results, is a steady-state altitude error that remains bounded well within the prescribed tolerance despite the presence of the aforementioned offset-inducing factors.

Taken together, the transient and steady-state altitude-tracking results support the conclusion that the PID parameter set selected through the Ziegler–Nichols procedure and subsequently refined through iterative manual adjustment is well suited to the vertical regulation demands of the autonomous landing maneuver. The combination of feedforward gravity compensation, proportional-derivative transient shaping, and integral steady-state correction constitutes a control structure whose individual components address distinct and complementary aspects of the altitude regulation problem, and whose aggregate behavior — as evidenced by the smooth convergence, minimal overshoot, and bounded steady-state error observed in simulation — is consistent with the performance requirements identified for reliable and repeatable autonomous touchdown.

3.2. Investigation of the influence of the Roll and Pitch angle control channels on the altitude control channel

The simulation results presented in Figures 4 and 5 provide direct quantitative evidence of the coupling pathway through which attitude deviations propagate into altitude channel disturbances, a dynamic interaction whose significance for landing control motivates careful examination. When the quadrotor is maintaining a commanded altitude of 10 m and a prescribed pitch deviation is introduced, the altitude response exhibits a pronounced downward excursion, with the vehicle descending to approximately 8 m before the controller initiates recovery — a displacement of roughly 2 m, corresponding to a relative altitude loss of approximately 20% of the nominal operating height. This behavior is a direct physical consequence of the geometric relationship between vehicle attitude and the vertical projection of total thrust: as the vehicle pitches, the thrust vector — nominally aligned with the body-fixed vertical axis — acquires an increasing horizontal component at the expense of its vertical component, reducing the effective lift force sustaining the vehicle against gravity. For small pitch angles, this reduction is proportional to the cosine of the pitch deviation and may be considered negligible; however, at the attitude magnitudes examined in this study, the thrust projection loss is sufficiently large to produce a measurable and practically significant altitude drop that the feedback controller cannot instantaneously compensate.

The recovery dynamics observed following the pitch-induced disturbance reveal an important characteristic of the altitude PID structure under cross-channel coupling conditions. The return to the commanded altitude is achieved, confirming that the integral term ultimately provides sufficient corrective authority to restore vertical regulation; however, the recovery trajectory is notably gradual rather than aggressive, reflecting the finite rate at which the integrator accumulates the residual tracking error generated by the sustained thrust deficit. This behavior is structurally inherent to integral action: unlike the proportional term, which responds instantaneously to the magnitude of the current error, the integrator generates its corrective contribution through temporal accumulation, meaning that a sustained disturbance of the kind introduced by a persistent attitude offset must persist for a finite duration before sufficient integral state is built up to counteract it. The practical implication for landing control is that altitude disturbances induced by attitude deviations during descent are not corrected instantaneously but are subject to a recovery lag whose duration depends on the integral gain and the magnitude of the thrust projection loss — a consideration that becomes particularly consequential during the terminal landing phase, where the available altitude margin for recovery is progressively diminishing.

A qualitatively comparable altitude excursion is observed when roll deviations of equivalent magnitude are introduced in place of pitch perturbations, as illustrated in Figure 5. The close correspondence between the pitch-induced and roll-induced altitude responses confirms that the observed coupling effect is not a channel-specific artifact of the pitch dynamics but a general geometric consequence of vehicle tilting applicable to any lateral attitude deviation. This symmetry is consistent with the structure of the quadrotor thrust model, in which the vertical thrust projection depends on the total tilt angle rather than on the direction of tilt, and it implies that the altitude disturbance risk during landing is present across the full range of attitude deviations that may arise from external disturbances, reference tracking transients, or control input asymmetries. Taken together, the pitch and roll coupling results establish that inter-axis dynamic interaction constitutes a substantive performance constraint for PID-based altitude control during autonomous landing, and that controller designs intended for deployment in realistic operating conditions must either explicitly account for this coupling through feedforward compensation or accept the recovery lag as a bounded performance limitation within which the landing trajectory must be designed to operate safely.

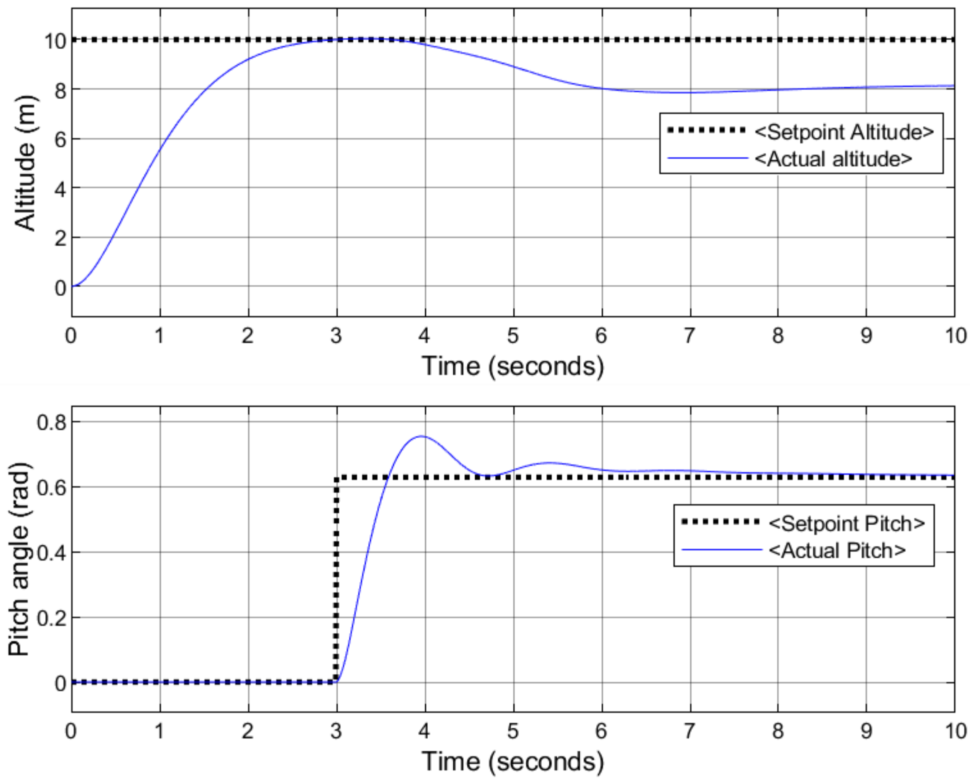

Fig. 4. The influence of pitch control channel to the altitude control channel

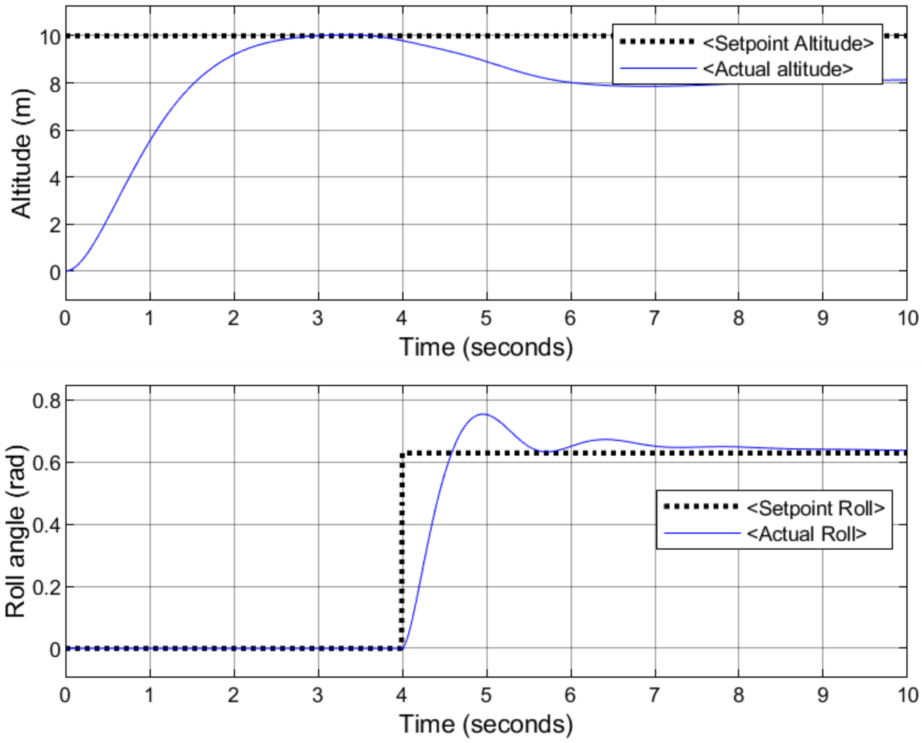

Fig. 5. The influence of roll control channel to the altitude control channel

The altitude excursions documented in the preceding section give concrete expression to a coupling mechanism that is intrinsic to the multirotor flight dynamics: any deviation in roll or pitch from the nominal hover attitude causes the body-fixed thrust vector to rotate away from the inertial vertical, redistributing thrust authority between the vertical and horizontal directions in a manner governed by the trigonometric projection of the thrust magnitude onto the world-frame vertical axis. The vertical thrust component available to counteract gravity is given by the product of total thrust and the composite attitude factor $\cos\varphi\cos\theta$, where φ and θ denote the roll and pitch angles, respectively; as either angle increases in magnitude, this factor decreases monotonically, reducing the effective lift force below the level required to sustain the commanded altitude unless the total thrust magnitude is increased in proportion. The consequence for closed-loop altitude control is that accurate attitude tracking by the inner loop does not, by itself, guarantee altitude maintenance: even when the attitude controller successfully drives roll and pitch to their commanded values, any non-zero attitude command or transient attitude deviation introduces a vertical thrust deficit that manifests in the outer loop as an effective reduction in the upward force acting on the vehicle, producing an unintended descent whose magnitude and duration depend on both the severity of the attitude deviation and the recovery authority available to the altitude controller.

This coupling pathway has direct implications for the adequacy of a conventional decoupled PID architecture for autonomous landing. The simulation results demonstrate that a standard PID structure retains the capacity to stabilize the altitude channel and recover from coupling-induced disturbances, confirming its baseline viability; however, the recovery lag and the magnitude of the intermediate altitude excursion establish that decoupled gain tuning is insufficient to render the controller indifferent to cross-channel interactions. Several design-level strategies present themselves as means of mitigating this limitation, each operating at a different point in the control architecture and offering a different trade-off between implementation complexity and compensation effectiveness.

The most direct mitigation consists of tilt-compensated thrust scaling, in which the total thrust command generated by the altitude PID is divided by the composite attitude factor $\cos\varphi\cos\theta$ prior to allocation to the individual rotors. This modification ensures that the vertical thrust component equals the PID output regardless of the instantaneous vehicle attitude, effectively decoupling altitude dynamics from attitude variations at the actuator level and eliminating the coupling-induced thrust deficit as a source of altitude disturbance. The compensation is straightforward to implement within an existing control architecture, requires only the attitude state estimates already available to the flight controller, and introduces no additional dynamic elements into the closed-loop system; its primary limitation is a proportional increase in total thrust demand — and therefore in power consumption — during periods of sustained attitude deviation, which may be consequential for energy-constrained missions.

An alternative or complementary approach involves adopting coordinated control architectures in which the altitude and attitude channels share state information and generate thrust commands jointly rather than independently. In a coordinated formulation, the altitude controller is made explicitly aware of the current attitude state and adjusts its thrust demand accordingly, while the attitude controller may simultaneously account for the altitude error when prioritizing its response to attitude commands. This approach addresses the coupling at the architectural level rather than through post hoc compensation and can provide more complete decoupling across a wider range of operating conditions; however, it requires a more substantial redesign of the control structure and introduces additional complexity to the gain-tuning and stability-analysis procedures.

Within the existing PID framework, targeted modifications to the integral channel offer a more incremental path toward improved coupling recovery. Increasing the integral gain accelerates the accumulation of corrective bias in response to the sustained altitude error introduced by attitude-induced thrust loss, reducing the recovery lag observed in the simulation results; however, this adjustment must be balanced against the risk of integrator-induced overshoot during recovery, which can itself produce altitude deviations of comparable magnitude to those being corrected. Anti-windup mechanisms — which limit the integrator state during periods when the control output is saturated or the tracking error is large — help constrain this risk by preventing excessive integral accumulation during the initial phase of a coupling-induced disturbance, while still permitting rapid corrective action once the attitude deviation has been resolved. A rate-limited integral formulation, in which the rate of change of the integrator state is bounded rather than the state itself, offers additional flexibility in shaping the recovery trajectory to satisfy both speed and overshoot constraints simultaneously.

Taken together, these observations and the mitigation strategies they motivate establish that the coupling between Euler-angle dynamics and altitude channel performance is not a marginal perturbation effect but a structurally significant feature of quadrotor flight mechanics that warrants explicit treatment in any controller design intended for autonomous landing applications. The selection among the available compensation strategies — tilt-aware thrust scaling, coordinated control architecture, or integral action refinement — should be guided by the specific performance requirements, implementation constraints, and computational resources of the target platform, and represents a productive direction for extending the present simulation-based findings toward a practically deployable autonomous landing system.

IV. CONCLUSION

This work examined quadrotor stabilization via four coupled control channels, with particular emphasis on reducing the disturbance to altitude holding caused by roll and pitch commands. Using numerical simulations, PID gains were tuned for each channel to achieve well-damped transients and tracking performance consistent with the stated requirements. The proposed structure combines gravity feedforward compensation with an additional tilt-related correction to offset the loss of vertical lift when the vehicle departs from level flight. The results show that this approach can better preserve altitude regulation during attitude changes, thereby improving the overall stability of the closed-loop system.

Despite these positive outcomes, the study relies on a simplified dynamic model that omits several aerodynamic and actuator effects (e.g., rotor inflow dynamics, drag, and other nonlinearities), potentially leading to discrepancies between simulation and real flight behavior. In addition, the simulations assume ideal state measurements, whereas practical implementations must contend with sensor noise, bias, and delays, as well as environmental disturbances such as wind and precipitation. Addressing these limitations will require model refinement and more realistic representations of sensing and disturbances.

Future work will extend the controller evaluation to trajectory-following and autonomous navigation tasks, including scenarios with degraded or intermittent GPS. Overall, the study provides a useful baseline for PID parameter selection and for understanding channel coupling in quadrotors, and it offers a foundation for developing higher-fidelity models and more robust control strategies suitable for real-world operating conditions.

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