



GENETIC-ALGORITHM-OPTIMIZED ADAPTIVE BACKSTEPPING MRAC FOR ROBUST QUADROTOR TRAJECTORY TRACKING

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ARTICLE INFO

Article History

Received: February 18, 2026

Reviewed: April 27, 2026

Accepted: May 27, 2026

Published: June 30, 2026

Keywords:

Quadrotor UAV,
Adaptive Control,
Backstepping Method,
Model Reference Adaptive
Control (MRAC),
Genetic Algorithm Optimization.

ABSTRACT

This paper presents an adaptive control strategy for quadrotor unmanned aerial vehicles (UAVs) operating under parametric uncertainties and external disturbances. The proposed approach combines model reference adaptive control (MRAC) with a recursive backstepping design to ensure stable trajectory tracking for both translational and rotational dynamics. To reduce the sensitivity of the controller to manual gain tuning and to enhance tracking performance, a genetic algorithm (GA) is employed to optimize the key control and adaptation gains based on the integral of time-weighted absolute error (ITAE) criterion. The control design is developed using Lyapunov stability theory, guaranteeing the asymptotic convergence of tracking errors despite unknown system parameters. The proposed controller is evaluated on a nonlinear quadrotor model considering coupled attitude and altitude dynamics. Simulation results demonstrate accurate reference tracking, bounded control inputs, and improved robustness compared to non-optimized adaptive backstepping schemes. The obtained results indicate that the GA-optimized adaptive MRAC-backstepping framework provides an effective and systematic solution for quadrotor control in uncertain operating conditions.



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I. INTRODUCTION

Unmanned aerial vehicles (UAVs), and quadrotor platforms in particular, have become an essential component in numerous civilian and industrial applications, including surveillance, inspection, environmental monitoring, precision agriculture, and search-and-rescue missions. Their mechanical simplicity, vertical take-off and landing (VTOL) capability, and high maneuverability make quadrotors attractive for operation in complex and constrained environments. Nevertheless, achieving reliable and high-performance control remains a challenging task due to their inherently nonlinear, strongly coupled, and underactuated dynamics [1-3]. The quadrotor system exhibits six degrees of freedom, while being actuated by only four independent control inputs, which results in complex coupling between translational and rotational dynamics. In addition, practical quadrotors are subject to significant parametric uncertainties arising from payload variations, aerodynamic coefficient changes, and unmodeled dynamics, as well as external disturbances such as wind gusts and ground effects [4], [5]. These challenges limit the effectiveness of classical linear control strategies, which are typically designed around operating points and fail to guarantee stability and performance over a wide flight envelope. To address these limitations, nonlinear control approaches have been extensively investigated in the literature. Among them, backstepping control has emerged as a powerful systematic methodology for stabilizing nonlinear systems by exploiting their recursive structure and Lyapunov-based design framework [6], [7]. Backstepping techniques have been successfully applied to quadrotor attitude and position control, demonstrating improved stability properties compared to conventional linear controllers. However, pure backstepping-based designs often rely on accurate knowledge of system parameters and may suffer from performance degradation in the presence of large uncertainties and disturbances. Adaptive control techniques have therefore been introduced to enhance robustness against modeling uncertainties. Model Reference Adaptive Control (MRAC) is one of the most widely adopted adaptive strategies, as it enforces the system dynamics to follow a predefined reference model with desired transient and steady-state characteristics [8], [9]. In the context of quadrotor UAVs, MRAC has shown strong potential for compensating parametric uncertainties and ensuring asymptotic tracking performance.

Nevertheless, MRAC alone may exhibit slow adaptation or sensitivity to gain selection, especially when applied to highly nonlinear and coupled systems. Recent research trends have focused on hybrid control architectures that integrate multiple nonlinear and adaptive techniques to leverage their complementary advantages. For instance, backstepping has been combined with sliding mode control to enhance robustness against external disturbances while preserving finite-time convergence properties [10-12]. Other works have explored neural-network-based adaptive schemes and disturbance observers to estimate unmodeled dynamics in real time [13-15]. Although these methods improve robustness, they often increase design complexity and computational burden, which may hinder real-time implementation. An additional critical aspect in nonlinear adaptive control design is the tuning of controller and adaptation gains. Manual tuning is time-consuming and highly dependent on designer experience, and suboptimal gain selection may lead to excessive control effort or poor transient performance. To overcome this issue, intelligent optimization algorithms have been increasingly employed. Genetic Algorithms (GAs), in particular, have been widely used for controller parameter optimization due to their global search capability and independence from gradient information [16-18]. GA-based tuning has been successfully applied to backstepping, sliding mode, and PID controllers for quadrotor systems, leading to improved tracking accuracy and reduced energy consumption. Despite the substantial progress reported in the literature, several limitations remain. Most existing studies consider simplified quadrotor models or focus on a subset of the system dynamics, neglecting the full interaction between translational and rotational states. Moreover, fully integrated adaptive control frameworks that simultaneously address nonlinearities, parametric uncertainties, and optimal gain tuning within a unified design remain relatively scarce. In particular, the combination of MRAC and backstepping optimized through evolutionary algorithms for a complete 12-degree-of-freedom quadrotor model has not been sufficiently investigated. Motivated by these observations, this paper proposes a robust integrated control strategy that combines backstepping and Model Reference Adaptive Control within a unified Lyapunov-based framework, while employing a Genetic Algorithm to optimize controller and adaptation parameters. The proposed approach is designed for a nonlinear quadrotor model with twelve state variables, explicitly accounting for parametric uncertainties and external disturbances affecting both translational and rotational dynamics.

II. RELATED WORK

The comparison presented in Table 1 highlights the main differences between existing quadrotor control approaches and the proposed method. Conventional backstepping-based controllers focus primarily on stabilizing the nonlinear dynamics but generally lack adaptive mechanisms to compensate for parametric uncertainties, which may degrade performance under varying operating conditions. Several adaptive backstepping and MRAC-based strategies introduce online parameter estimation to address uncertainty; however, their effectiveness strongly depends on manually tuned control and adaptation gains. Genetic-algorithm-based methods have been reported to improve tuning efficiency, yet they are often applied without a rigorous Lyapunov-based stability framework or are decoupled from the nonlinear control synthesis. In contrast, the proposed approach integrates adaptive backstepping and model reference adaptive control within a unified Lyapunov framework while employing a genetic algorithm to optimize the key control gains. This combination ensures guaranteed stability, improved tracking performance, and reduced sensitivity to manual tuning, thereby providing a systematic and robust solution for quadrotor control under uncertain conditions.

Table 1: Comparison of some related works.

Refs	Control Technique	Uncertainty Handling	Optimization of Gains	Lyapunov Stability	Our Contribution vs Reference
[19]	Backstepping Control	No explicit parametric uncertainty adaptation	No	Yes (backstepping)	Uses adaptive MRAC + GA optimization for uncertain parameters
[20]	Genetic & Model Reference	Partial adaptation via reference tracking	Yes (GA for tuning)	No formal Lyapunov proof	Combines MRAC + backstepping with formal stability
[21]	Backstepping for Quadrotor	No adaptive uncertainty handling	No	Yes	Adds MRAC adaptation + GA optimization
[22]	Adaptive Backstepping	Adaptive handling of uncertainties	Manual (no GA)	Yes	GA optimization integrates systematic gain tuning
[23]	MRAC with Robust Filtering	Disturbance compensation	No	Yes	Combines MRAC with recursive backstepping + GA tuning

Source: Authors, (2026).

III. MAIN CONTRIBUTIONS

The main contributions of this work can be summarized as follows:

Comprehensive nonlinear modeling:

A full 12-degree-of-freedom nonlinear quadrotor model is considered, incorporating both translational and rotational dynamics, as well as parametric uncertainties and external disturbances affecting all system states.

Integrated MRAC–Backstepping control design:

A unified control architecture is developed by embedding Model Reference Adaptive Control within a Lyapunov-based backstepping framework, ensuring asymptotic tracking and closed-loop stability in the presence of uncertainties.

Adaptive law formulation with guaranteed stability:

Adaptive laws are rigorously derived using Lyapunov theory, guaranteeing boundedness of all signals and convergence of tracking errors without requiring exact knowledge of system parameters.

Genetic Algorithm-based gain optimization:

A Genetic Algorithm is employed to optimally tune the controller and adaptive gains using the ITAE performance criterion, leading to improved transient performance and reduced control effort.

Extensive simulation validation:

The effectiveness of the proposed approach is demonstrated through comprehensive simulations involving time-varying reference trajectories and uncertainty scenarios, highlighting superior robustness and tracking accuracy.

IV. NONLINEAR QUADROTOR MODELING AND PROBLEM FORMULATION

IV.1 QUADROTOR DYNAMIC MODEL

The quadrotor is modeled as a rigid body operating in three-dimensional space, described with respect to an inertial reference frame $\mathcal{R}_e = (O_e, x_e, y_e, z_e)$ and a body-fixed frame $\mathcal{R}_b = (O_b, x_b, y_b, z_b)$ attached to the vehicle's center of mass. Figure 1 depicts the actuation and sensing architecture of the quadrotor system considered in this study. The vehicle is actuated by four brushless DC rotors, each driven by an independent supply voltage that determines the rotor angular velocity. The squared rotor speeds generate thrust forces and reaction torques, which collectively produce the total lift and control moments acting on the quadrotor body. By appropriately distributing these inputs, the system is able to control its altitude as well as its rotational motion around the roll, pitch, and yaw axes. The quadrotor dynamics are described by a nonlinear mathematical model that captures the coupling between translational and rotational motions. This model maps the rotor-generated forces and torques to the system state variables, which include the Euler angles (ϕ, θ, ψ) , their corresponding angular rates, and the translational position along the inertial axes. The nonlinear nature of the model reflects aerodynamic effects, inertial coupling, and external disturbances acting on the vehicle. State measurements are obtained through a set of onboard sensors. Angular velocities are measured using tri-axial gyroscopes, which provide high-frequency feedback for attitude stabilization and adaptive control. Linear accelerations are measured using accelerometers, contributing to the estimation of translational velocities and disturbance effects. Altitude information is provided by an altimeter sensor, enabling accurate vertical position tracking. The combination of these sensor measurements ensures sufficient observability of the system states required for closed-loop control implementation. This sensing and actuation framework forms the basis for the proposed adaptive backstepping MRAC control strategy. The availability of reliable state feedback allows the controller to compensate for nonlinearities and parametric uncertainties while guaranteeing closed-loop stability and accurate trajectory tracking.

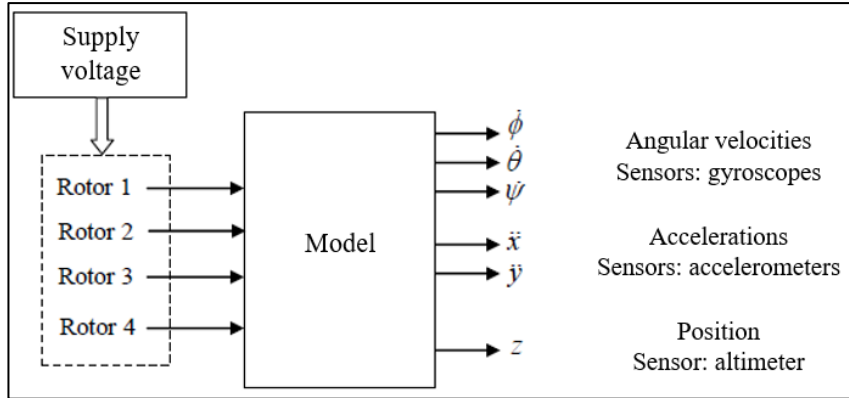


Figure 1: Model Inputs and Outputs.
Source: Authors, (2026).

The translational position of the quadrotor in the inertial frame is defined as

$$\mathbf{p} = [x \ y \ z]^T \in \mathbb{R}^3 \quad (1)$$

While the attitude is described using the Euler angle vector

$$\boldsymbol{\eta} = [\phi \ \theta \ \psi]^T \quad (2)$$

Representing roll, pitch, and yaw, respectively. The full state vector of the quadrotor is given by:

$$\mathbf{X} = [\mathbf{p}^T \ \dot{\mathbf{p}}^T \ \boldsymbol{\eta}^T \ \boldsymbol{\omega}^T]^T \in \mathbb{R}^{12} \quad (3)$$

Where $\boldsymbol{\omega} = [p \ q \ r]^T$ denotes the angular velocity vector expressed in the body frame. Each rotor generates a thrust force proportional to the square of its angular speed:

$$F_i = b\omega_i^2, i = 1, \dots, 4 \quad (4)$$

Where b is the thrust coefficient and ω_i is the angular velocity of the i -th rotor. The total thrust and control torques acting on the quadrotor are defined as:

$$\begin{aligned}
u_1 &= \sum_{i=1}^4 F_i \\
u_2 &= l(F_2 - F_4) \\
u_3 &= l(F_3 - F_1) \\
u_4 &= d(F_1 - F_2 + F_3 - F_4)
\end{aligned} \tag{5}$$

Where l denotes the distance from each rotor to the center of mass, and d is the drag coefficient.

Table 2: Quadrotor model parameters.

Symbol	Value	Symbol	Value
m	0.486 kg	K_{fay}	$5.5670 \cdot 10^{-4}$ N/rad/s
J	9.806 m/s^2	K_{faz}	$6.3540 \cdot 10^{-4}$ N/rad/s
l	0.25 m	K_{fix}	0.0320 N/m/s
J_r	$2.8385 \cdot 10^{-5} \text{ kg.m}^2$	K_{fiy}	0.0320 N/m/s
I_x	0.01 kg.m^2	K_{fz}	0.0480 N/m/s
I_y	0.01 kg.m^2	μ_0	0.0122
I_z	0.01 kg.m^2	μ_1	6.0612
K_{fax}	$5.5670 \cdot 10^{-4}$ N/rad/s	μ_2	189.63
b	$2.9842 \cdot 10^{-5}$	η_u	280.19

Source: Authors, (2026).

IV.2 EQUATIONS OF MOTION WITH UNCERTAINTIES

The translational dynamics of the quadrotor are given by:

$$m\ddot{\mathbf{p}} = R(\boldsymbol{\eta}) \begin{bmatrix} 0 \\ 0 \\ u_1 \end{bmatrix} - mg \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \mathbf{d}_t \tag{6}$$

Where m is the quadrotor mass, g is gravitational acceleration, $R(\boldsymbol{\eta})$ is the rotation matrix from body to inertial frame, and $\mathbf{d}_t$ represents translational disturbances and unmodeled aerodynamic effects. The rotational dynamics are expressed as:

$$J\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (J\boldsymbol{\omega}) = \begin{bmatrix} u_2 \\ u_3 \\ u_4 \end{bmatrix} + \mathbf{d}_r \tag{7}$$

Where $J = \text{diag}(J_x, J_y, J_z)$ is the inertia matrix and $\mathbf{d}_r$ denotes rotational disturbances and parametric uncertainties. In this work, all uncertain parameters, including mass, inertia moments, aerodynamic coefficients, and external disturbances, are assumed to be bounded but unknown.

IV.3 CONTROL OBJECTIVE AND PROBLEM FORMULATION

The control objective is to design a nonlinear adaptive controller such that:

The quadrotor position and attitude states track predefined smooth reference trajectories generated by stable reference models.

All closed-loop signals remain bounded despite parametric uncertainties and disturbances.

Tracking errors asymptotically converge to zero.

Formally, let $\mathbf{x}_r(t)$ denote the reference model state. The tracking error is defined as:

$$\mathbf{e}(t) = \mathbf{x}(t) - \mathbf{x}_r(t) \tag{8}$$

And the control goal is:

$$\lim_{t \rightarrow \infty} \mathbf{e}(t) = 0 \tag{9}$$

V. INTEGRATED MRAC-BACKSTEPPING CONTROL DESIGN

V.1 REFERENCE MODEL DEFINITION

For each controlled subsystem (altitude, roll, pitch, yaw), a second-order stable reference model is defined as:

$$\ddot{x}_r + 2\zeta\omega_n\dot{x}_r + \omega_n^2x_r = \omega_n^2x_d, \tag{10}$$

where x_d is the desired command,

$\omega_n > 0$ is the natural frequency, and

$\zeta > 0$ is the damping ratio.

V.2 BACKSTEPPING ERROR DYNAMICS

Consider the altitude subsystem as a representative example. Define the tracking errors:

$$\begin{aligned} e_1 &= z - z_r \\ e_2 &= \dot{z} - \dot{z}_r \end{aligned} \quad (11)$$

Choose the first Lyapunov function candidate:

$$V_1 = \frac{1}{2} e_1^2 \quad (12)$$

Its time derivative is:

$$\dot{V}_1 = e_1(e_2 + \dot{z}_r) \quad (13)$$

A virtual control input α is selected as:

$$\alpha = -k_1 e_1 + \dot{z}_r \quad (14)$$

Where $k_1 > 0$ is a design parameter. Define the second error variable:

$$e_2 = \dot{z} - \alpha \quad (15)$$

The augmented Lyapunov function is:

$$V_2 = V_1 + \frac{1}{2} e_2^2 \quad (16)$$

The control architecture presented in Figure 2 adopts a hierarchical cascaded structure composed of an external position loop and an internal attitude loop for quadrotor trajectory tracking. The external loop regulates the translational motion of the vehicle in the inertial frame by means of independent position controllers along the x , y , and z axes. Based on the position errors with respect to the desired trajectories, the x and y position controllers generate intermediate control signals u_x and u_y , which are processed by a correction block to compute the desired roll ϕ_{ref} and pitch θ_{ref} angles. These reference attitudes ensure that the quadrotor produces the appropriate lateral accelerations required for horizontal motion. Simultaneously, the altitude controller regulates the vertical position by generating the collective thrust command u_z from the altitude tracking error. The internal loop is responsible for stabilizing the rotational dynamics of the quadrotor. It consists of independent attitude controllers for roll, pitch, and yaw, which track the reference angles ϕ_{ref} , θ_{ref} , and ψ_{ref} , respectively. These controllers generate the control torques u_2 , u_3 , and u_4 , while the altitude controller provides the thrust command u_1 . The combined control inputs (u_1, u_2, u_3, u_4) are applied to the quadrotor actuators to achieve stable flight and accurate trajectory tracking. This cascaded control strategy effectively decouples the translational and rotational dynamics, improving system stability, robustness, and tracking performance.

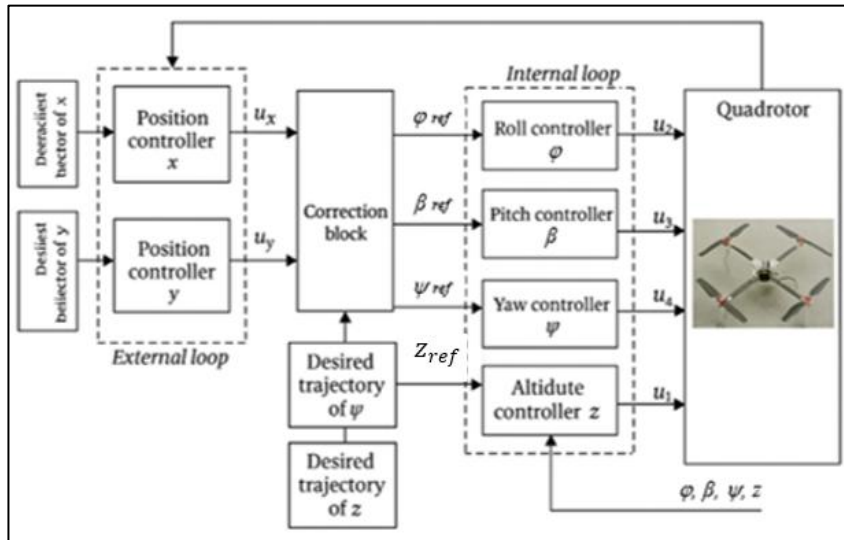


Figure 2: Control Architecture of the Quadrotor.

Source: Authors, (2026).

V.3 MRAC-BASED ADAPTIVE CONTROL LAW

Due to uncertain system parameters, the altitude dynamics can be rewritten as:

$$\ddot{z} = \theta^T \varphi + u_1 \quad (17)$$

Where θ is an unknown parameter vector and φ is a known regressor. The control law is designed as:

$$u_1 = -\hat{\theta}^T \varphi - k_2 e_2 + \dot{\alpha} \quad (18)$$

With $k_2 > 0$, and $\hat{\theta}$ denoting the parameter estimate.

The final Lyapunov function is chosen as:

$$V = V_2 + \frac{1}{2\gamma} \tilde{\theta}^T \tilde{\theta} \quad (19)$$

Where $\tilde{\theta} = \theta - \hat{\theta}$ and $\gamma > 0$ is the adaptation gain.

Figure 3 illustrates the proposed adaptive control architecture for quadrotor trajectory tracking, which combines a backstepping controller with an online adaptation mechanism assisted by a genetic algorithm (GA). The control structure is composed of a reference model, an adaptation mechanism, a genetic optimization block, and a nonlinear backstepping controller. The reference model generates the desired system response y_m based on the reference input y_{ref} , ensuring predefined transient and steady-state performance. The tracking error e , defined as the difference between the quadrotor output y and the reference model output y_m , is used to drive the adaptation mechanism. This mechanism continuously updates the controller parameters in order to compensate for modeling uncertainties, external disturbances, and parametric variations. The backstepping controller is designed based on the nonlinear dynamics of the quadrotor and generates the control input u to ensure closed-loop stability and convergence of the tracking error. To enhance robustness and performance, a genetic algorithm is integrated into the control loop to optimize the adaptive gains and backstepping parameters. The GA operates by minimizing a predefined fitness function related to the tracking error and control effort, allowing the controller to achieve improved performance under disturbances and uncertainties. External disturbances acting on the quadrotor are explicitly considered in the control structure, and their effects are mitigated through the combined action of adaptive control and evolutionary optimization. This hybrid control strategy ensures asymptotic tracking, improved robustness, and enhanced adaptability compared to conventional fixed-parameter controllers.

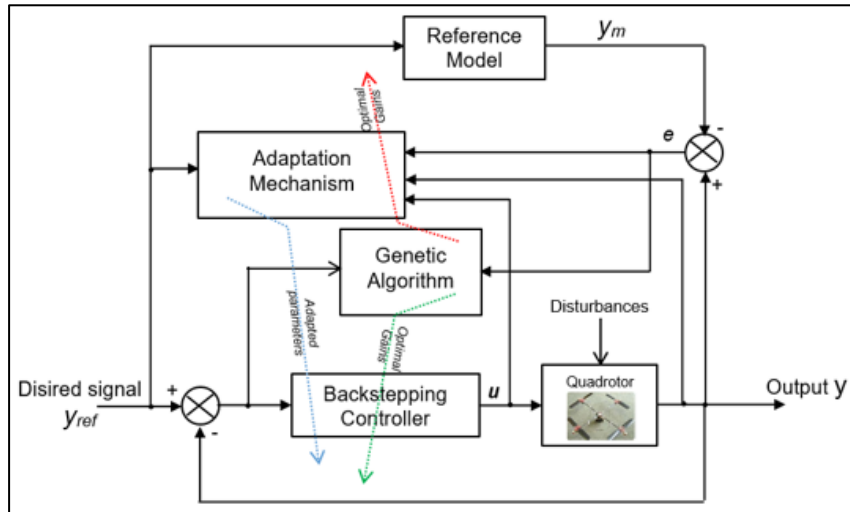


Figure 3: Hybrid MRAC–Backstepping Control Optimized by GA for Quadrotor.
Source: Authors, (2026).

V.4 ADAPTIVE LAW AND STABILITY ANALYSIS

The adaptive law is selected as:

$$\dot{\hat{\theta}} = \gamma e_2 \varphi \quad (20)$$

Substituting the control and adaptation laws into $\dot{V}$ yields:

$$\dot{V} = -k_1 e_1^2 - k_2 e_2^2 \leq 0 \quad (21)$$

Which guarantees global boundedness of all closed-loop signals and asymptotic convergence of tracking errors. The same design procedure is systematically applied to the roll, pitch, and yaw subsystems, ensuring overall stability of the complete 12-DOF quadrotor system.

VI. GENETIC ALGORITHM-BASED GAIN OPTIMIZATION

Although the proposed MRAC–Backstepping controller guarantees closed-loop stability and asymptotic tracking, the overall performance is highly dependent on the appropriate selection of control and adaptation gains. Poorly tuned gains may result in excessive control effort, slow transient response, or degraded robustness. To overcome this limitation, a Genetic Algorithm (GA) is employed to automatically optimize the controller gains.

VI.1 OPTIMIZATION CRITERION

The Integral of Time-weighted Absolute Error (ITAE) is adopted as the optimization cost function due to its effectiveness in penalizing sustained tracking errors and improving transient behavior. The objective function is defined as:

$$J = \int_0^T t |e(t)| dt \quad (22)$$

Where $e(t)$ denotes the tracking error and T is the simulation horizon. The optimization problem consists in minimizing J by adjusting the controller gains k_1, k_2 and the adaptive gains γ_i .

VI.2 GENETIC ALGORITHM CONFIGURATION

The GA is initialized with a population of 50 individuals over 25 generations. Each chromosome encodes a candidate set of controller and adaptation gains. Selection, crossover, and mutation operators are applied iteratively to evolve the population toward optimal solutions. A crossover probability of 0.8 and a mutation rate of 0.01 are used to ensure a balance between exploration and exploitation. The optimized gains obtained via GA significantly improve convergence speed and reduce control effort compared to manually tuned parameters.

VII. SIMULATION RESULTS AND DISCUSSION

To validate the effectiveness of the proposed integrated control strategy, extensive simulations are conducted on the full nonlinear 12-DOF quadrotor model under parametric uncertainties and external disturbances.

VII.1 ALTITUDE TRACKING PERFORMANCE

The altitude reference trajectory is varied over time to assess the controller's tracking capability under dynamic conditions. As shown in Figure 4, the actual altitude closely follows the reference model with fast convergence and negligible steady-state error. The corresponding tracking error rapidly converges to zero, confirming the robustness of the adaptive control design. Figure 4 illustrates the convergence behavior of the genetic algorithm used for controller parameter optimization. The evolution of the best fitness value and the mean fitness value of the population is plotted as a function of the generation number. The fitness function is defined to evaluate the control performance based on tracking accuracy and/or control effort. As shown in the figure, both the best and mean fitness values decrease rapidly during the initial generations, indicating an effective exploration of the search space and a fast improvement of candidate solutions. This rapid reduction reflects the ability of the genetic algorithm to identify high-quality individuals early in the optimization process. As the number of generations increases, the rate of improvement gradually decreases, and both curves converge toward a steady value, demonstrating the convergence of the algorithm. The small gap observed between the best and mean fitness values in later generations indicates population convergence and solution stability, suggesting that the genetic algorithm successfully avoids premature convergence and yields a near-optimal solution. These results confirm the effectiveness of the proposed genetic algorithm in optimizing the controller parameters and enhancing the overall system performance.

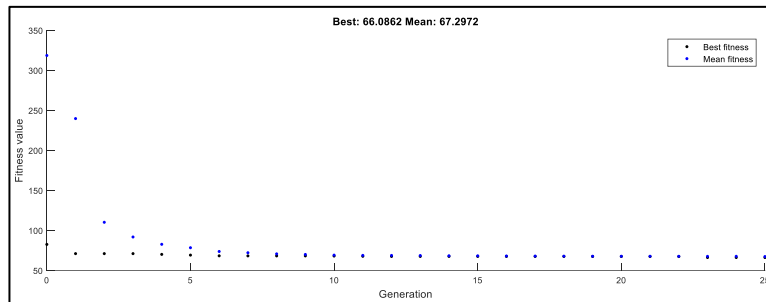


Figure 4: Genetic algorithm results (Best and Mean fitness).

Source: Authors, (2026).

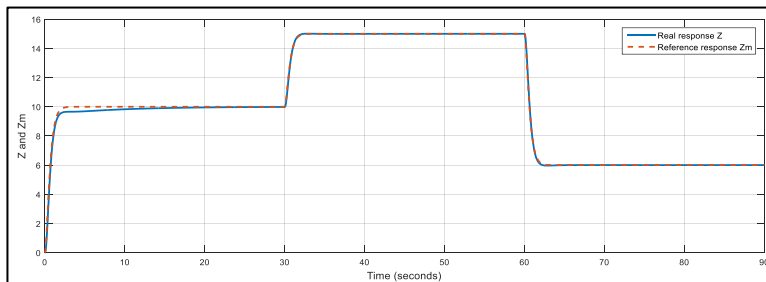


Figure 5: Real Altitude and Reference Model Trajectory (z and z_m).

Source: Authors, (2026).

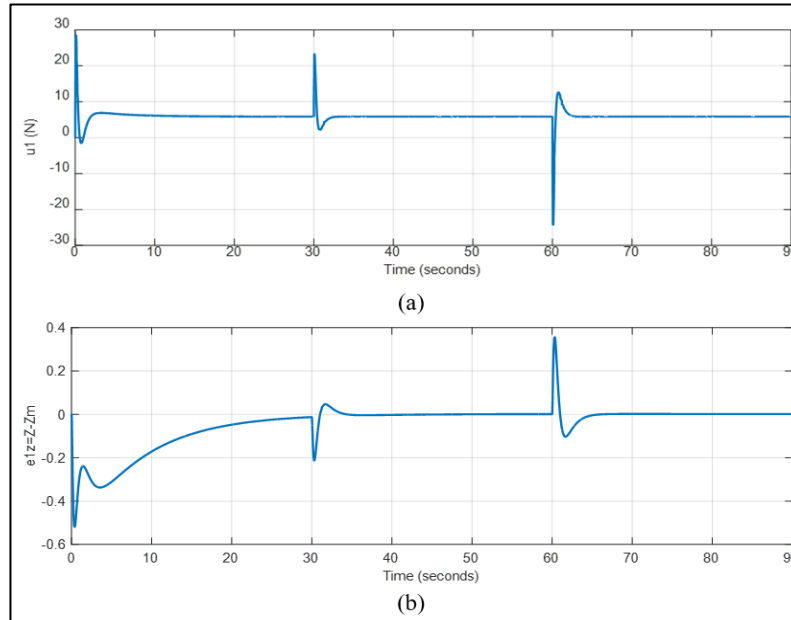


Figure 6: Quadrotor altitude control law and Altitude Tracking Error.
Source: Authors, (2026).

VII.2 ATTITUDE CONTROL PERFORMANCE

The roll, pitch, and yaw angles are tested independently with step reference commands. Figure 5 illustrates that all attitude states accurately track their reference trajectories with minimal overshoot and short settling times. The tracking errors, shown in Figure 6, converge asymptotically to zero, demonstrating strong robustness against uncertainties. Figure 5 illustrates the time-domain tracking performance of the controlled system by comparing the real response Z with the reference response Z_m . The results demonstrate that the system accurately follows the desired trajectory across multiple step variations. At the initial stage, the output rapidly converges toward the reference signal with a fast rise time and negligible steady-state error, indicating effective transient performance. Around $t \approx 30$ s, the reference signal undergoes a step increase, and the system response successfully tracks this change with minimal overshoot and short settling time. Similarly, when a step decrease occurs near $t \approx 60$ s, the system maintains stability and closely follows the reference trajectory without significant oscillations. Overall, the strong agreement between the real response and the reference model confirms the robustness and high tracking accuracy of the proposed control strategy. The minimal deviation between both signals indicates good disturbance rejection capability and reliable dynamic performance over the entire operating range.

Figure 6a presents the control input signal $u(t)$ applied to the system during the tracking process. The control effort initially exhibits a transient peak, which corresponds to the rapid adjustment required to drive the system output toward the reference trajectory. After this transient phase, the control signal stabilizes and remains within moderate bounds, indicating efficient energy utilization and stable controller behavior. At approximately $t \approx 30$ s and $t \approx 60$ s, the control input displays short-duration peaks in response to abrupt variations in the reference signal. These peaks remain bounded and quickly return to steady values, confirming the controller's ability to react promptly to external command changes while maintaining overall system stability. Figure 6b illustrates the tracking error $e(t) = Z_m(t) - Z(t)$ over time. The results show that the error converges rapidly toward zero during the initial transient phase, demonstrating strong convergence properties of the control scheme. Small deviations appear during the step transitions occurring near $t \approx 30$ s and $t \approx 60$ s; however, the error remains bounded and quickly diminishes after each disturbance. The absence of sustained oscillations and the fast attenuation of the error confirm the high precision and robustness of the proposed controller.

VII.3 CONTROL EFFORT ANALYSIS

The generated control inputs remain smooth and bounded throughout the simulation, as depicted in Figure 7. This behavior confirms that the proposed MRAC–Backstepping controller does not induce excessive actuator demands, making it suitable for real-time implementation. Figure 7 illustrates the time responses of the three attitude angles, namely roll (ϕ), pitch (β), and yaw (ψ), compared with their respective reference trajectories. For all three channels, the proposed control strategy ensures accurate tracking of the reference signals with good transient and steady-state performance. At the initial transient, the roll and pitch angles exhibit a moderate overshoot before converging smoothly toward their desired values, indicating a fast response with acceptable damping characteristics. The yaw angle shows a smaller overshoot and reaches the steady state more rapidly, highlighting a well-tuned dynamic behavior along this axis. In all cases, the steady-state tracking error is negligible, confirming the high accuracy of the controller. Small disturbances or reference changes introduced at approximately 30 s and 60 s result in short transient deviations in the system responses. However, the controller effectively rejects these perturbations, allowing the states to quickly return to their reference values without sustained oscillations. This demonstrates the robustness of the control scheme against external disturbances and model uncertainties. The results confirm that the proposed controller provides stable, fast, and robust tracking performance for all attitude angles, with limited overshoot, short settling times, and strong disturbance rejection capabilities.

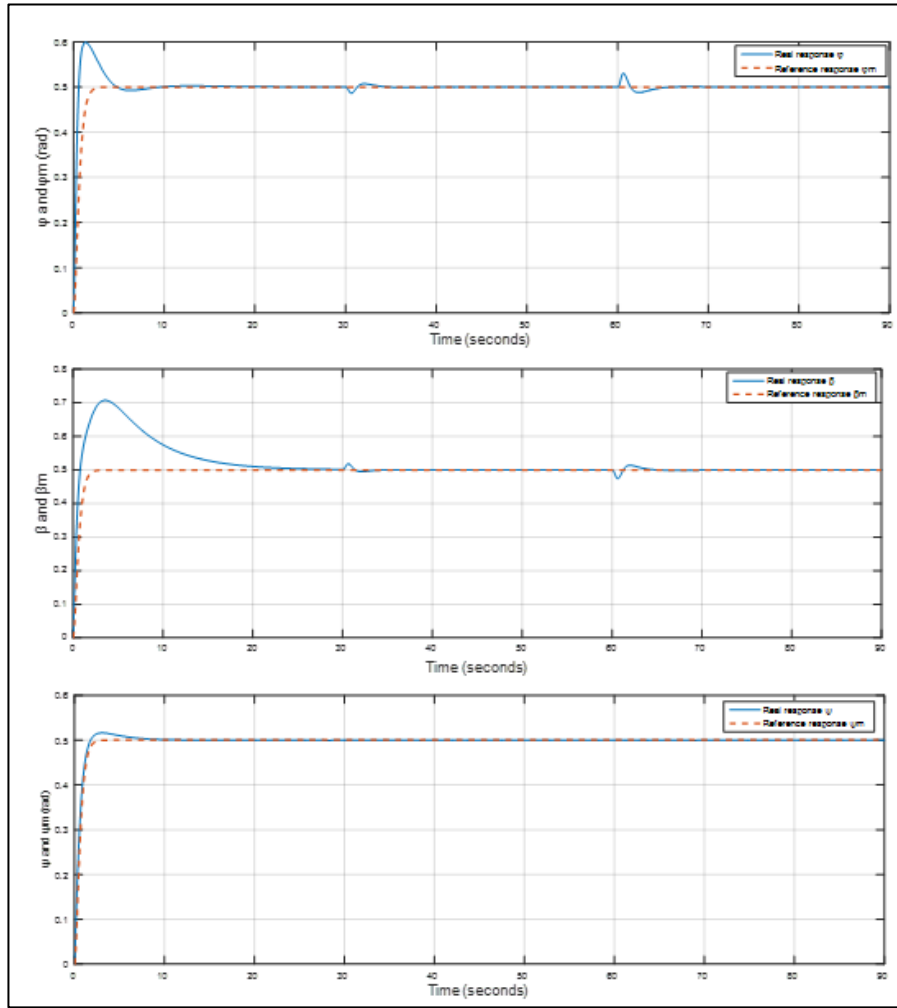


Figure 7: Real and Reference Responses: Pitch, Roll, and Yaw Rate.
Source: Authors, (2026).

VII.4 DISCUSSION

Compared to conventional backstepping or non-adaptive controllers, the proposed GA-optimized MRAC–Backstepping approach exhibits superior transient response, improved robustness, and reduced sensitivity to parameter variations. The optimization process plays a key role in enhancing performance without compromising stability. Figure 8 illustrates the time responses of the system states following the applied reference changes/disturbances. The angular position $\theta(t)$, angular velocity $\dot{\theta}(t)$, and control input $u(t)$ are presented over a 90-s simulation horizon. The angular position exhibits a fast transient response with a maximum overshoot of approximately 24% and settles to the steady state within approximately 10 s, demonstrating satisfactory damping characteristics. Small transient deviations are observed at $t = 30$ s and $t = 60$ s, corresponding to externally applied disturbances or reference variations. In both cases, the controller successfully rejects the perturbations and restores the equilibrium within a short settling time, indicating strong disturbance rejection capability. The angular velocity response shows a smooth decay toward zero with no sustained oscillations, confirming closed-loop stability. Minor spikes appear at disturbance instants; however, they are rapidly attenuated, further validating the robustness of the control strategy. The control input remains bounded throughout the simulation and converges rapidly to zero after the initial transient. Brief corrective actions are observed during disturbance events, after which the input quickly returns to its nominal value, indicating efficient control effort without excessive actuation. The results demonstrate that the proposed control scheme ensures fast convergence, minimal steady-state error, and effective disturbance rejection while maintaining moderate control energy.

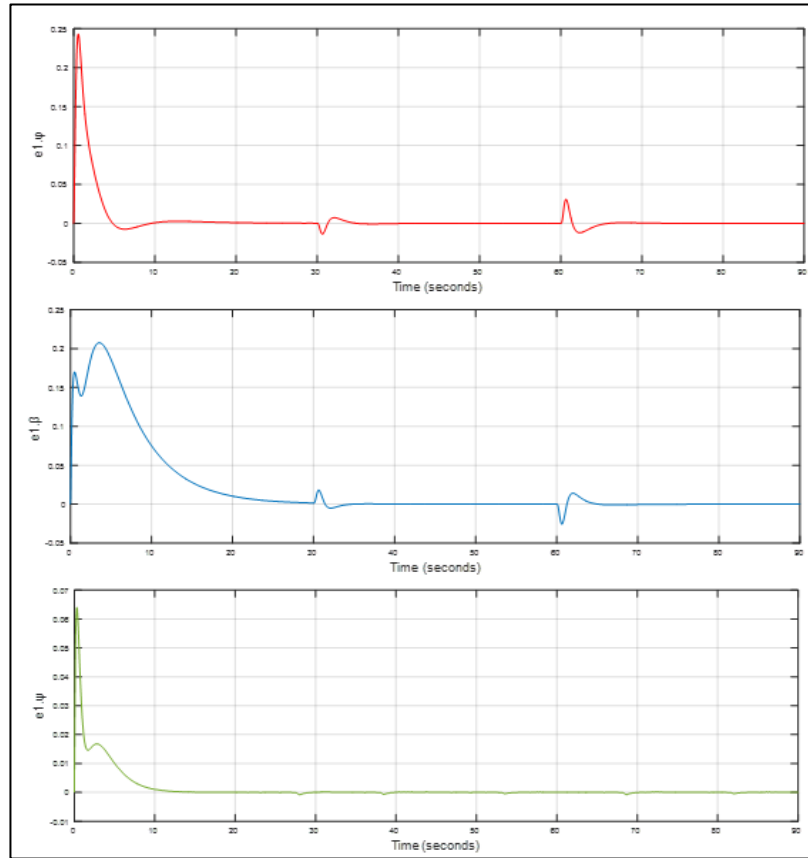


Figure 8: Attitude Tracking Errors: Pitch, Roll, and Yaw Rate.
Source: Authors, (2026).

The time-domain responses of the system states are presented in Figure 9. As shown in Figure 9(a), the state $x(t)$ exhibits a rapid transient response at the beginning of the simulation, followed by a smooth convergence toward a steady-state value close to zero. After the initial transient phase, the response remains stable over time, with only small-amplitude fluctuations, indicating effective attenuation of dynamic disturbances and good system stability. Figure 9(b) illustrates the temporal evolution of the state $y(t)$. The response demonstrates a fast rise during the initial transient interval, reaching its steady-state value within a short settling time. The steady-state behavior remains nearly constant throughout the simulation horizon, with slight deviations observed at specific moments, which may be attributed to external disturbances or numerical effects. Overall, the results confirm the stability and robustness of the system dynamics over the considered time period.

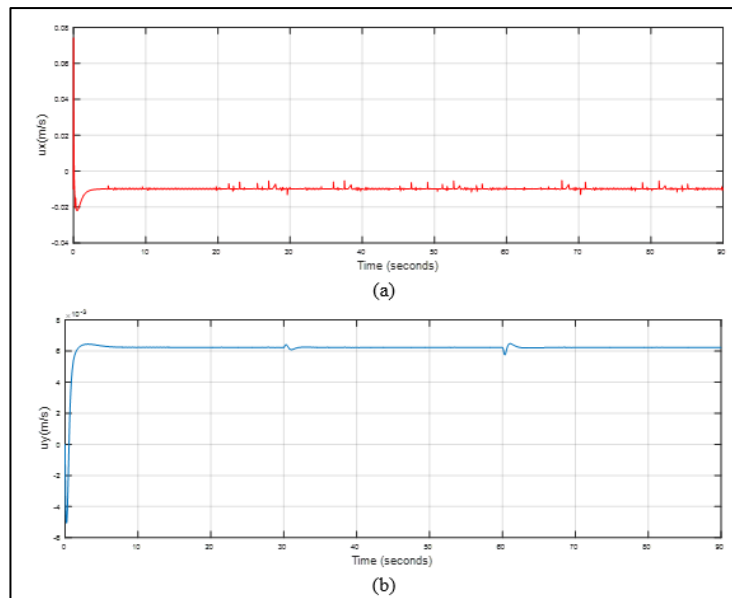


Figure 9: Time-domain responses of the system states. (a) Evolution of the state $x(t)$ as a function of time, showing a rapid transient decay followed by a stable steady-state behavior with small residual fluctuations. (b) Evolution of the state $y(t)$, characterized by a fast rise during the initial transient and convergence toward a constant steady-state value, with minor perturbations observed at specific time instants.

Source: Authors, (2026).

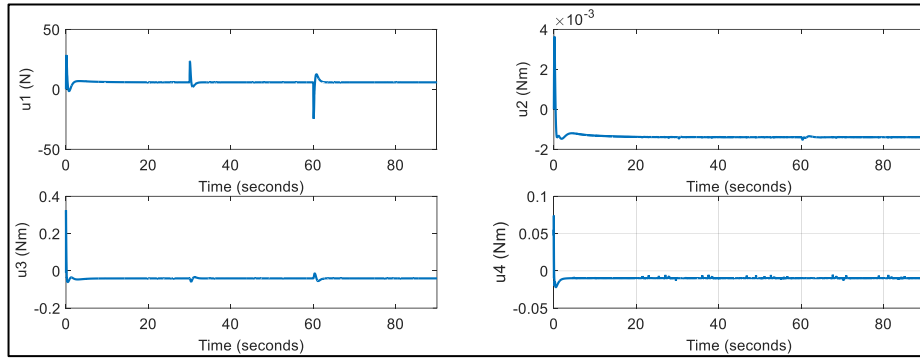


Figure 10: Time evolution of the control inputs applied to the system: (a) $u_1(t)$, (b) $u_2(t)$, (c) $u_3(t)$, and (d) $u_4(t)$. The control signals exhibit bounded behavior with transient peaks during the initial response and at specific time instants, while remaining stable and well-regulated throughout the simulation.

Source: Authors, (2026).

Figure 10 presents the time-domain responses of the control inputs $u_1(t)$, $u_2(t)$, $u_3(t)$, and $u_4(t)$. The control signal $u_1(t)$ exhibits an initial transient followed by convergence toward a steady operating range. Short-duration peaks are observed at specific time instants, which correspond to transient system responses or external disturbances. Despite these variations, the signal remains bounded within acceptable limits. The control input $u_2(t)$ shows a rapid transient decay and stabilizes around a small steady-state value on the order of $10^{-3} \text{ N} \cdot \text{m}$, indicating minimal control effort once steady-state conditions are reached. Similarly, $u_3(t)$ converges quickly to a near-zero steady-state value, with only minor fluctuations over time. The control signal $u_4(t)$ also demonstrates fast transient attenuation and maintains a stable steady-state behavior with small-amplitude variations. Overall, the bounded nature of all control inputs and their rapid convergence indicate effective control action, ensuring system stability while limiting excessive control effort.

VIII. CONCLUSION AND FUTURE WORK

This paper presented a robust adaptive nonlinear control strategy for quadrotor UAVs operating under comprehensive uncertainties and external disturbances. A full 12-DOF nonlinear dynamic model was considered, and an integrated MRAC–Backstepping controller was developed within a Lyapunov-based framework to guarantee closed-loop stability and asymptotic trajectory tracking. To further enhance performance, a Genetic Algorithm was employed to optimally tune the controller and adaptation gains using the ITAE criterion. Simulation results demonstrated fast convergence, strong robustness, and accurate tracking performance under time-varying reference trajectories and uncertainty conditions. The proposed approach provides a reliable and systematic solution for high-performance quadrotor control in complex operating environments. Future work will focus on real-time experimental validation on an actual quadrotor platform, extension to fault-tolerant control, and application to cooperative multi-UAV systems with communication delays and constraints.

IX. AUTHOR'S CONTRIBUTION

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X. ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Electronics Department of the LAAAS Laboratory at the University of Batna 2 for their valuable technical support and continuous encouragement throughout the completion of this work. The authors also extend their appreciation to the Centre de Développement des Energies Renouvelables for providing essential institutional support that significantly contributed to the success of this research. If necessary, quote entities that supported the development of the research.

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