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Adaptive Robust Constraint-Based Nonlinear Control for Trajectory Tracking and Dynamic Obstacle Avoidance in Multi-copter UAVs

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Abstract

An adaptive robust nonlinear control system for multi-copter unmanned aerial vehicles (UAVs) trajectory tracking and obstacle avoidance is presented in this research. The suggested approach addresses nonlinear dynamics and environmental uncertainties by combining adaptive disturbance estimates with constraint-based control. Nonlinear differential equations are used to simulate the motion of the UAV, with obstacle avoidance represented as an inequality constraint and trajectory tracking as an equality constraint. The Udwadia–Kalaba method is used to create an analytical control law, which is then improved with adaptive and Lyapunov-based design to increase resilience against shocks and modeling mistakes. In order to enable smooth and continuous avoidance of dynamic barriers, a transformation technique is presented that transforms restricted safety restrictions into an unbounded domain. The closed-loop system's stability is determined via Lyapunov analysis. The suggested method is appropriate for real-world UAV applications, as demonstrated by simulation results that show precise trajectory tracking, efficient disturbance rejection, and dependable collision avoidance under various conditions.

Keywords: UAV, adaptive nonlinear control, trajectory tracking, obstacle avoidance, disturbance rejection, Lyapunov stability, constraint-based control

INTRODUCTION

The usage of unmanned aerial vehicles (UAVs), particularly multi-copters, is growing in fields such as autonomous distribution, agriculture, disaster response, and surveillance. They are extremely valuable because of their capacity to function in intricate and limited surroundings, but this also presents serious difficulties. In real-world situations, UAVs have to maneuver through surroundings with dynamic impediments, outside disturbances like wind, and system modeling uncertainty. One of the main research challenges in these situations is ensuring safe, dependable, and effective navigation [1].

Two essential prerequisites for autonomous UAV operation are trajectory tracking and obstacle avoidance. These issues have historically been handled independently, with control strategies emphasizing either collision avoidance or precise path following. Real-world applications, however, require a cohesive strategy that can manage both goals concurrently. The existence of disturbances and the intrinsically nonlinear dynamics of UAVs further complicate this, necessitating the use of robust and adaptive control strategies [2].

To enhance tracking performance and system stability, recent research has investigated a number

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of nonlinear control techniques, such as backstepping, sliding mode control, and geometric control. Constraint-based methods, which describe obstacle avoidance as inequality constraints, have been developed concurrently to directly integrate safety criteria into the control design. Although each of these approaches has demonstrated encouraging outcomes on its own, there is still little integration of various approaches into a unified adaptive framework.

Inspired by these difficulties, this work suggests an adaptive robust constraint-based nonlinear control system that combines disturbance rejection, obstacle avoidance, and trajectory tracking. The suggested method seeks to enhance the resilience and safety of UAV navigation in dynamic and uncertain situations by fusing constraint-based modeling with adaptive control methods [3].

RELATED WORKS

Because of its remarkable robustness against shocks and model uncertainties, sliding mode control (SMC) has been frequently used in UAV systems. Hybrid techniques that combine sliding mode control with backstepping have been developed to further increase performance, providing better tracking precision and stability. Nevertheless, these techniques may result in chattering effects and require more management. Because they avoid the singularities associated with traditional Euler angle representations by modeling UAV dynamics on nonlinear manifolds like SO(3) and SE(3), geometric control techniques have also attracted a lot of attention. Although these techniques yield formulations that are universally consistent, they frequently include intricate mathematical structures [4].

Artificial potential field techniques are widely employed for obstacle avoidance due to their ease of use and adaptability for real-time applications. However, these techniques may not always yield the best trajectories and may have problems with local minima. Model predictive control (MPC) and other optimization-based techniques provide better accuracy and predictive power, but they usually need a lot of processing power. Constraint-based control techniques, which represent trajectory tracking and obstacle avoidance as equality and inequality constraints, respectively, have been introduced more recently. This architecture allows for a uniform formulation, but it frequently lacks the adaptive elements needed to deal with disruptions [5].

The current study builds on these advancements by combining constraint-based obstacle avoidance with adaptive nonlinear control to provide a reliable and computationally effective solution for UAV navigation in dynamic situations [6].

MATHEMATICAL MODEL

The UAV nonlinear dynamics are given by:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$$

Where,

$q = [x, y, z, \phi, \theta, \psi]^T$
$M \rightarrow$ inertia matrix
$C \rightarrow$ Coriolis matrix
$G \rightarrow$ gravity

Constraint Formulation:

$$A(q,\dot{q})\ddot{q} = b(q,\dot{q})$$

Define Tracking Error:

$$e = r - r_d$$
$$\ddot{e} + k_1\dot{e} + k_2 e = 0$$

Obstacle Avoidance (Inequality Constraint):

$$(x - x_0)^2 + \left(y - y_0\right)^2 > R^2$$

Transform:

$$\xi = \ln((x - x_0)^2 + (y - y_0)^2 - R^2)$$

Control design
Total control law:

$$\tau = \tau_e + \tau_i$$

$$\tau_e = M^{\frac{1}{2}}(AM^{\frac{-1}{2}}) + (b - AM^{-1}(-C\dot{q} - G))$$

Inequality Constraint Control:

$$\tau_i = M(I - A^+A)r$$

Where

$$r = -k1\xi - k2\dot{\xi}$$

Adaptive Disturbance Extension:

$$\tau = \tau_e + \tau_i - \hat{d}$$

$$\dot{\hat{d}} = \gamma e$$

Stability Analysis:
Choose Lyapunov function:

$$V = \frac{1}{2}e^2 + \frac{1}{2}\dot{e}^2 + \frac{1}{2}\hat{d}^2$$

Derivative:

$$\dot{V} = -k\dot{e}^2 \leq 0$$

Therefore:

$$e(t) \rightarrow 0$$

Hence, the drone follows the path, and the system is stable with error e(t) = 0

$$e(t) \rightarrow 0 \Rightarrow r(t) \rightarrow rd(t)$$

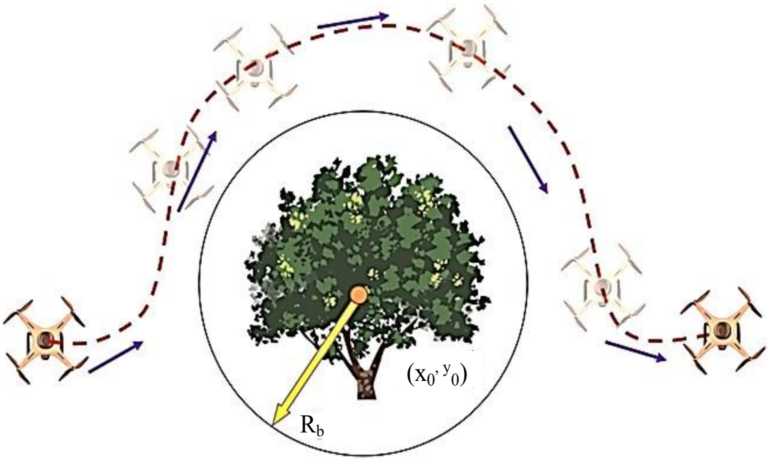

Figure 1. Visual representation of obstacle avoidance.

Conceptual representation of obstacle avoidance and UAV trajectory tracking. In order to keep a safe distance within the boundary Rb, the UAV deviates from the intended trajectory as it approaches the obstacle [7]. Once it has successfully avoided the obstacle, it returns to the reference path (Figure 1).

The tree represents an obstacle located at position (x_0,y_0).

SIMULATION RESULTS AND ANALYSIS

All simulation results presented in this section were generated by using MATLAB R2025b to evaluate the performance of the proposed control frameworks (Figure 2).

Trajectory tracking with obstacle avoidance [8]. The UAV deviates from the desired path near the obstacle to ensure collision avoidance and subsequently converges back toward the reference trajectory, demonstrating stable and robust control performance (Figure 3).

Over time, control inputs u_x and u_y. Large tracking error causes a high initial control effort, which is followed by oscillatory behavior as the UAV stabilizes along the trajectory [9]. As the UAV gets closer to the obstruction, sharp peaks appear, indicating that the avoidance mechanism has been activated. The inputs fluctuate smoothly between these occurrences, suggesting that tracking is operating normally [10]. The control signals' restricted nature attests to the suggested controller's steady and effective operation (Figure 4).

Performance of trajectory tracking in the absence of obstacles. The UAV exhibits efficient tracking by closely adhering to the intended circular path. The difference in beginning location causes an initial divergence, but over time, the tracking error steadily reduces [11]. The error shows consistent and smooth convergence with negligible fluctuations, peaking during the transient phase and then progressively settling to a tiny steady-state value (Figure 5).

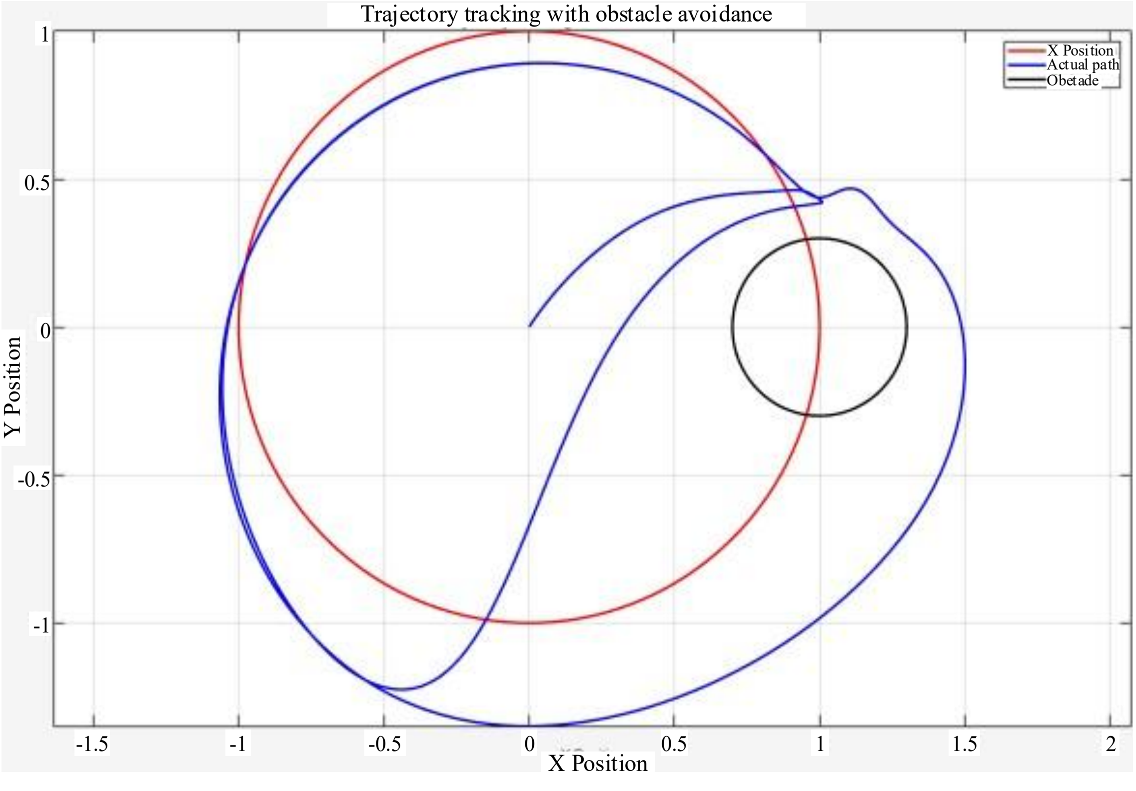

Figure 2. Trajectory tracking with obstacle tracking.

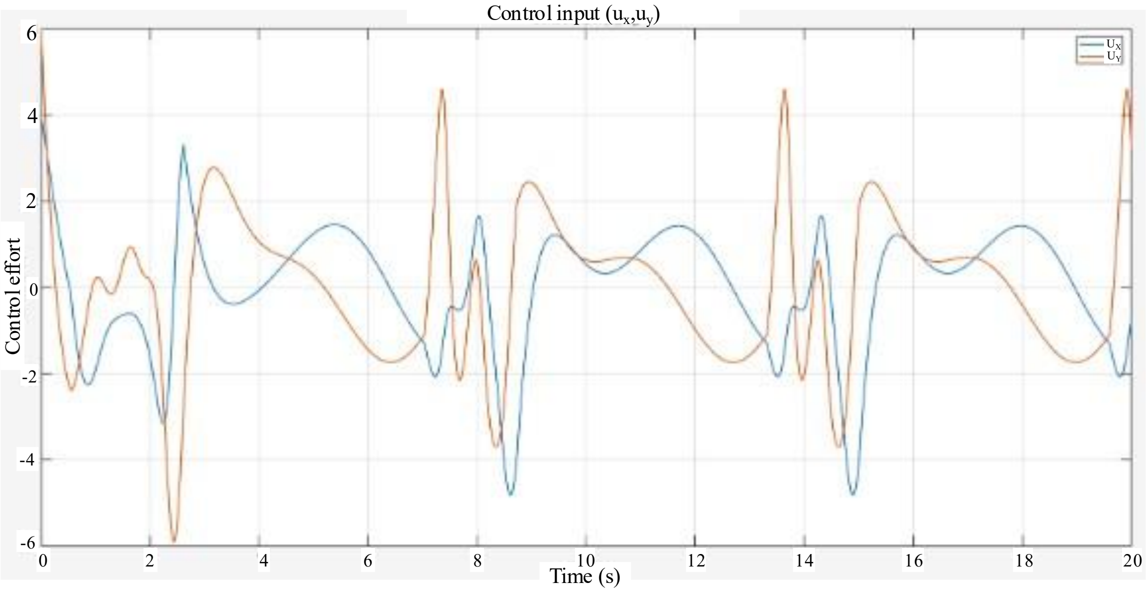

Figure 1. Control inputs.

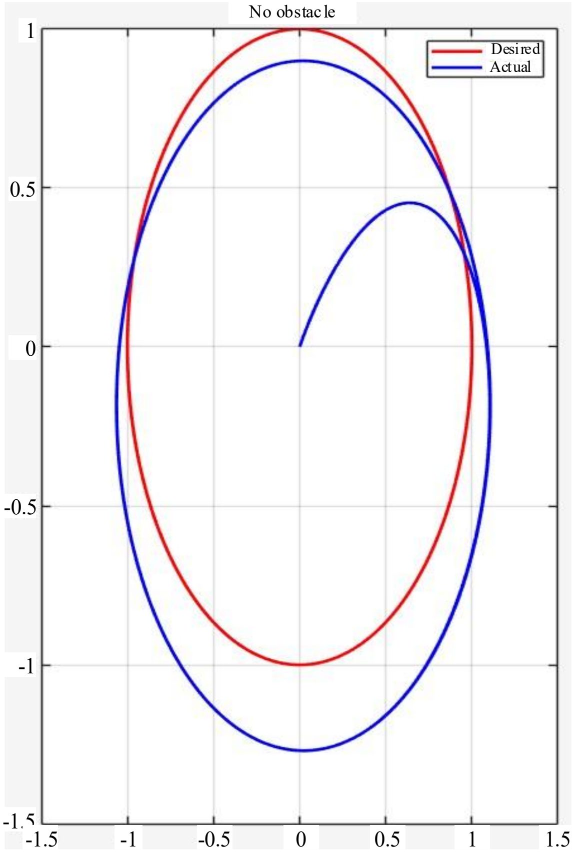

Figure 4. Obstacle-free condition.

Monitoring a trajectory while facing a stationary object. The avoidance mechanism is activated when the UAV deviates from the intended circular course as it gets closer to the obstacle. Effective tracking and avoidance coordination is demonstrated by the trajectory's seamless avoidance of the obstacle and gradual return to the reference path [12]. Repulsive control action causes the tracking error to momentarily increase close to the barrier, but it stays confined, indicating stable system behavior in line with Lyapunov-based analysis (Figure 6).

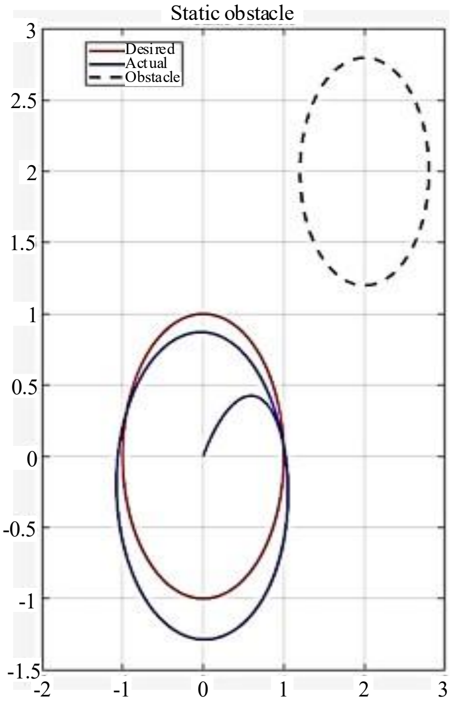

Figure 5. Static obstacle.

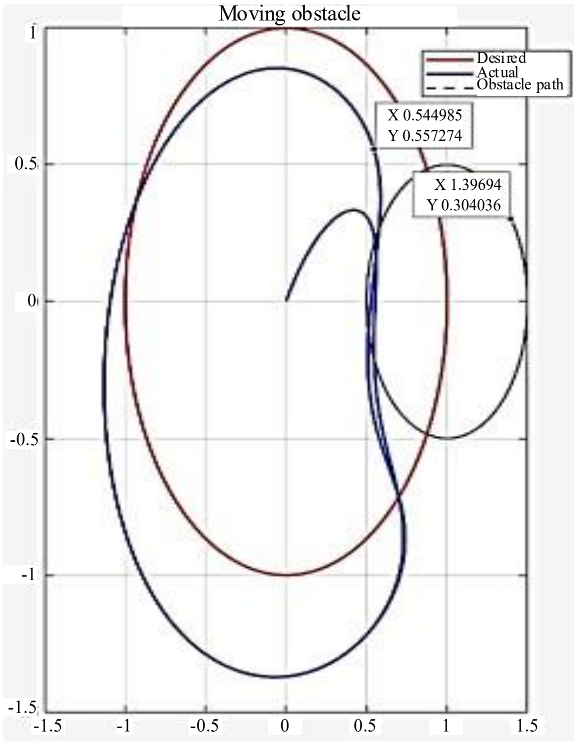

Figure 6. Moving obstacle.

Monitoring a trajectory while an obstruction moves. Larger deviations than in the static example arise from the UAV's constant course adjustments in reaction to the obstacle's movements. The UAV effectively avoids collisions despite the added complexity, and once it has cleared the obstacle, it returns to the intended trajectory. The tracking error stays confined, indicating the resilience of the suggested controller in dynamic situations, even though convergence is slower than in the obstacle-free scenario [13].

CONCLUSION

An adaptive robust nonlinear control system for trajectory tracking and obstacle avoidance in multi-copter unmanned aerial vehicles (UAVs) operating in dynamic and uncertain settings is presented in this research. The suggested method successfully tackles major issues resulting from nonlinear system dynamics, external disturbances, and the requirement for real-time collision avoidance by fusing constraint-based control principles with adaptive disturbance estimation. This methodology enables a coherent and methodical control design by formulating trajectory tracking as an equality constraint and obstacle avoidance as an inequality constraint.

By adding adaptive processes, the controller can correct for unknown disruptions, increasing the system's overall stability and robustness. Additionally, the convergence of tracking errors over time is confirmed by Lyapunov-based analysis, which rigorously establishes the stability of the closed-loop system. Simulation studies carried out under various conditions, such as obstacle-free, static obstacle, and moving obstacle settings, show the efficacy of the suggested approach. The UAV consistently maintains stable behavior in the face of disturbances and securely avoids collisions while successfully following the intended route.

All things considered, the suggested architecture provides a workable and effective solution for autonomous UAV navigation. It is appropriate for a variety of real-world applications, such as surveillance, infrastructure inspection, and search and rescue operations, due to its capacity to manage complicated situations.

Future Scope

The suggested work can be expanded in a number of ways to improve its performance and usefulness. First, putting the control framework into practice on real-time hardware platforms—like quadrotor UAVs—would be a useful way to verify its viability. The method can also be applied to multi-UAV systems to facilitate coordinated collision avoidance and cooperative navigation among several agents.

In order to enable UAVs to function well in unfamiliar and unstructured situations, future research may concentrate on combining the suggested control system with simultaneous localization and mapping (SLAM) techniques. Additionally, using learning-based techniques could enhance disturbance estimation and allow for more precise obstacle motion prediction in dynamic situations. The creation of energy-efficient control techniques to maximize power usage and increase flight duration is another crucial path. Lastly, the framework's applicability for intricate real-world applications can be improved by expanding it to handle completely three-dimensional situations with numerous moving obstacles.

Limitations

The suggested method shows good results; there are certain drawbacks to take into account. A precise mathematical model of the UAV is necessary for the control design, and discrepancies between the model and actual system dynamics could affect overall performance. Furthermore, the obstacle avoidance technique may not accurately reflect the complexity of real-world settings because it relies on simplified geometric representations.

When there are several dynamic impediments, the method's computational demand may also rise, which could have an impact on real-time implementation. Although adaptive disturbance estimation increases resilience, it might react more slowly when disturbances change quickly. Furthermore, additional experimental research on actual UAV platforms is required to thoroughly assess the practical robustness and usability of the suggested framework, as the current validation is based on simulation data.

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