

Optimized Synergetic Control based on Equilibrium Optimizer for Quadcopter Under External Disturbances and Parameter Uncertainties

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Abstract— Quadcopters are frequently utilized in different industries considering their special characteristics. However, the control of quadcopters under-actuated systems, has specific challenges, including high-performance trajectory tracking and stability in the presence of disturbances and parametric uncertainties. This work investigates the development of Optimized Synergetic Control (SC) approach using Equilibrium Optimizer (EO) algorithm, this approach gives quick convergence and limits chattering problems. To further improve the robustness of the system in practical applications, the closed-loop stability of the quadcopter system is proved by using the Lyapunov function. Finally, several simulations under different situations in terms of external disturbances, parametric uncertainties, and mass variation are carried out to evaluate the efficiency of the SC technique proposed in this research. In addition, a comparative study is presented at the end of this work and effectively shows the outperformance of the proposed control.

Keywords— *Quadcopter, Synergetic Control, Equilibrium Optimizer, Uncertainties parameters, External disturbances.*

I. INTRODUCTION

In recent years, unmanned aerial vehicles (UAVs) have attracted significant research attention, driven by rapid advancements in technology. Among them, quadcopters stand out for their mechanical simplicity, symmetric structure, and exceptional maneuverability, enabling vertical take-off and navigation through confined or complex environments [1]. These capabilities make them suitable for a wide range of applications, including surveillance, agriculture, environmental monitoring, biological studies, indoor reconnaissance, and logistics [2].

Various control strategies have been developed for quadrotor systems, encompassing both classical and advanced approaches. Traditional techniques include the Proportional-Integral-Derivative (PID) controller [3], [4], the Linear Quadratic Regulator (LQR) [5], and Sliding Mode Control (SMC) [6]. In addition, intelligent control methodologies have

gained significant attention, such as Neural Network Control [7], Fuzzy Logic Control [8], [9][10]. Furthermore, hybrid control schemes have emerged by integrating multiple strategies, such as Fuzzy Sliding Mode Control utilizing the Backstepping approach [10].

In this work, we present a SC based on an optimization approach using EO algorithm. The effectiveness of the proposed controller is validated through its application to a quadcopter system, demonstrating its capability in ensuring precise trajectory tracking and robust stability under various operating conditions.

The rest of this paper is organized into four main sections. Section 1 presents the modeling of the quadcopter system. Section 2 represent the control architecture consisting of SC and EO algorithm. Section 3 showcases the simulation results and includes a comparative analysis between the proposed SC approach and SMC method, based on Root Mean Square Error (RMSE). Finally, Section 4 concludes the study by summarizing the key findings and highlighting the effectiveness of the developed control strategy.

II. QUADROTOR MODELING

The quadrotor consists of four propellers arranged in a cross configuration, with each opposing pair rotating in opposite directions to counteract torque. Vertical movement is achieved by uniformly increasing or decreasing the speed of all four rotors, thereby adjusting the lift force. Roll rotation sideways tilting with lateral movement is generated by varying the speeds of propellers 2 and 4 in opposite directions. Pitch rotation, which tilts the drone forward or backward, results from altering the speeds of propellers 1 and 3 inversely. The yaw rotation, which controls the drone's horizontal orientation, is more intricate and arises from the imbalance of reactive torques between the counter-rotating pairs. The quadcopter configuration is shown in Fig. 1.

To simplify the dynamics modeling of the quadrotor, the following assumptions are commonly made:

1. The quadrotor's structure is rigid and symmetric.

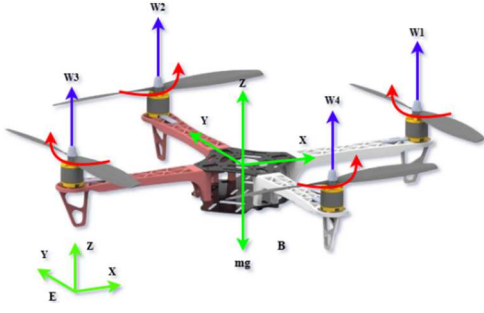


Fig. 1. Quadcopter configuration.

2. All propellers are considered rigid.

3. Thrust and drag forces generated by each rotor are proportional to the square of its rotational speed.

Taking into account frictional effects arising from aerodynamic torques, drag forces, gyroscopic interactions, and rotor dynamics, the translational and rotational behavior of the quadrotor is modeled using the Newton-Euler formalism, are illustrated as follow [11]:

$$\begin{cases} \ddot{\phi} = \frac{1}{I_x} (\dot{\theta}\dot{\psi}(I_y - I_z) - J_r \dot{\theta}\dot{\Omega}_r - K_{f_{ax}} \dot{\phi}^2 + I U_2) + d_\phi \\ \ddot{\theta} = \frac{1}{I_y} (\dot{\phi}\dot{\psi}(I_z - I_x) - J_r \dot{\phi}\dot{\Omega}_r - K_{f_{ay}} \dot{\theta}^2 + I U_3) + d_\theta \\ \ddot{\psi} = \frac{1}{I_z} (\dot{\phi}\dot{\theta}(I_x - I_y) - K_{f_{az}} \dot{\psi}^2 + U_4) + d_\psi \\ \ddot{x} = \frac{1}{m} (U_x U_1 - K_{f_{dx}} \dot{x}) + d_x \\ \ddot{y} = \frac{1}{m} (U_y U_1 - K_{f_{dy}} \dot{y}) + d_y \\ \ddot{z} = \frac{1}{m} ((\cos(\theta)\cos(\phi))U_1 - K_{f_{dz}} \dot{z}) - g + d_z \end{cases} \quad (1)$$

with:

$\Omega_r = w_1 - w_2 + w_3 - w_4$ and U_x, U_y are the virtual control inputs defined as:

$$\begin{cases} U_x = c\phi s\theta c\psi + s\phi s\psi \\ U_y = c\phi s\theta s\psi - s\phi c\psi \end{cases} \quad (2)$$

where all parameters are defined in [12].

III. CONTROL ARCHITECTURE

In this section, a robust control strategy is proposed for both the inner and outer loop subsystems, addressing the challenges posed by external disturbances and parametric uncertainties. The controller is designed to ensure accurate tracking of the reference position trajectory while stabilizing the quadrotor's attitude, even under wind gusts and unknown additive perturbations. The control structure is shown in Fig.2.

The model presented in equation (1) can be generalized to a broader class of affine nonlinear systems, typically expressed in the following form:

$$\Sigma: \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x)U + d \end{cases} \quad (3)$$

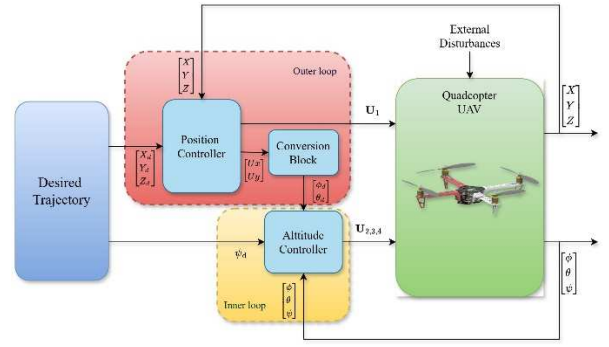


Fig. 2. Control structure.

Where $x = [x_1 \ x_2] \in \mathbb{R}^{6 \times 2}$ is the state vector, $x_1 = [\phi \ \theta \ \psi \ x \ y \ z]^T \in \mathbb{R}^6$, $x_2 = [\dot{\phi} \ \dot{\theta} \ \dot{\psi} \ \dot{x} \ \dot{y} \ \dot{z}]^T \in \mathbb{R}^6$, $U = [U_2 \ U_3 \ U_4 \ U_x \ U_y \ U_1]^T$ is the control input vector and $d = [d_\phi \ d_\theta \ d_\psi \ d_x \ d_y \ d_z] \in \mathbb{R}^6$ represents the bounded disturbances, $f(x)$ and $g(x)$ are nonlinear functions describing the system.

A. Synergetic control

In The key advantages of SC technique stem from its suitability for digital implementation, its ability to maintain a constant switching frequency during operation, and its superior control performance due to the absence of the chattering effect commonly observed in other robust control methods such as sliding mode control.

By selecting the macro-variable function Ψ as a function of the tracking error, the control law is constructed to drive the error toward zero in a stable and smooth manner. Let choose Ψ as linear function of the tracking error:

$$\Psi = \Gamma e + \dot{e} \quad (4)$$

where $\Gamma = \text{diag}[\Gamma_\phi \ \Gamma_\theta \ \Gamma_\psi \ \Gamma_x \ \Gamma_y \ \Gamma_z] \in \mathbb{R}_{+}^{6 \times 6}$.

For the selected macro-variable Ψ , the dynamic evolution function is typically defined to ensure exponential convergence toward the invariant manifold. A commonly used form is:

$$K\dot{\Psi} + \Psi = 0 \quad (5)$$

where $K = \text{diag}[K_\phi \ K_\theta \ K_\psi \ K_x \ K_y \ K_z] \in \mathbb{R}_{+}^{6 \times 6}$.

Let:

$$\begin{cases} e = x_{1d} - x_1 \\ \dot{e} = \dot{x}_{1d} - \dot{x}_2 \end{cases} \quad (6)$$

The time derivative of (4) given as:

$$\dot{\Psi} = \Gamma(\dot{x}_{1d} - \dot{x}_2) + (\ddot{x}_{1d} - \ddot{x}_2) \quad (7)$$

From (5) and (7), we obtain:

$$\Gamma(\dot{x}_{1d} - \dot{x}_2) + \ddot{x}_{1d} - f(x) - g(x)U = -K^{-1}\Psi \quad (8)$$

Then the control law is given as:

$$U = g(x)^{-1} [K^{-1}(\Gamma(\dot{x}_{1d} - \dot{x}_1) + (\dot{x}_{1d} - \dot{x}_2)) + \Gamma(\dot{x}_{1d} - \dot{x}_2) - f(x) + \ddot{x}_{1d}] \quad (9)$$

TABLE I. PHYSICAL PARAMETERS OF THE QUADROTOR

Parameters	Values	Parameters	Values
m	0.486 (Kg)	$K_{f_{ax}},$ $K_{f_{ay}},$ $K_{f_{az}}$	5.567×10^{-4} (N/m/s),
			5.567×10^{-4} (N/m/s),
			6.354×10^{-4} (N/m/s)
$I_x,$ $I_y,$ I_z	3.8278×10^{-3} (N.m/rad/s ²), 3.8278×10^{-3} (N.m/rad/s ²), 7.6566×10^{-3} (N.m/rad/s ²)	$K_{f_{ax}},$ $K_{f_{ay}},$ $K_{f_{az}}$	5.567×10^{-4} (N/rad/s),
			5.567×10^{-4} (N/rad/s),
			6.354×10^{-4} (N/rad/s)
J_r	2.8385×10^{-5} (Kg.m ²)	l, g	0.25 (m), 9.81(m/s ²)

Simulation results, presented in Fig. 3 to Fig. 8, illustrate the quadcopter's trajectory tracking under external disturbances, parameter uncertainties, and abrupt mass changes. Fig. 3 shows the position and yaw dynamics, while Fig. 4 presents roll and pitch responses. SC methods consistently outperform SMC in accuracy and convergence. Notably, at $t=30$ s, SC maintains reliable tracking despite mass variation, whereas SMC struggles to stabilize the system.

Figs. 5 and 6 demonstrate improved tracking accuracy in SC relative to SMC, with SC yielding lower error and more consistent behaviour. Fig. 7 illustrates the control inputs, where chattering is effectively mitigated in SC. Fig. 8 presents the intended flight path in both 2D and 3D representations, confirming SC superior trajectory-following capability.

B. Quantitative comparison

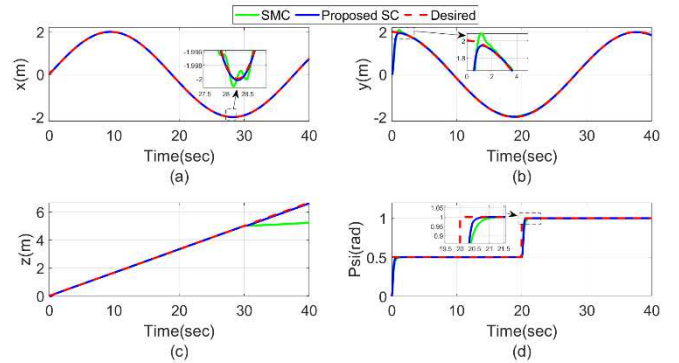
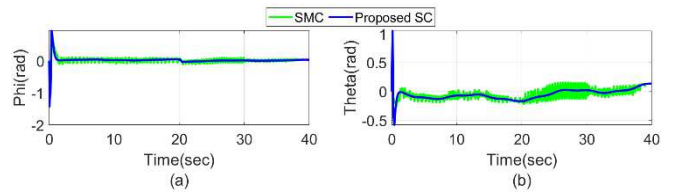
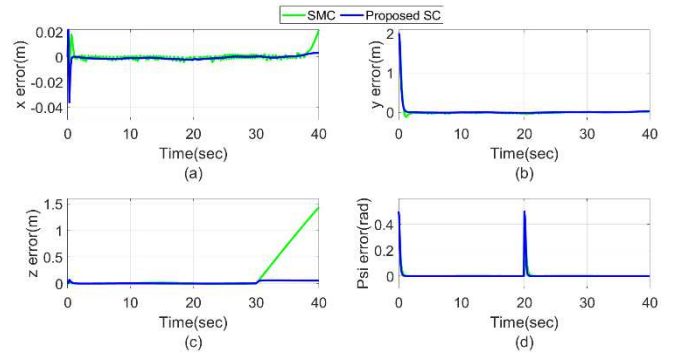
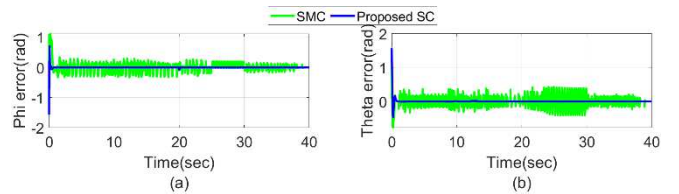
Table II presents the Root Mean Square Error (RMSE) values, demonstrating that SC achieves superior tracking accuracy compared to SMC.

V. CONCLUSION

The proposed SC strategy, enhanced by EO, effectively improves quadcopter trajectory tracking under external disturbances, parametric uncertainties, and sudden mass variations. It ensures fast convergence, smooth control action, and significantly reduces chattering compared to traditional methods. Stability is theoretically guaranteed using Lyapunov analysis, and simulation results confirm the superior performance of SC over SMC, particularly in terms of tracking accuracy and robustness. The RMSE metrics highlight the precision of the optimized SC approach. Additionally, EO successfully tunes the control parameters for optimal system behavior. These results demonstrate that the proposed method is well-suited for real-world UAV applications requiring high reliability and adaptability.

TABLE II. RMSE PERFORMANCE INDICES

State	SC	SMC
x	1.3176e-04	1.7113e-04
y	0.0084	0.0092
z	0.0015	0.0210
φ	0.0024	0.0080
θ	0.0030	0.0081
ψ	0.0023	0.0024

Fig. 3. (x, y, z) positions and yaw angle (ψ).Fig. 4. Roll and pitch angles (φ, θ).Fig. 5. Tracking errors of (x, y, z) positions and yaw angle (ψ).Fig. 6. Tracking errors of roll and pitch angles (φ, θ).

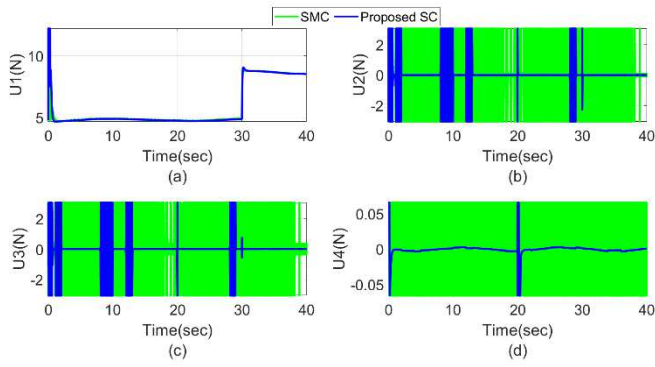


Fig. 7. Control inputs of the quadcopter.

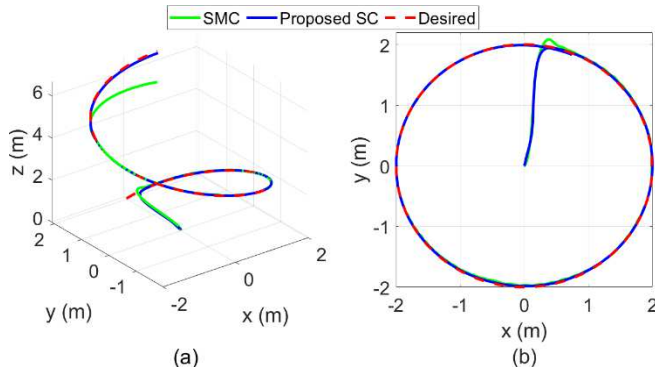


Fig. 8. 3D and 2D Position tracking result.

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