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Dumbbell: a high efficiency coaxial unmanned helicopter

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The coaxial unmanned helicopter offers advantages of high payload capacity, compact structure, and enhanced aerodynamic efficiency, making it suitable for space-constrained applications. In contrast to multi-rotor unmanned aerial vehicles (UAVs), whose thrust efficiency is restricted by rotor diameter, the coaxial configuration achieves higher energy utilization through the use of two large rotors instead of multiple smaller ones [1]. Furthermore, by employing counter-rotating rotor to offset the main rotor torque and provide yaw control, the coaxial design avoids the additional power loss of a conventional helicopter's tail rotor, thereby improving overall hovering efficiency.

Despite the considerable advantages of coaxial helicopters, their configuration also imposes significant challenges on structural design. The swashplate, serving as the core component of a coaxial unmanned helicopter, drives the cyclic pitch variation of the rotor blades through its tilting motion, thereby enabling attitude regulation and directional flight. While this mechanism offers clear benefits in the control of medium and large-scale helicopters, its application to micro-scale helicopters often leads to structural complexity and control coupling issues. Refs. [2, 3] discussed UAVs based on the conventional coaxial configuration (hereinafter referred to as Normal Coaxial), as illustrated in Figure 1(e). In this configuration, the rotors are powered by two brushless motors, while horizontal motion is achieved through swashplate manipulation driven by two servos. However, the introduction of the swashplate not only increases the assembly and maintenance complexity of coaxial UAVs but also raises the likelihood of mechanical failure. Moreover, the control input coupling induced by the swashplate further complicates the process of flight control decoupling.

To improve the swashplate mechanism, Ref. [4] proposed a novel coaxial dual-rotor UAV: its two upper rotors provide lift and yaw control, while four servos at the bottom (each connected to a flap) regulate roll and pitch. However, the structure remains complex, and the numerous servos complicate the control system. A more advanced coaxial rotor configuration was later explored in [5,6], as illustrated in Figure 1(d) (hereinafter referred to as NYTU Coaxial). In this design, two vertically aligned servo actuators replace the swashplate to independently control roll and pitch. Compared with the UAVs described in [2–4], the NYTU Coaxial eliminates the structural complexity of the swashplate, while allowing two servos to directly govern the two horizontal degrees of freedom. This not only simplifies the overall structure but also reduces the difficulty of decoupling in flight control. Another advantage of this configuration over the swashplate-based design is its wider variation range of rotor thrust along the axial direction, which enables more aggressive flight maneuverability. Nevertheless, a limitation of the design lies in the short spacing between the upper and lower rotors, which induces strong aerodynamic coupling and high aerodynamic noise, thereby reducing the overall aerodynamic efficiency.

To address the above issues, a novel coaxial UAV with a simpler mechanical structure and higher aerodynamic efficiency, referred to as Dumbbell due to its appearance, is proposed in Figure 1(a). As shown in Figures 1(b) and (c), the configuration retains the fundamental features of coaxial UAVs and exhibits higher inherent flight efficiency than quadrotors. By rearranging the motors and servos, the spacing between the upper and lower rotors is increased, significantly reducing aerodynamic coupling. This design effectively mitigates the aerodynamic coupling issues observed in the NYTU coaxial drone while maintaining decoupled control capability. Experiments demonstrate that, under identical payloads, the Dumbbell achieves superior flight efficiency.

The Dumbbell fuselage is an octagonal prism with two sets of coaxially aligned rotors and motors mounted symmetrically along its vertical axis. Servos and their brackets are arranged axially to control the rotor tip-plane orientation, with a deflection range of $[-90°, 90°]$. The fuselage is assembled from carbon fiber plates, nylon, and resin to achieve a lightweight structure. Each carbon fiber plate is precision-machined via CNC to include locating holes and fastened with 304 stainless steel screws through nylon positioning posts. This assembly ensures uniform layer height and prevents torsional deformation during construction, maintaining the upper and lower motors along the fuselage central axis.

The propulsion system comprises a pair of brushless DC motors paired with 13-inch propellers, with electronic speed controllers (ESCs) rated for a continuous current of 60 A. The servo system uses actuators with a torque of 35 kg · cm and a response time of 0.11 s/60°. Power is supplied by a 4000 mAh Li-ion battery pack, with a power distribution board (PDB) monitoring current and voltage in real time to compute flight power. The flight control system features a custom high-performance flight controller board (FCB) operating at 800 Hz, capable of rapid response and command execution. A high-precision barometer measures altitude, while an inertial measurement unit (IMU)—comprising a gyro-

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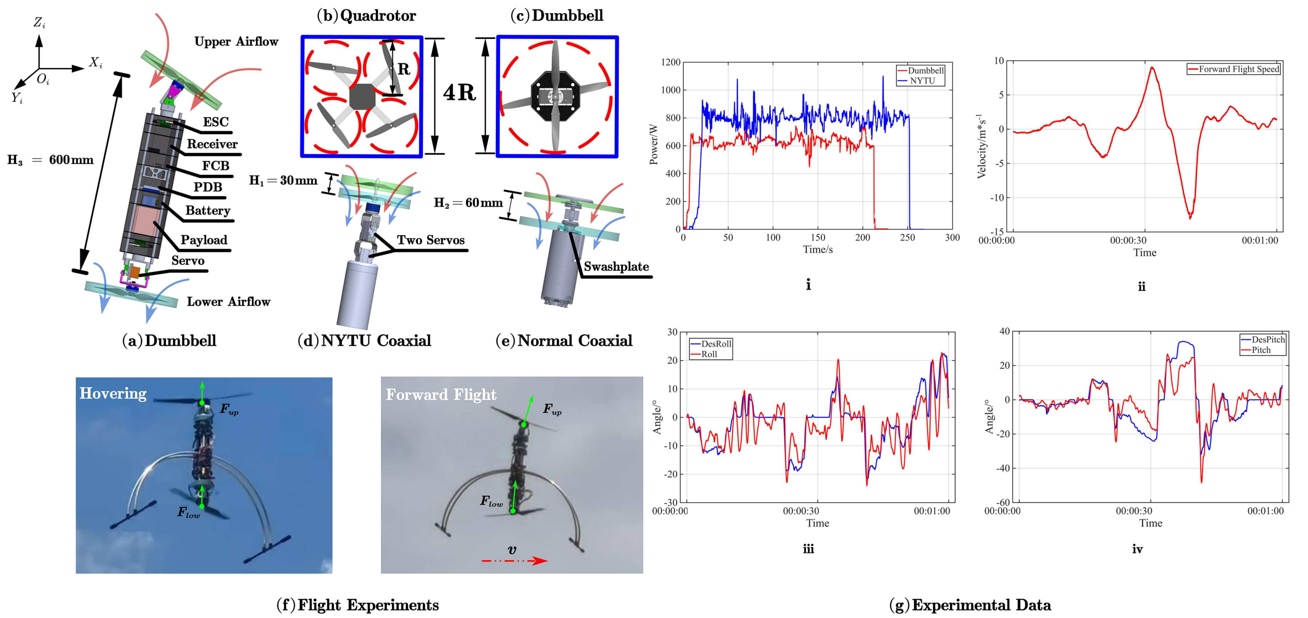

Figure 1 (Color online) (a) Overall design of the Dumbbell and airflow directions during forward flight; (b) and (c) are top views of a quadrotor and the Dumbbell with identical projected area; (d) and (e) are the NYTU and Normal Coaxial configurations exhibit different levels of aerodynamic coupling during forward flight due to variations in rotor spacing; (f) hovering and forward flight; (g) the experimental data refer to power comparison, forward flight speed, and attitude tracking.

scope and an accelerometer—provides attitude data processed via an extended Kalman filter (EKF). A GPS module supplies real-time position and velocity information.

The Dumbbell controls altitude and yaw by adjusting the speeds of the two motors, while pitch and roll are regulated by tilting the rotor tip-planes via the upper and lower servos. During forward flight, for example, a forward tilt of the upper servo generates forward thrust and torque from the upper rotor, pitching the fuselage from hover to forward motion. Once the desired pitch angle and forward speed are reached, a rearward tilt of the upper servo produces a counteracting torque to maintain attitude. Simultaneously, the lower rotor's thrust vector pitch component, synchronized with tilted fuselage attitude, combines with the upper rotor's to produce forward propulsion. This process requires dynamic coordination between servo deflections and motor speeds to ensure both attitude stability and velocity control.

To design the control system of the Dumbbell, we first establish its dynamic model. It is assumed that the local coordinate system is an inertial system: O_i-$X_iY_iZ_i$. The origin of the body coordinate system O_b-$X_bY_bZ_b$ is at the center of gravity, and its orientation is consistent with that of the local coordinate system. We use $p = [x, y, z]^{\mathrm{T}} \in \mathbb{R}^3$ and Euler angles $a = [\phi, \theta, \psi]^{\mathrm{T}} \in \mathbb{R}^3$ to represent the position and rotation angle of the body relative to the inertial system, respectively. The kinematic model of the body can be expressed as follows:

$$\dot{p} = [\dot{x}, \dot{y}, \dot{z}]^{\mathrm{T}} = R_p V_b, \ \dot{a} = \left[\dot{\Phi}, \dot{\theta}, \dot{\psi}\right]^{\mathrm{T}} = R_a \omega_b,$$

where $V_b = [V_x, V_y, V_z]^{\mathrm{T}} \in \mathbb{R}^3$ and $\omega_b = [\omega_x, \omega_y, \omega_z]^{\mathrm{T}} \in \mathbb{R}^3$ are the translational velocity and rotational angular velocity in the body coordinate system, respectively; R_p and R_a are rotation matrices.

Given that the Dumbbell operates at relatively low flight speeds and undergoes minimal changes in maneuvering attitudes, we may neglect the effects of Coriolis and centrifugal forces for the sake of analytical simplicity. Thus, the system dynamics can be described by the following equations:

$$\dot{V}_b = \frac{F_b}{m} + \frac{F_g}{m}, \ \dot{\omega}_b = J^{-1} M_b,$$

where m is the mass of the coaxial helicopter; $J = diag\left(J_{xx}, J_{yy}, J_{zz}\right)$ is the inertia matrix; F_b is the thrust vector; F_g is the projection of the gravity vector in the body coordinate system; and M_b is the aerodynamic moment vector:

$$F_b = \begin{pmatrix} F_{x,up,rotor} + F_{x,low,rotor} + F_{x,body} \\ F_{y,up,rotor} + F_{y,low,rotor} + F_{y,body} \\ F_{z,up,rotor} + F_{z,low,rotor} + F_{z,body} \end{pmatrix},$$

$$M_b = \begin{pmatrix} M_{x,up,rotor} + M_{x,low,rotor} + M_{x,body} \\ M_{y,up,rotor} + M_{y,low,rotor} + M_{y,body} \\ M_{z,up,rotor} + M_{z,low,rotor} \end{pmatrix}.$$

The subscripts $(\cdot)_{up,rotor}, (\cdot)_{low,rotor}, (\cdot)_{body}$ refer to the upper and lower rotors, fuselage body, respectively.

For the control system of the Dumbbell, we focus on its control allocation problem. To ensure a linear relationship between the actual motor output and the controller output, we first perform a compensation calculation for the thrust, obtaining the compensated roll, pitch, yaw, and throttle thrust:

$$F_c = [F_r, F_p, F_y, F_t]^{\mathrm{T}} = kF_{in},$$

where k is the compensation coefficient and F_{in} is the controller output. The larger value between F_r and F_p is taken as $F_{rp_{max}}$. Then, the scaling ratio $P_{rp_{scale}}$ for adjusting roll and pitch is obtained according to the yaw input, and thus the maximum servo force $F_{s_{max}}$ is obtained:

$$F_{s_{max}} = 2(1 - P_{rp_{scale}} \times F_{rp_{max}}).$$

Next, the minimum thrust $F_{rpy_{min}}$ without restricting roll, pitch, and yaw is calculated:

$$F_{rpy_{min}} = max[P_{rp_{scale}} \times F_{rp_{max}}, F_y].$$

When the throttle thrust is greater than the minimum thrust, the throttle thrust serves as the final output thrust ${F_t}'$; otherwise, the minimum thrust becomes the final output thrust, that is

$$ {F_t}' = max(F_t, F_{rpy_{min}}). $$

Actuator outputs are normalized:

$$ \delta_{Mu_n} = F_t + 0.5 \times F_y,\ \delta_{Su_n} = \frac{F_r}{F_t}, $$

$$ \delta_{Ml_n} = F_t - 0.5 \times F_y,\ \delta_{Sl_n} = \frac{F_p}{F_t}. $$

Finally, it is converted into PWM wave values according to the upper and lower limits of motor speed ω_{max}, ω_{min}, and the servo travel R:

$$ \begin{aligned} \delta_{Mu} &= \omega_{min} + (\omega_{max} - \omega_{min}) \times \delta_{Mu_n}, \\ \delta_{Ml} &= \omega_{min} + (\omega_{max} - \omega_{min}) \times \delta_{Ml_n}, \\ \delta_{Su} &= R \times \delta_{Su_n}, \\ \delta_{Sl} &= R \times \delta_{Sl_n}. \end{aligned} $$

After realizing the stable control of the body, we continue to discuss the flight efficiency of the Dumbbell. First, we will explain the inherent flight efficiency advantages of Dumbbell compared to multi-rotor (using the common quadcopter as a reference point). As shown in Figures 1(a) and (b), according to the relevant theories of aerodynamics, the total thrust of the quadrotor UAV can be obtained as

$$ F_Q = 4F_{Q1} = 4\rho C_T \pi \omega^2 R^4, $$

where ρ is the air density, C_T is the lift coefficient, and ω is the angular velocity of the propeller. Similarly, when the rotational angular velocity of the propellers is the same, the total thrust of the coaxial UAV can be obtained as

$$ F_C = 2F_{C1} = 32\rho C_T \pi \omega^2 R^4. $$

From the above comparison, it can be concluded that under identical total aircraft weight conditions, Dumbbell generates higher thrust and demonstrates superior flight efficiency compared to the quadrotor.

As representative types of coaxial rotor drones, both the NYTU Coaxial and Normal Coaxial configurations exhibit small inter-rotor spacing. Consequently, the downwash generated by the upper rotor fails to fully contract before reaching the lower rotor, resulting in aerodynamic interference that covers a majority of the lower rotor's disk area. This interference alters the effective angle of attack and induces lift fluctuations. Such aerodynamic coupling not only reduces flight efficiency but also introduces additional challenges to flight stability. In contrast, the Dumbbell configuration structurally mitigates this issue.

To study the aerodynamic coupling problem of coaxial twin rotors in a general way, we use the spacing ratio $Z = H/D$ to represent the relationship between the spacing of the upper and lower rotors and the propeller diameter, where H is the spacing between the upper and lower rotors, and D is the propeller diameter. According to the discussion in [7] on the influence of coaxial spacing on flight efficiency, when $Z > 0.15$, the flight efficiency of the system is basically unaffected; when $Z < 0.15$, the system efficiency decreases under high thrust conditions. As shown in Figures 1(a), (d), and (e), the propellers are all 13-inch propellers, i.e., $D \approx 430$ mm, and the values of Z in these three models are, respectively

$$ Z_{Dumbbell} \approx 1.40, Z_{NYTU} \approx 0.07, Z_{Normal} \approx 0.14. $$

Obviously, the Dumbbell improves the problem of aerodynamic coupling by virtue of its sufficiently large spacing between the upper and lower rotors, so it theoretically has the highest energy efficiency. Typically, the flight efficiency of a UAV refers to the ratio of thrust to mechanical power. Here, we approximate the easier-to-measure electric power as mechanical power. As shown in Figure 1(g)(iv), the Dumbbell configuration consumes approximately 20% less power. This observation is also supported by Figure 4 in [8].

Conlusion. This work presents a novel coaxial unmanned helicopter named Dumbbell. Compared with conventional coaxial UAVs, its optimized rotor layout and decoupled control strategy significantly improve aerodynamic efficiency. The integrated control of motor speeds and servo deflections enables omnidirectional motion while maintaining attitude stability during complex maneuvers. Experimental results demonstrate that the Dumbbell achieves notable improvements in structural simplicity, efficiency, and control performance, outperforming other coaxial UAVs in flight tests and validating the effectiveness of the design.

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Supporting information Video and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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