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Design and hovering control of a twin rotor tail-sitter UAV

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The tail-sitter unmanned aerial vehicles (UAVs) combine the vertical takeoff and landing (VTOL) capabilities of rotary-wing UAVs and the efficient long-distance flight capability of fixed-wing UAVs. When compared with other hybrid aircraft configurations such as tilt-rotor [1] and tilt-wing [2] UAVs, the tail-sitter UAV possesses the simplest configuration and requires no extra mechanisms for performing the VTOL maneuver. This brings several benefits including high payload and low susceptibility to malfunctions.

Despite its several advantages, the tail-sitter UAV poses considerable challenges, among which the major challenge is the configuration design. One popular configuration in [3] is the single-propeller tail-sitter, which solely relies on the propeller wash flowing over its control surfaces to conduct attitude control during the hovering flight. Because these UAVs are not specifically designed for tail-sitters, control effectiveness is rather low during the low-speed vertical flight. The Quadrotor tail-sitter is another type of configuration that purely uses the differential thrust for attitude control in its full flight envelope [4]. Although differential thrust can be used to achieve an excellent attitude control performance in the hovering flight, its effectiveness can be degraded during level flight because of decreased rotor thrust under high-speed flight conditions. Another common design [5], which attempts to balance the two aforementioned configurations, uses the differential thrust of two rotors and the deflection of elevons to effect control. These tail-sitter UAVs are designed with dual rotors and elevons that are mounted on two opposite sides of the fuselage. During the hovering flight, the velocity of the propeller wash is considerably weakened by the fuselage, which can cause impaired control capability of the elevons. Apart from these three common types of configurations, other designs, such as U-lion [6], which exhibits relatively high complexity, can increase the vulnerability of the system to malfunctions.

Inspired by previous designs, a novel configuration design exhibiting a high control capability has been proposed for the twin rotor tail-sitter. The designed tail-sitter and its flight envelope are illustrated in Figures 1(a) and (b), respectively. Unlike previous twin-rotor configurations, our designed tail-sitter can achieve high control capability without the requirement of any additional devices. In particular, the rotors of the tail-sitter are moved down from the front of the fuselage and placed right above the elevons. This design decreases the distance between rotors and elevons, thereby ensuring that the elevons can maximize the high-speed airflow to generate adequate control torque and stabilize the aircraft in the presence of large disturbances. In our configuration, the fuselage of the tail-sitter is truncated for mounting rotors, which may lead to different aerodynamic characteristics especially in cruise flight. The computational fluid dynamics techniques are applied for exploiting the aerodynamics of the proposed aircraft configuration. The results indicate that truncation

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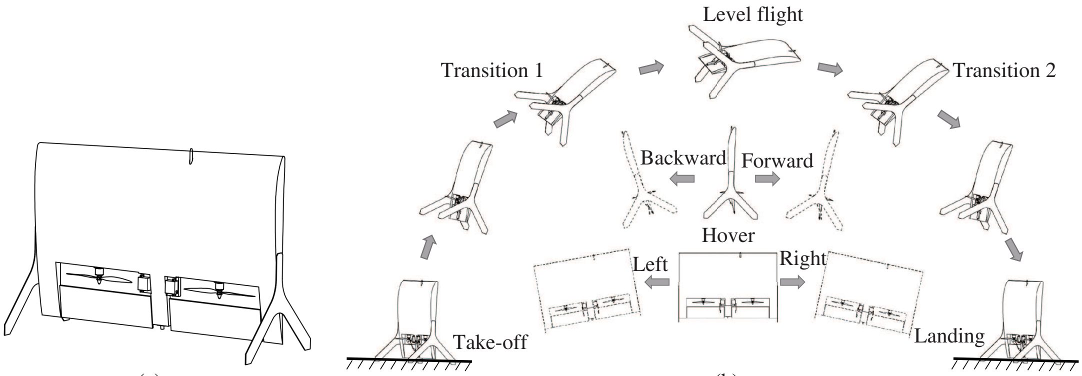

Figure 1 Designed twin rotor tail-sitter (a) and its flight envelope (b).

of the wing causes decreased cruise flight efficiency but to an acceptable degree. Our design attempts to balance the control capability and cruise flight efficiency.

Fuselage and propulsion. The fuselage of the tail-sitter comprises a main wing and a set of landing gear. The main wing, having a span of 0.9 m and a chord length of 0.69 m, is manufactured from flat foam sheets and strengthened by the carbon fiber rods to make the tail-sitter suitably lightweight and solid. Two elevons are made of flat plates and actuated by two servos hidden in the wing, and they can deflect between $[-20°, +20°]$ to provide sufficient control torques with respect to the corresponding axes. The landing gear manufactured from carbon fiber is designed to guarantee successive autonomous takeoff and landing as well as to increase the lateral stability. A 6s LIPO battery is selected to power two 400 W brushless electrical motors, which actuate two propellers with a diameter of 10 inches.

Actuation mode. Because of the inherent underactuated character of the developed tail-sitter, translational movement is achieved by initially tilting its body to a certain attitude so that the thrust components can drive the tail-sitter toward the target position. Further, attitude control is achieved by diverting the airflow stream over elevons and the differential thrust. During different flight modes, the source of airflow stream can vary a lot. For example, in hovering flight the propeller wash dominates while in level flight both propeller wash and freestream count.

Avionics. The commercially available Pixhawk Autopilot [1)] is adopted as the core avionics. Measurements obtained from tri-sensors including accelerometers, gyroscopes, and magnetometers, are fused for estimating the tail-sitter's attitude using the gradient-decent algorithm. A barometer sensor and an ultrasonic distance sensor are utilized as the altitude sensors. Position and velocity of the tail-sitter are estimated using the Kalman Filter [7] based on GPS measurements. Furthermore, a differential pressure sensor and a pitot tube are mounted in the front of the main wing for airspeed measurement.

Besides configuration design, the hovering control of such an aircraft is also challenging due to its highly unstable nature similar to that of an inverted pendulum. To stabilize the aircraft, a nonlinear backstepping controller [8] derived in the quaternion space by utilizing the Lyapunov stability theory is proposed. It is first assumed that accelerations due to aircraft rotation and non-diagonal moment inertia terms are both neglected. The dynamic model can then be formulated in a compact form as

$$\begin{aligned} &\dot{p} = v, \quad \dot{v} = ge_3 + \frac{R(q)^{\mathrm{T}} f_F}{m}, \\ &\dot{q} = \frac{1}{2}\begin{bmatrix} 0 \\ \omega \end{bmatrix} \otimes q, \quad I\dot{\omega} = -\omega \times I\omega + f_M, \end{aligned} \tag{1}$$

where p and v refer to the position and velocity vector expressed in the inertial frame respectively. $e_3 = [0, 0, 1]^{\mathrm{T}}$ is a unit vector and I is the diagonal matrix composed of moments of inertia. q is the attitude quaternion and $R(q)$ denotes its corresponding rotation matrix. m denotes the aircraft mass and g represents the gravity constant. ω is the angular velocity while f_F and f_M are the vector-valued force and moment functions which can be calculated as follows:

$$f_F = \begin{bmatrix} T_l\left(1 - \frac{SC_{D_{\delta_e}}\delta_l}{S_{\text{disk}}}\right) + T_r\left(1 - \frac{SC_{D_{\delta_e}}\delta_r}{S_{\text{disk}}}\right) \\ 0 \\ \frac{(T_l\delta_l + T_r\delta_r)SC_{L_{\delta_e}}}{S_{\text{disk}}} \end{bmatrix},$$

1) Pixhawk Autopilot Research Project. https://pixhawk.org.

$$f_M = \begin{bmatrix} \tau(T_r - T_l) + \frac{l_x(T_l\delta_l+T_r\delta_r)SC_{L_{\delta_e}}}{S_{\text{disk}}} \\ l_y\left(\frac{(T_l\delta_l+T_r\delta_r)SC_{L_{\delta_e}}}{S_{\text{disk}}}\right) \\ l_zT_l\left(1-\frac{SC_{D_{\delta_e}}\delta_l}{S_{\text{disk}}}\right)-l_zT_r\left(1-\frac{SC_{D_{\delta_e}}\delta_r}{S_{\text{disk}}}\right) \end{bmatrix}. \tag{2}$$

In the aforementioned equations, $C_{L_{\delta_e}}$ and $C_{D_{\delta_e}}$ denote the coefficient derivatives of elevons. S is the reference area, S_{disk} is the disk area of the spinning propeller, and τ refers to the propeller's torque-to-thrust ratio. δ_l and δ_r are the deflection angles of elevons, whereas T_l and T_r are the thrusts of two rotors. l_x, l_y, and l_z are the lengths of moment arms of each axis.

Let the subscript c represent the virtual control input, $\tilde{p}$, $\tilde{v}$, $\vec{\tilde{q}}$ and $\tilde{\omega}$ denote the corresponding error terms, $\hat{\omega}$ denote the rotational rate of q_c. Suppose the matrices $K_i \in \mathbb{R}^{3\times3}$ $(i = 1, 2, \ldots, 4)$ are all positive definite matrices. The derived backstepping controller can be summarized given the desired position p_d and its derivative $\dot{p}_d$.

$$\begin{aligned} &v_c = -K_1\tilde{p} + \dot{p}_d, \quad \mu_c = -K_2\tilde{v} - ge_3 + \dot{v}_c - \tilde{p}, \\ &\omega_c = -2\overline{S}^{-1}(K_3\vec{\tilde{q}} - M^{\mathrm{T}}\tilde{v}) + R(\tilde{q})\hat{\omega}, \\ &\delta = W^{-1}(-K_4\tilde{\omega} - \overline{S}^{\mathrm{T}}\vec{\tilde{q}} + S(\omega_c)I\tilde{\omega} - \sigma), \\ &\mu_c = \frac{1}{m}R(q_c)^{\mathrm{T}}f_F, \quad ||f_F|| = m||\mu_c||, \end{aligned} \tag{3}$$

where

$$\begin{aligned} &\overline{S} = S(\vec{\tilde{q}}) + \tilde{q}_0I_3, \quad \sigma = S(I\omega_c)\omega_c - I\dot{\omega}_c, \\ &S(i) = \begin{bmatrix} 0 & -i_3 & i_2 \\ i_3 & 0 & -i_1 \\ -i_2 & i_1 & 0 \end{bmatrix}, \quad i = \omega_c, I\tilde{\omega}, I\omega_c, \\ &W = \frac{1}{S_{\text{disk}}}\begin{bmatrix} -\tau S_{\text{disk}} & l_xSC_{L_{\delta_e}} & l_xSC_{L_{\delta_e}} \\ 0 & l_ySC_{L_{\delta_e}} & l_ySC_{L_{\delta_e}} \\ l_zS_{\text{disk}} & l_zSC_{D_{\delta_e}} & l_zSC_{D_{\delta_e}} \end{bmatrix}, \\ &M = \frac{2R(q_c)^{\mathrm{T}}(\tilde{q}_0I_3 - S(\vec{\tilde{q}}))^{\mathrm{T}}S(f_F)}{m}. \end{aligned} \tag{4}$$

The derived backstepping controller can naturally tackle nonlinear dynamics and theoretically guarantee system stability. In addition, the proposed backstepping controller can automatically handle all the flight modes in a unified framework without any requirement to separately design the linear controllers for each flight mode. Hovering flight experimental results show that both the attitude and altitude of the developed tail-sitter can be well controlled in a tight range of corresponding reference values even in the presence of large disturbances.

In conclusion, we propose a new configuration for the twin rotor tail-sitter that can take full advantage of the propeller airflow to increase attitude control effectiveness without the requirement of any additional actuators. Further, a simplified yet effective dynamic model of the designed tail-sitter in hovering state is established, based on which a nonlinear backstepping controller is derived directly in the quaternion space using the Lyapunov theory. Effectiveness of both the proposed configuration and controller performance are verified through indoor flight experiments.

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Supporting information Videos 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.

References

1 Song Y G, Wang H J. Design of flight control system for a small unmanned tilt rotor aircraft. Chin J Aeronaut, 2009, 22: 250–256
2 Sato M, Muraoka K. Flight controller design and demonstration of quad-tilt-wing unmanned aerial vehicle. J Guid Control Dyn, 2015, 38: 1071–1082
3 Kita K, Konno A, Uchiyama M. Transition between level flight and hovering of a tail-sitter vertical takeoff and landing aerial robot. Adv Robot, 2010, 24: 763–781
4 Oosedo A, Abiko S, Konno A, et al. Development of a quad rotor tail-sitter VTOL UAV without control surfaces and experimental verification. In: Proceedings of the IEEE International Conference on Robotics and Automation, Karlsruhe, 2013. 317–322
5 Verling S, Weibel B, Boosfeld M, et al. Full attitude control of a VTOL tailsitter UAV. In: Proceedings of the IEEE International Conference on Robotics and Automation, Stockholm, 2016. 3006–3012
6 Wang K L, Ke Y J, Chen B M. Autonomous reconfigurable hybrid tail-sitter UAV U-Lion. Sci China Inf Sci, 2017, 60: 033201
7 Simon D. Optimal State Estimation: Kalman, H_∞ and Nonlinear Approaches. Hoboken: John Wiley & Sons, Inc., 2006
8 Zhang Z, Wang F, Guo Y, et al. Multivariable sliding mode backstepping controller design for quadrotor UAV based on disturbance observer. Sci China Inf Sci, 2018, 61: 112207