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

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Introduction

X47-B

MQ-8

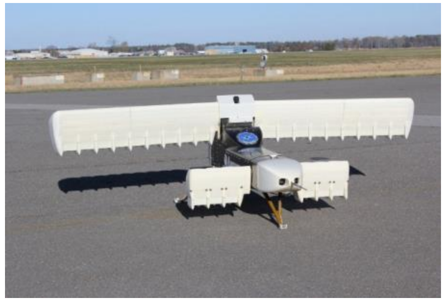
Fixed Wing UAV:
High speed
Efficient cruise flight
Inflexible take-off and landing

Rotary Wing UAV:
low speed
Inefficient cruise flight
Vertical take-off and landing

VTOL Fixed Wing UAVs

Tilt-rotor UAV

Tilt-body UAV

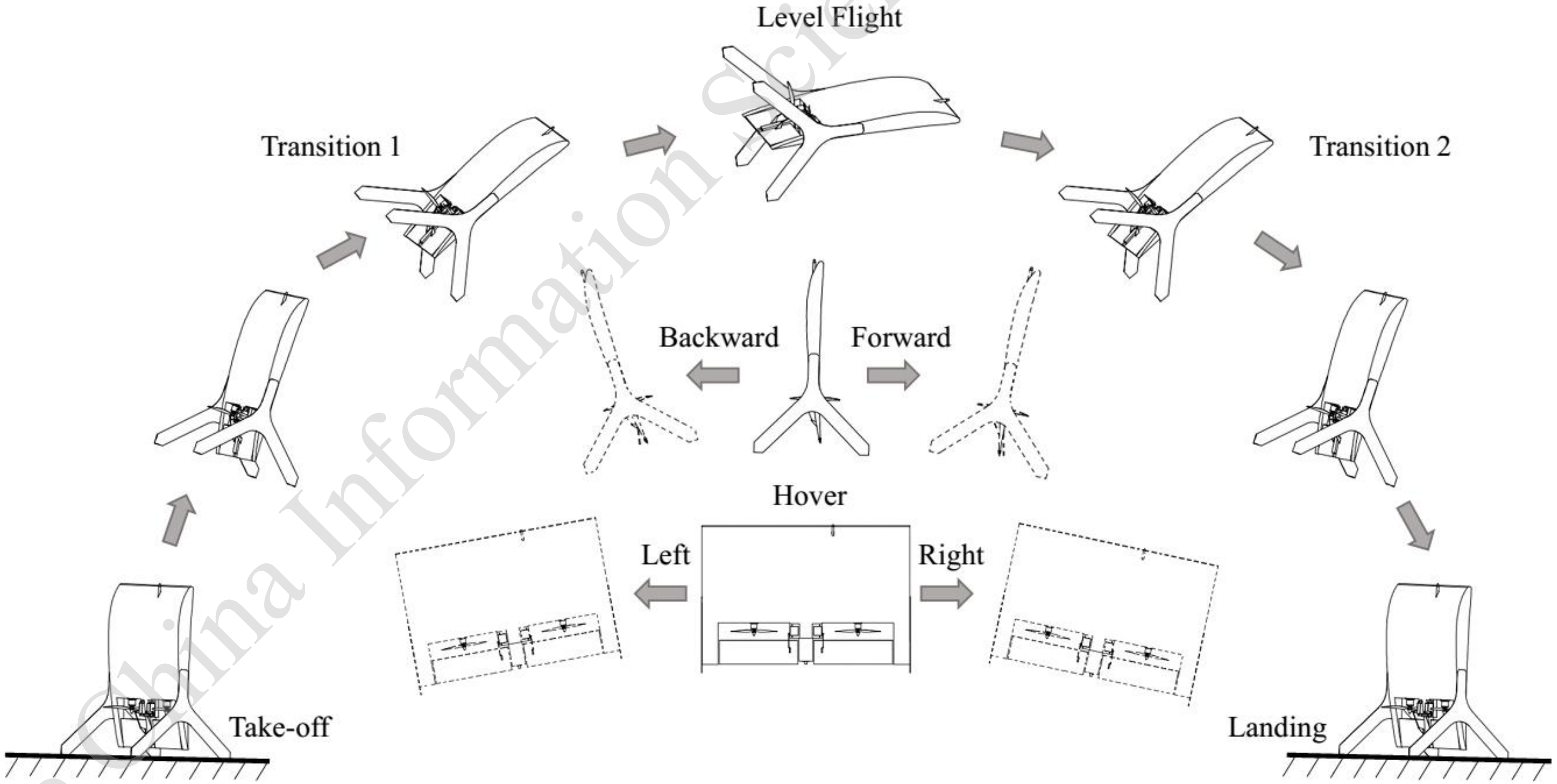


Tilt-wing UAV

Tail-sitter UAV

Configuration Design

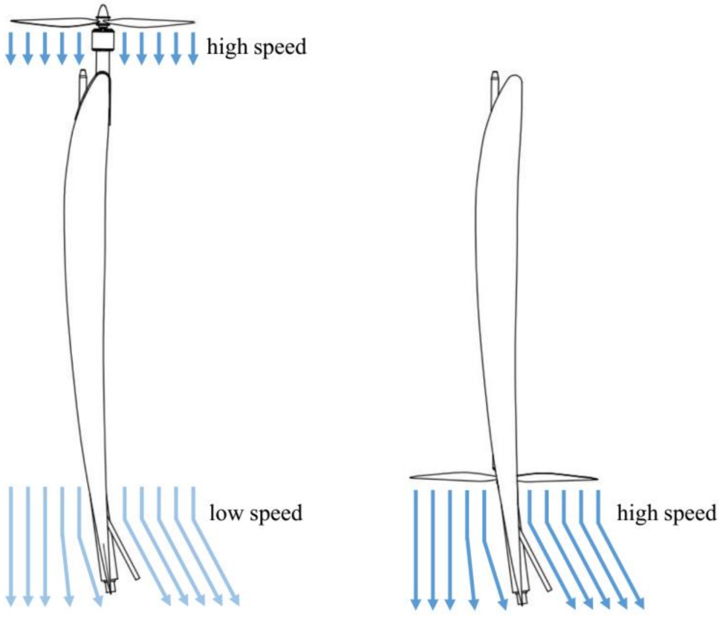
Developed Tail-sitter



Flight Envelope

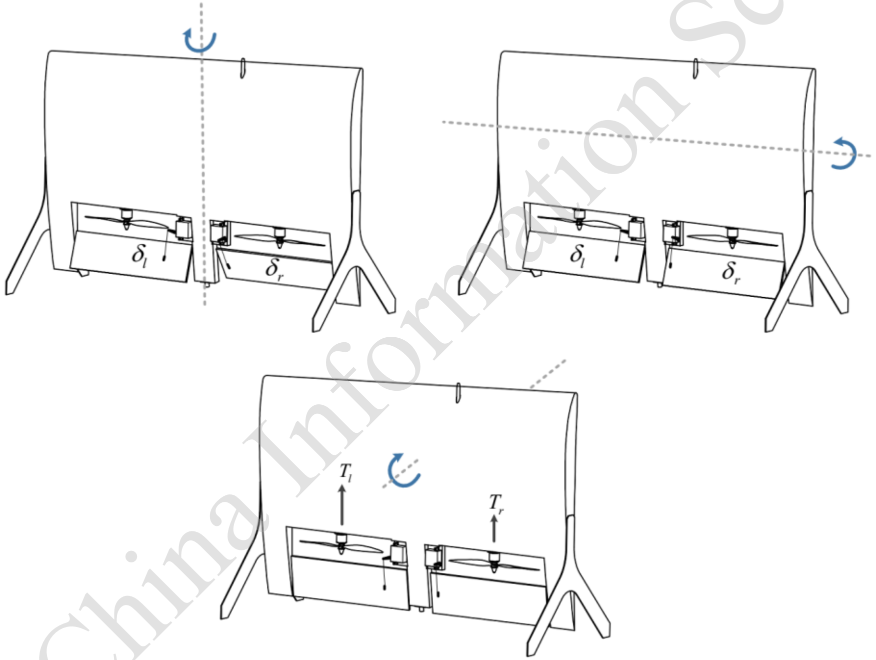
The designed tail-sitter can achieve comparable or even higher control capability without requiring any extra devices.

Configuration Design

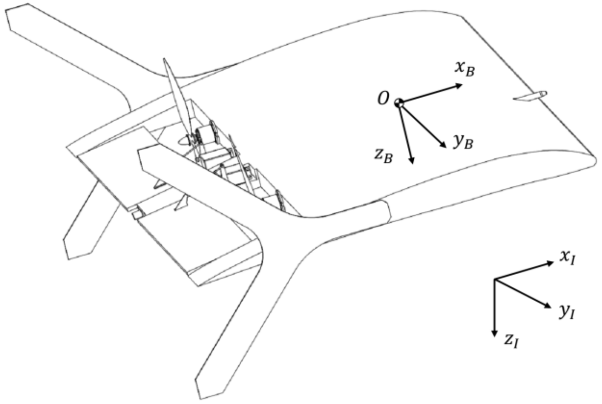


(a) traditional design (b) our design

Comparison with traditional design



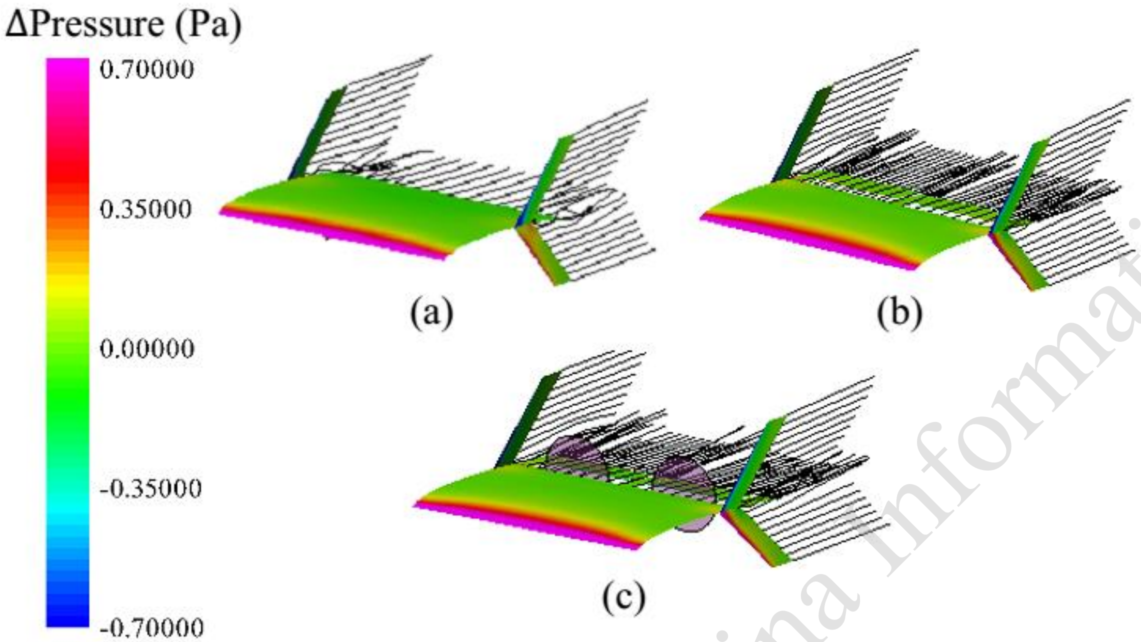
Actuation mode



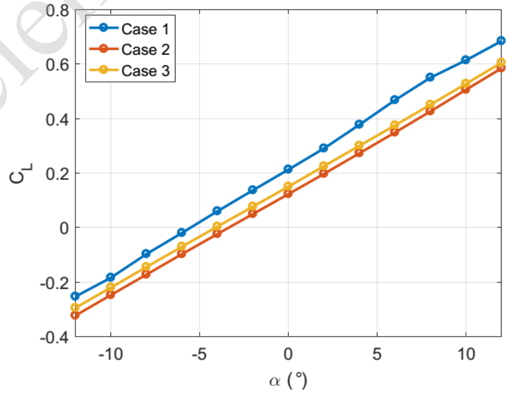
Coordinate system definition

In our design, elevons can take the most of high-speed airflow to generate adequate control torque to stabilize the aircraft.

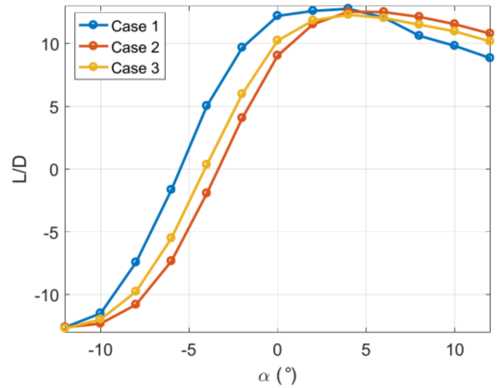
Configuration Design



Pressure Contour ($\alpha = 2^{\circ}$, $\beta = 0^{\circ}$, speed=15m/s)
(a) fuselage without truncation
(b) truncated fuselage without rotors
(c) truncated fuselage with rotors



Lift Coefficient ($\beta = 0^{\circ}$, speed=15m/s)



Lift-drag-ratio ($\beta = 0^{\circ}$, speed=15m/s)

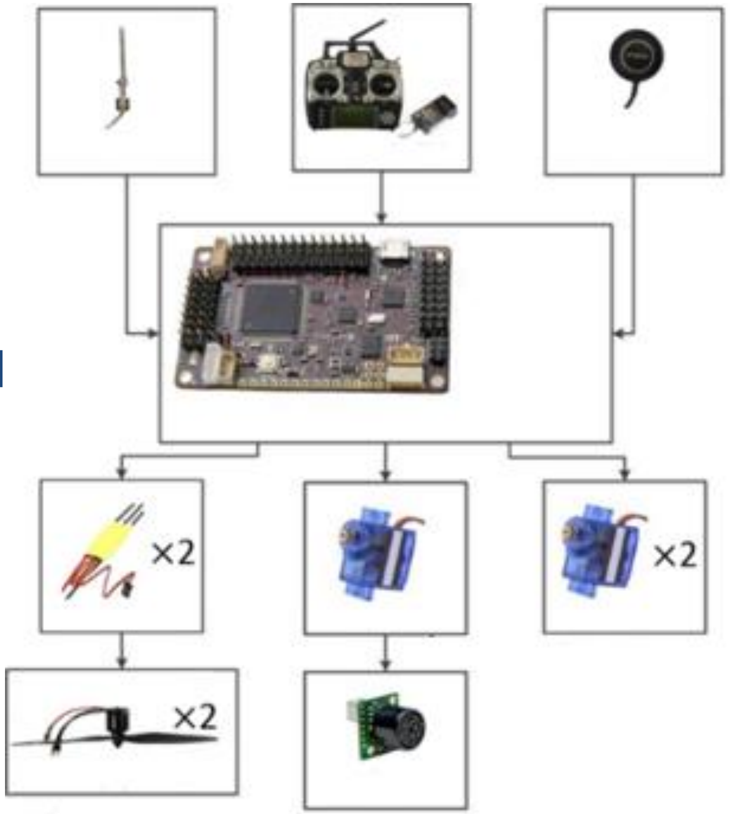
Truncation of the wing leads to decrease of cruise flight efficiency but to an acceptable degree. **Our design strikes a balance between control capability and cruise flight efficiency.**

Configuration Design

Performance Data

Performance Parameter	Value
m	$1.36\ kg$
b_{ref}	$0.9\ m$
c_{ref}	$0.69\ m$
S_{ref}	$0.621\ m^2$
$V_{\max\ cruise}$	$30\ m/s$
$(\frac{L}{D})_{cruise}$	12.3
$T_{\max\ cruise}$	$1\ h$
Thrust-to-weight ratio	1.6
Propeller	10×47
Motor kv	980
Battery capacity	$3300\ mAh$

Developed Tail-sitter



Avionics

Control Scheme

Simplified Model

$$\dot{p} = v$$

$$\dot{v} = ge_3 + \frac{R(q)^T f_F}{m}$$

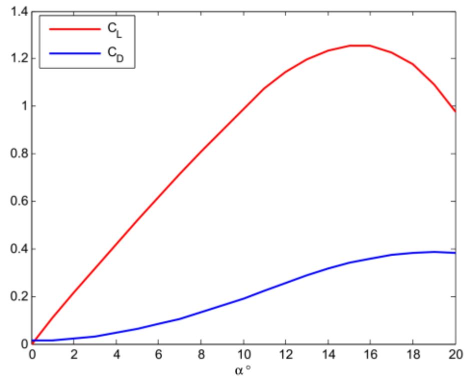
$$\dot{q} = \frac{1}{2}\begin{bmatrix}0\\ \omega\end{bmatrix} \otimes q$$

$$I\dot{\omega} = -\omega \times I\omega + f_M$$

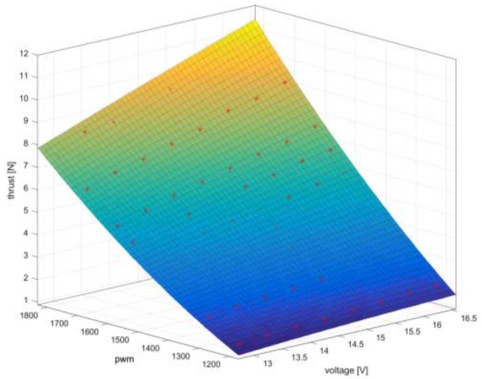
Force and moment functions

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

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



Lift and drag coefficients of elevon



Fitting result of propeller thrust data

Assumptions:

Accelerations caused by the rotation of the aircraft are negligible.

The term I_{xz} is far smaller than diagonal terms I_{xx}, I_{yy}, I_{zz} and is eliminated.

Control Scheme

Step 1: Position Control

Suppose the continuous signals p_d and $\dot{p}_d$ are known, consider the following dynamics

$$\dot{\tilde{p}} = v_c + \tilde{v} - \dot{p}_d$$

where

$$\tilde{p} = p - p_d \qquad \tilde{v} = v - v_c$$

Considering the following Lyapunov function

$$V_1 = \frac{1}{2}\tilde{p}^T\tilde{p}$$

whose derivative is

$$\dot{V}_1 = \tilde{p}^T(v_c + \tilde{v} - \dot{p}_d)$$

Let $v_c = -K_1\tilde{p} + \dot{p}_d$, it can be obtained that

$$\dot{V}_1 = -\tilde{p}^T K_1\tilde{p} + \tilde{p}^T\tilde{v}$$

Step 2: Velocity Control

Suppose the continuous signals v_c and $\dot{v}_c$ are known, consider the following dynamics

$$\dot{\tilde{v}} = ge_3 + \frac{R(q)^T f_F}{m} - \dot{v}_c$$
$$= ge_3 + \mu_c + \tilde{\mu} - \dot{v}_c$$

Where the desired thurst T_{l_c}, T_{r_c} and attitude q_c are identified by μ_c.

Considering the following Lyapunov function

$$V_2 = V_1 + \frac{1}{2}\tilde{v}^T\tilde{v}$$

whose derivative is

$$\dot{V}_2 = \dot{V}_1 + \tilde{v}^T(ge_3 + \mu_c + \tilde{\mu} - \dot{v}_c)$$

Let $\mu_c = -K_2\tilde{v} - ge_3 + \dot{v}_c - \tilde{p}$ yeilds

$$\dot{V}_2 = -\tilde{p}^T K_1\tilde{p} - \tilde{v}^T K_2\tilde{v} + \tilde{v}^T\tilde{\mu}$$

Control Scheme

Step 3: Attitude Control

Error quaternion dynamics are given by

$$\dot{\tilde{q}} = \frac{1}{2}\begin{bmatrix} 0 \\ \omega_c + \tilde{\omega} - R(\tilde{q})\hat{\omega} \end{bmatrix} \otimes \tilde{q}$$

where $\omega = \omega_c + \tilde{\omega}$, $\hat{\omega}$ is the rotational rate of q_c.
Let the Lyapunov function be

$$V_3 = V_2 + \frac{1}{2}(1 - \tilde{q}_0^2)$$

whose derivative is

$$\dot{V}_3 = -\tilde{p}^T K_1 \tilde{p} - \tilde{v}^T K_2 \tilde{v} + \tilde{v}^T \tilde{\mu} + \vec{\tilde{q}}^T \frac{1}{2} \bar{S}[\omega_c + \tilde{\omega} - R(\tilde{q})\hat{\omega}]$$

where

$$\bar{S} = S(\vec{\tilde{q}}) + \tilde{q}_0 I_3 \qquad S(\vec{\tilde{q}}) = \begin{bmatrix} 0 & -\tilde{q}_3 & \tilde{q}_2 \\ \tilde{q}_3 & 0 & -\tilde{q}_1 \\ -\tilde{q}_2 & \tilde{q}_1 & 0 \end{bmatrix}$$

Assume $T_l = T_{l_c}$, $T_r = T_{r_c}$, it can be obtained

$$\tilde{\mu} = \frac{[(R(\tilde{q}) - I_3)R(q_c)]^T f_F}{m}$$

$$= \frac{2R(q_c)^T \left(\tilde{q}_0 I_3 - S(\vec{\tilde{q}})\right)^T S(f_F)\vec{\tilde{q}}}{m}$$

$$= M\vec{\tilde{q}}$$

As a result, it can be obtained

$$\dot{V}_3 = -\tilde{p}^T K_1 \tilde{p} - \tilde{v}^T K_2 \tilde{v} + \tilde{v}^T M \vec{\tilde{q}} + \vec{\tilde{q}}^T \frac{1}{2} \bar{S}[\omega_c + \tilde{\omega} - R(\tilde{q})\hat{\omega}]$$

Choosing $\omega_c = -2\bar{S}^{-1}\left(K_3 \vec{\tilde{q}} - M^T \tilde{v}\right) + R(\tilde{q})\hat{\omega}$ leads to

$$\dot{V}_3 = -\tilde{p}^T K_1 \tilde{p} - \tilde{v}^T K_2 \tilde{v} - \vec{\tilde{q}}^T K_3 \vec{\tilde{q}} + \vec{\tilde{q}}^T \bar{S} \tilde{\omega}$$

Control Scheme

Step 4: Angular Rate Control

The dynamics of the angular rate error $\tilde{\omega}$ is given by

$$I\dot{\tilde{\omega}} = \Sigma\tilde{\omega} + S(I\omega_c)\omega_c - I\dot{\omega}_c + W\delta$$

where

$$\Sigma = S(I\tilde{\omega}) + S(I\omega_c) - S(\omega_c)I$$

$$W = \frac{1}{S_{disk}}\begin{bmatrix} -\tau S_{disk} & l_x SC_{L_{\delta_e}} & l_x SC_{L_{\delta_e}} \\ 0 & l_y SC_{L_{\delta_e}} & l_y SC_{L_{\delta_e}} \\ l_z S_{disk} & l_z SC_{D_{\delta_e}} & l_z SC_{D_{\delta_e}} \end{bmatrix}$$

$$\delta = \begin{bmatrix} T_l - T_r \\ T_l\delta_l \\ T_r\delta_r \end{bmatrix}$$

Let the Lyapunov function be

$$V_4 = V_3 + \tilde{\omega}^T I\tilde{\omega}$$

whose derivative is

$$\dot{V}_4 = \dot{V}_3 + \tilde{\omega}^T[\Sigma\tilde{\omega} + S(I\omega_c)\omega_c - I\dot{\omega}_c + W\delta]$$

Choosing

$$\delta = W^{-1}(-K_4\tilde{\omega} - \bar{S}^T\vec{\tilde{q}} + S(\omega_c)I\tilde{\omega} - S(I\omega_c)\omega_c + I\dot{\omega}_c)$$

leads to

$$\dot{V}_4 = -\tilde{p}^T K_1\tilde{p} - \tilde{v}^T K_2\tilde{v} - \vec{\tilde{q}}^T K_3\vec{\tilde{q}} - \tilde{\omega}^T K_4\tilde{\omega}$$

Step 5: Control Allocation

Since $\mu_c = \frac{1}{m}R(q_c)^T f_F$, we can have

$$\|f_F\| = m\|\mu_c\|$$

Along with the constraint of thrust difference of two rotors, the desired thrust T_{l_c} and T_{r_c} can be determined.

Control Scheme

Revisiting the Nonlinear Backstepping Controller

Linear attitude controller

$$\delta = \underbrace{K_1^l \vec{\tilde{q}} - K_2^l \omega}_{feedback}$$

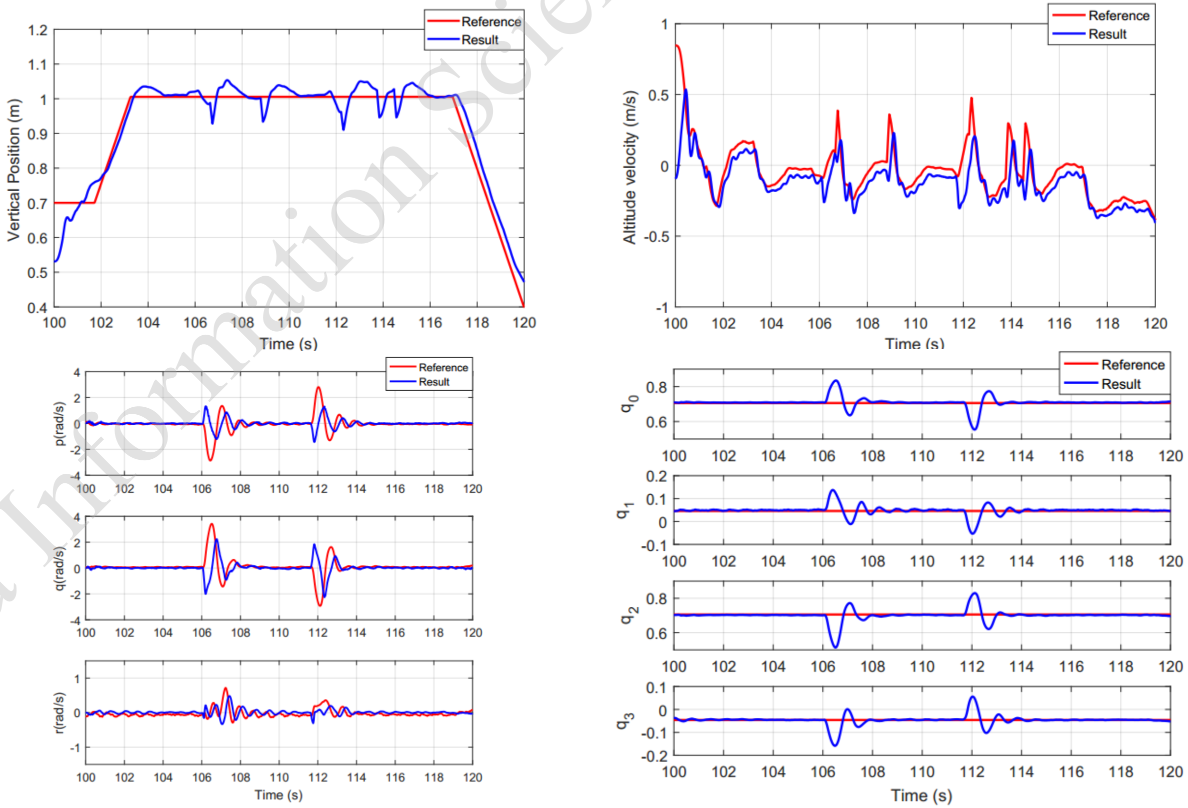
Our designed controller

$$\delta = \underbrace{W^{-1}}_{actuation\ model} \left(\underbrace{-K_4 \tilde{\omega} - \bar{S}^T \vec{\tilde{q}} + S(\omega_c) I \tilde{\omega}}_{feedback} + \underbrace{I \dot{\omega}_c + S(\omega_c) I \omega_c}_{feedforward} \right)$$

- **Naturally address nonlinear dynamics through feedforward control**
- **Theoretically guarantee system stability**
- **Automatically handle all flight modes in a unified framework**

Control Scheme

Indoor Hover Flight. (Only IMU and ultrasonic sensors are used for measurements)



Tracking Performance

Both attitude and altitude can be well controlled in a tight range of corresponding reference inputs even in the presence of large disturbances.

Conclusion

- A new configuration with high control effectiveness is designed for the twin rotor tail-sitter UAV.
- A nonlinear backstepping controller is derived based on a simplified yet effective dynamic model directly in the quaternion space using the Lyapunov theory.
- Effectiveness of both the proposed configuration and controller performance are verified through indoor flight experiments.

Future work will be focused on the transition flight control.

Thanks